

2014

# Performance of basalt fibre mixed concrete

Padmanabhan Iyer  
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**PERFORMANCE OF BASALT FIBRE MIXED CONCRETE**

By

Padmanabhan Iyer

A Thesis

Submitted to the Faculty of Graduate Studies  
through the Department of Civil and Environmental Engineering  
in Partial Fulfillment of the Requirements for  
the Degree of Master of Applied Science  
at the University of Windsor

Windsor, Ontario, Canada

2014

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# **PERFORMANCE OF BASALT FIBRE MIXED CONCRETE**

by

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## DECLARATION OF ORIGINALITY

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## ABSTRACT

In this research, the mechanical properties of smart concrete made of chopped basalt fibre were investigated. Two different types of basalt fibres (bundles and filaments) were used. The basalt fibre specimens were cast using basalt fibres of varying length (12 mm, 36 mm, and 50 mm) and varying fibre dosage (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>). The results indicated that the 50 mm basalt bundled fibre at 8 kg/m<sup>3</sup> was the optimum fibre length and fibre volume for basalt bundled fibres. It provided the optimum increase in flexural strength, compressive strength, and split tensile strength when compared with plain concrete. Similarly, the 36 mm basalt filament at 8 kg/m<sup>3</sup> was the optimum fibre length and fibre volume for basalt filaments. It provided the optimum increase in flexural strength, compressive strength, and split tensile strength when compared with plain concrete.

## DEDICATION

To my family and friends, who have shown tremendous support and understanding.

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## LIST OF ABBREVIATIONS/SYMBOLS

|  |   |
|--|---|
| a  | Distance between the line of fracture and the nearest support measured along the centerline of the bottom surface of the beam |
| AR-glass   | Alkali resistant glass  |
| b  | Average width of the specimen   |
| BB   | Basalt bundle   |
| BF   | Basalt filament   |
| BFRC   | Basalt fibre reinforced concrete  |
| CI   | Confidence interval   |
| CV   | Coefficient of variation  |
| d  | Average depth of the specimen   |
| DF   | Degree of freedom   |
| FRC  | Fibre reinforced concrete   |
| $f'_c$   | Compressive strength  |
| GFRC   | Glass fibre reinforced concrete   |
| HPFRC  | High-performance fibre reinforced composites  |
| H <sub>0</sub>                                     | Null hypothesis   |
| H <sub>1</sub>                                     | Alternative hypothesis  |
| I <sub>5</sub> , I <sub>10</sub> , I <sub>20</sub> | Toughness indices   |
| $l$  | Span length   |
| l/d  | Aspect ratio (length/diameter)  |
| LDT  | Linear Displacement Transducer  |
| MOR, R, $f_r$                                      | Modulus of rupture  |

|                   |                                       |
|-------------------|---------------------------------------|
| n                 | Number of tests                       |
| n <sub>A</sub>    | Number of specimens in sample group A |
| n <sub>B</sub>    | Number of specimens in sample group B |
| P                 | Maximum applied load                  |
| PAN               | Polyacrylonitrile                     |
| PC                | Plain concrete                        |
| PP                | Polyolefin fibre                      |
| R <sup>2</sup>    | Coefficient of determination          |
| R <sub>5,10</sub> | Residual strength factor              |
| s                 | Sample standard deviation             |
| s <sub>A</sub>    | Standard deviation of sample group A  |
| s <sub>B</sub>    | Standard deviation of sample group B  |
| SCC               | Self-compacting concrete              |
| SD                | Standard deviation                    |
| SF                | Steel fibre                           |
| SFRC              | Steel fibre reinforced concrete       |
| SNFRC             | Synthetic fibre reinforced concrete   |
| t                 | Tested t-value                        |
| μ                 | Population mean                       |
| μ <sub>0</sub>    | Assumed mean                          |
| μ <sub>1</sub>    | Mean of sample group A                |
| μ <sub>2</sub>    | Mean of sample group B                |

|                       |  |
|-----------------------|--|
| $\mu\text{m}$         | Micrometre (Micron)  |
| $\bar{X}$             | Sample mean  |
| $\sigma$              | Population standard deviation  |
| $\bar{s}$             | Pooled standard deviation or Statistical average standard deviation    |
| $t_{\text{critical}}$ | Critical t-value under specific confidence level and degree of freedom |
| $\alpha$              | Level of significance  |
| $\lambda$             | Constant for density of concrete                                       |

# 1. INTRODUCTION

## 1.1. GENERAL

Plain concrete is weak in tension because it contains numerous micro-cracks. The micro-cracks begin to propagate in the matrix when load is applied. Consequently, plain concrete members cannot sustain tensile stresses developed due to the applied forces without the addition of reinforcing elements (re-bar or wire mesh) in the tensile zone. The propagation of micro-cracks and macro-cracks, however, still cannot be arrested or slowed by the sole use of continuous reinforcement. The addition of randomly spaced discontinuous fibres help in arresting the propagation of the micro-cracks and macro-cracks. Randomly dispersed fibres in concrete help in reducing the crack width thus, reduces the permeability of concrete. In addition to crack control, fibres also improve the mechanical properties of plain concrete such as fracture resistance, resistance to impact, and resistance to dynamic loads.

Concrete containing hydraulic cement, water, aggregate, and randomly dispersed fibres is called *fibre reinforced concrete* (FRC). Different types of commercially available fibres used in concrete and examples of these fibres are steel fibres, glass fibres, polypropylene fibres, carbon fibres, and basalt fibres.

Basalt fibre is an inorganic material produced from volcanic rock called Basalt. The production of basalt fibres does not create any environmental waste and it is non-toxic in use. Basalt fibre is a unique construction material with high tensile strength, good thermal endurance, and stable in all aggressive environments. It is believed that Basalt fibre reinforced concrete (BFRC) will revolutionize the construction industry because it is cheaper, greener, lighter, and eliminates the problem of corrosion of reinforcement bars and corrosion led damages in the concrete structures. Two types of chopped Basalt fibres are available and these are bundled fibres and filaments.

## **1.2 PROBLEM STATEMENT**

One of the major problems faced in reinforced concrete construction is the corrosion of reinforcing steel, which significantly affects the life and durability of concrete structures. Randomly dispersed basalt fibres as a replacement to welded wire mesh for slabs on grade can effectively eliminate the problem of corrosion as they are immune to corrosion. In addition to high tensile strength, light weight, and good chemical resistance basalt fibres also possess high thermal resistance and they do not conduct electricity. However, there has only been a limited number of research found in open literature concerning chopped basalt filament fibre reinforced concrete. However, no previous research was conducted using basalt bundled fibres. Hence, this study was developed to investigate the effect of chopped basalt fibres in improving the mechanical properties (flexure, compressive, and split tensile) of plain concrete.

## **1.3 OBJECTIVES**

The following are the objectives of this research.

- Determine the optimum fibre length and volume of basalt bundled fibres and basalt filaments required to improve the flexural strength, compressive strength, and split tensile strength of BFRC from plain concrete.
- Compare the performance (flexural, compressive, and split tensile strength of BFRC specimens) of bundled fibres with basalt filaments of various lengths (12 mm, 36 mm, and 50 mm) at various fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>).
- Compare the performance (flexural, compressive, and split tensile strength) of the bundled fibre specimens and the basalt filament fibre specimens with plain concrete, concrete made of steel fibre, and macro synthetic fibres.

## 1.4 SCOPE OF WORK

The scope of this research includes the following.

- Undertaking detailed literature review
- Mix design for the plain concrete control mix
- Preparation of BFRC beam and cylinder specimens
- Preparation of control steel fibre and control macro synthetic fibre beam and cylinder specimens
- Curing of test specimens for seven days and twenty eight days
- Preparation of test specimens for flexural, compression, and split tensile testing
- Testing the specimens with required instrumentation and data acquisition system
- Analyzing the test results
- Undertaking statistical analyses
- Writing thesis

## 1.5 METHODOLOGY

A total of 126 beam specimens and 252 cylindrical specimens were cast and tested. In each batch, 8 cylinders were prepared for compression test (4 cylinders each for 7 day and 28 day test), 4 cylinders were prepared for split tensile test, and 6 beams were cast for flexural test. Plain concrete specimens were prepared using 1:1.4:2.8 (cement: fine aggregate: coarse aggregate) mix proportion (by weight). The water-cement ratio was kept constant at 0.5 for the mixes. All FRC specimens were prepared using the same mix proportion. BFRC beam and cylinder specimens were cast using basalt fibres (16  $\mu\text{m}$  in diameter) of varying length (12 mm, 36 mm, and 50 mm) and varying fibre dosage (4  $\text{kg}/\text{m}^3$ , 8  $\text{kg}/\text{m}^3$ , and 12  $\text{kg}/\text{m}^3$ ). Similarly, steel fibre control specimens were prepared using steel fibres 0.9 mm in diameter and 38 mm long at a fibre dosage of 40  $\text{kg}/\text{m}^3$ . Macro synthetic fibre control specimens were cast using 40 mm long polyolefin fibres with an aspect ratio of 90 at a fibre dosage of 4.5  $\text{kg}/\text{m}^3$ .

Flexural strength, compressive strength, and split tensile strength tests were conducted. The compressive strength of concrete cylinders was tested on the 7<sup>th</sup> day and 28<sup>th</sup> day. The flexural strength and split tensile strength were tested at the age of 28 days. The third-point loading method according to CSA A23.2-8C (2009a) was used to determine the flexural strength of the beam specimens. The compressive strength and split tensile strength of cylinder specimens were determined according to CSA A23.2-9C (2009a) and CSA A23.2-13C (2009a), respectively. The test results were then analyzed and statistical analyses were completed to draw conclusions.

## **1.6 ORGANIZATION OF THESIS**

This thesis is organized as follows:

Chapter 1 – Introduction

Chapter 2 – Literature review: This chapter contains a detailed review of previous works which relate to the current research.

Chapter 3 – Test procedure: This chapter describes the procedure followed in casting and testing beam and cylindrical specimens.

Chapter 4 – Statistical Analysis: This chapter discusses the various statistical techniques used in comparing the mean flexural strength, compressive strength, and split tensile strength of various specimens.

Chapter 5 – Results and discussion: This chapter provides a detailed discussion on how test data were reduced, organized, analyzed, and used to make several conclusions.

Chapter 6 – Summary Conclusion and Recommendations: This chapter contains the summary of test results. Conclusions are drawn and future research recommendations are made.

## **2. LITERATURE REVIEW**

Concrete has been the most widely used material in the construction industry as it has high compressive strength, low cost, and is available in abundance. Plain concrete has low tensile strength, low flexural strength, poor toughness, almost no ductility, low shock resistance, high plastic shrinkage and cracking, which restricts its applications. The tensile strength of concrete is low because plain concrete normally contains numerous micro-cracks. These micro-cracks propagate rapidly when concrete is subjected to tensile stress. To overcome these deficiencies and to improve the performance of concrete, various additives are added (Fibres Unlimited, 2013).

The incorporation of fibres into a brittle cement matrix serves to increase the fracture toughness of the composite by the crack arresting processes, and increase in the tensile, and flexural strengths (Beaudoin, 1990).

The purpose of this literature review is to review previous researches completed in this area.

### **2.1 FIBRE REINFORCED CONCRETE**

Since ancient times, fibres have been used to reinforce brittle materials. Straw was used to reinforce bricks. Fibre reinforced concrete (FRC) is made of hydraulic cement containing fine aggregate, coarse aggregate, and discontinuous discrete fibres. Fibres suitable for reinforcing concrete are produced from steel, glass, polymers (synthetic fibres), and other materials. The concrete matrices may be mortars, normally proportioned mixes, or mixes specifically formulated for a particular application. Generally, the length and diameter of the fibres used for FRC do not exceed 76 mm and 1 mm, respectively (ACI 544.1R-96, 2002).

Fibres are primarily used in concrete to provide early plastic shrinkage control, long-term crack control, economical design, improvements to residual strength, and a practical means of reinforcing concrete (CSA A23.1 Annex H, 2009c).

### **2.1.1 FIBRE REINFORCED CONCRETE VERSUS CONVENTIONALLY REINFORCED CONCRETE**

The shortcomings of plain concrete can be reduced by adding reinforcing bars or pre-stressing steel. Reinforcing steel is continuous and is specifically located in the structure to increase performance. Fibres are discontinuous and are generally distributed randomly throughout the concrete matrix. Randomly dispersed fibres provide a three-dimensional reinforcement compared to the traditional rebar which provides two-dimensional reinforcement. Fibre reinforced concrete can be a cost effective and useful construction material because of the flexibility in methods of fabrication. In slabs on grade, mining, tunneling, and excavation support applications, steel and synthetic fibre reinforced concrete and shotcrete have been used in lieu of welded wire fabric reinforcement (ACI 544.1R-96, 2002).

One of the greatest benefits gained by using fibre reinforcement is improved long-term serviceability of the structure or product if properly engineered. Serviceability is the ability of the specific structure or part to maintain its strength, integrity, and to provide its designed function over its intended service life. Fibres can prevent the occurrence of large cracks. These cracks permit water and contaminants to enter causing corrosion of reinforcing steel. In addition to crack control and serviceability benefits, use of fibres at high volume percentages (5% to 10% or higher by volume) can substantially increase the tensile strength of FRC (ACI 544.1R-96, 2002).

According to CCI (2010), for the effective use of fibres in hardened concrete the following aspects should be satisfied.

- Fibres should have significantly higher modulus of elasticity (stiffer) than the matrix.
- Fibre content by volume must be adequate.
- There must be a good fibre-matrix bond.
- Fibre must have sufficient length.
- Fibres must have a high aspect ratio, i.e. they must be long relative to their diameter.

## 2.2 TYPES OF FIBRE

There are numerous types of fibres available for commercial and experimental use. Fibres currently used in concrete can broadly be classified into two following categories.

- Fibres with low modulus of elasticity and a high elongation property
- Fibres with high modulus of elasticity

Natural and synthetic fibres such as nylon, polypropylene, and polyethylene are of the first category. These fibres normally do not lead to strength improvement, however, they improve toughness, resistance to impact, and resistance to explosive loading. High modulus of elasticity fibres such as steel, glass, asbestos, and carbon, on the other hand, produce stronger concrete. They primarily improve the strength and the stiffness of the concrete matrix (Ahmad and Lagoudas, 1991).

In relation to the elastic modulus, fibres are divided into two types, those where the elastic modulus of fibres is less than the elastic modulus of the matrix: i.e. cellulose fibre, polypropylene fibre, poly-acrylonitrile fibre, etc.; and those where the elastic modulus of fibres is greater than the elastic modulus of the matrix: i.e. asbestos fibres, glass fibre, steel fibre, carbon fibre, aramid fibre, etc. Fibre reinforced concrete (FRC) has been successfully used in construction because of its excellent impact resistance, impermeability, frost resistance, toughness, shock resistance, and resistance to plastic shrinkage cracking. The improvement in the properties of FRC are dependent on the mechanical, and bonding properties of the fibre, as well as the quantity, length, and distribution of fibres within the matrix (Fibres Unlimited, 2013).

Modern-day use of fibres in concrete started in the early 1960s. In the beginning, only straight steel fibres were used. The major improvement occurred in the areas of ductility and fracture toughness in addition to slight improvement in the flexural strength (Ramakrishnan et al., 1998).

Fibres used in concrete can be classified based on the following criteria.

- *Fibre materials*: The fibres that are commonly used in fibre reinforced cement-based composites are steel fibres, synthetic fibres (carbon, and polymeric - acrylic, aramid, nylon, polyester, polyethylene, and polypropylene), glass fibres, basalt fibres, and natural fibres (wood cellulose, sisal, coir or coconut) (Li, 2011).
- *Fibre volume*: Based on the fibre volume, fibre reinforced concrete can be classified as low (0.1% - 1%), moderate (1% - 3%), and high (3% - 12%) fibre volume matrix (Ramakrishnan et al., 1998).
- *Fibre geometry*: The various shapes of fibres used in concrete are: straight, deformed (crimped), round, flat, and glued bundles of fibres with crimped ends. (Nemati, 2013) Most common steel fibres are round in cross-section, have a diameter ranging from 0.4 to 0.8 mm, and length ranging from 25 to 60 mm. Their aspect ratio ( $l/d$ ), is generally less than 100, with a common range from 40 to 80. The length and diameter of synthetic fibres vary greatly. Single filament carbon fibre have a diameter ranging from 7  $\mu\text{m}$  to 15  $\mu\text{m}$ . Generally in concrete applications, the aspect ratio of very fine fibres exceeds 100, while that of coarse fibres is less than 100 (Naaman, 2003).

## **2.2.1 CLASSIFICATION BASED ON FIBRE MATERIAL**

### **2.2.1.1 STEEL FIBRES**

Steel fibres are commercially available in various aspect ratios ( $l/d$ ), cross sections, anchorages, and tensile strengths. Steel fibres provide no plastic shrinkage cracking control, but are used to improve crack control and redistribute stresses in the hardened concrete created by dynamic and static loading conditions. Improvements in the performance of concrete by the addition of fibres is generally proportional to the following (CSA A23.1 Annex H, 2009c).

- (a) the volume of fibre added
- (b) the quality of anchorage of the fibre
- (c) the tensile strength of the fibre

A typical amount of steel fibre used in a concrete mix is estimated to be 15 kg/m<sup>3</sup> to 40 kg/m<sup>3</sup> (about 0.2% to 0.5% by volume). Steel fibres are used as crack-control reinforcement in commercial, industrial, and residential applications such as, floor slabs, machine pads, overlays, and exterior pavements (CSA A23.1 Annex H, 2009c). Fibre content in excess of 2% by volume generally result in poor workability and poor fibre distribution (CCI, 2010).

The main problem with steel fibres is to introduce a sufficient volume of uniformly dispersed fibres required to achieve the desired improvements in mechanical behaviour. One of the major difficulties in obtaining a uniform fibre distribution is the tendency for steel fibres to ball or clump together (Bentur and Mindess, 2007).

Balling occurs frequently at higher volume fractions for long fibres. Balling could be avoided by restricting the size of coarse aggregate, by using short fibres, and by increasing the mortar (cement and sand paste) fraction of concrete (Ramakrishnan et al., 1998).

In general, the problems of both workability and uniform distribution increase with increasing fibre length and volume. Deformed steel fibres bond with the concrete through mechanical anchoring, which is more efficient than the frictional shear bond stress mechanism associated with straight fibres. Mangat and Azari (1984) estimated that the coefficient of friction is about 0.09 for hooked end fibres, and 0.04 for straight fibres. Steel fibres tend to corrode because of chloride penetration and carbonation (Bentur and Mindess, 2007). Another disadvantage of the steel fibre is its high density which can increase the dead load of a composite (Li, 2011).

#### **2.2.1.2 SYNTHETIC FIBRES**

Synthetic fibres are man-made fibres resulting from research and development in the petrochemical and textile industries (CCI, 2010).

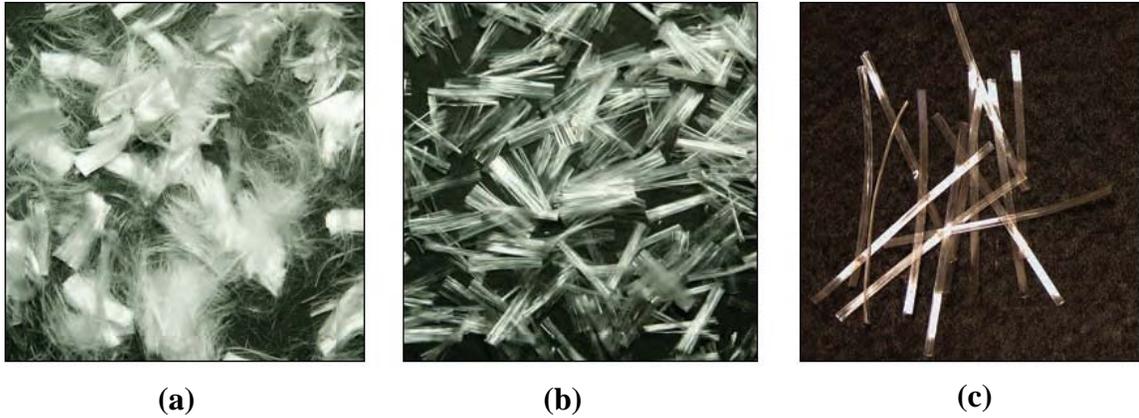
### **2.2.1.2.1 POLYMERIC FIBRES**

Two types of polymeric fibres currently used in concrete are: (a) Micro synthetic fibres and (b) Macro synthetic fibres. Different types of polymeric fibres are shown in Figure 2.1. Micro fibres are typically found in the form of very fine monofilament or fibrillated synthetic material. It is commonly added in relatively low volumes ( $0.6 \text{ kg/m}^3$  to  $0.9 \text{ kg/m}^3$ ) for the control of plastic shrinkage cracking. The relatively high surface area of micro fibres makes their use difficult at higher volumes without causing a severe impact on the workability of the concrete mixture. Hence, the use of micro fibres is limited to improvements to the plastic shrinkage characteristics of concrete (CSA A23.1 Annex H, 2009).

The length of micro synthetic fibre ranges from 6 mm to 64 mm. Monofilament micro fibres (Figure 2.1a) are fine, cylindrical strands that separate during mixing. They do not anchor into the cement matrix as well as fibrillated micro fibres (Figure 2.1b), because they are smooth and have a smaller surface area. The cement paste penetrates into the network of fibrillated micro fibres, resulting in better bonding with the concrete. Lower volumes of fibrillated micro fibres than of monofilament fibres are needed to improve the properties of concrete (Laning, 1992).

Macro synthetic fibres (Figure 2.1c) are coarse monofilaments. Macro fibres can be used at higher volume than micro fibres, and have a positive impact on the hardened characteristics of concrete because of their relatively low surface area. The benefits of using macro synthetic fibres are: improved fatigue and impact resistance, improved crack control, and improved post-cracking strength (CSA A23.1 Annex H, 2009c).

Polyolefin fibres (Figure 2.1c) are macro synthetic polymeric fibres with a low aspect ratio similar to steel fibres. They can be mixed with concrete in large quantities, as much as 20% (by volume) without causing any balling, segregation or increase in air entrainment in concrete. There are a number of advantages for polyolefin fibres, such as no corrosion potential, chemical inertness, and no hazardous conditions when fibres become loose or protrude from the concrete surface (Ramakrishnan et al., 1998).



**Figure 2.1: Polymeric fibres**  
**(a) Monofilament micro fibre (b) Fibrillated micro fibre (c) Macro fibre**  
 (Grace Construction Products, 2007)

The use of polymeric fibres began in the early 1960s. Polymeric fibres are hydrophobic. Hence, they do not absorb water and have no effect on the mixing water requirements. They have a low density and are also chemically inert. Polymeric fibres are most commonly added to concrete for slab-on-grade construction to reduce early plastic shrinkage cracking and increase impact resistance, abrasion resistance, and toughness (Ramakrishnan et al., 1998)

Polymeric fibres melt and volatilize during a fire, leaving behind empty channels and additional porosity which is the main disadvantage of this fibre (Bentur and Mindess, 2007). The major shortcomings of polymeric fibres are low modulus of elasticity, poor bond with the cement matrix, combustibility, and low melting point. Their bond to cement matrix is improved by twisting several fibres together or by treating the fibre surface (Ramakrishnan et al., 1998).

#### **2.2.1.2.2 CARBON FIBRES**

Carbon fibres consist of tows (untwisted bundles of continuous filaments), each made up of numerous filaments. The filaments are 7  $\mu\text{m}$  to 15  $\mu\text{m}$  in diameter and consist of small crystallites of ‘turbostratic’ graphite, which is one of the allotropic forms of carbon. Carbon

fibres are manufactured from polyacrylonitrile (PAN carbon fibres), and petroleum and coal tar pitch (pitch carbon fibres) (Bentur and Mindess, 2007).

Carbon fibres are not affected by alkaline environment in cement-based matrices; however they are fragile and hence, they are prone to damage by conventional mechanical mixing. They have high elastic modulus and high tensile strength. Carbon fibres are generally characterized by high aspect ratio which makes them difficult to disperse uniformly in a matrix at fibre contents greater than about 1% by volume unless dispersing additives are added (Johnston, 2010).

Carbon fibres also possess excellent resistance to moisture and chemicals and these fibres are insensitive to fatigue damage. The drawbacks of carbon fibre are its low impact resistance, low ultimate strain, and high price (Li, 2011). Carbon fibres have potential for special applications that require high tensile and flexural strength, though its cost is higher than polymeric and other fibres. Carbon fibres have an elastic modulus as high as steel and are two to three times stronger than steel. (Ramakrishnan et al., 1998)

### **2.2.1.3 GLASS FIBRES**

Glass fibre in the form of filaments is also commonly used in FRC. Glass fibres are supplied in a continuous roving and can be chopped into short fibres. Glass fibres have high tensile strength and high fracture strain. However, these fibres have low modulus of elasticity. Moreover, ordinary borosilicate glass fibres (E-glass) and soda-lime glass fibres (A-glass) can be easily attacked by alkali solution in cement-based composites. Hence, they are less durable and should be used with caution. Alkali-resistant glass fibres (AR glass) contain about 16% to 20% of Zirconia ( $ZrO_2$ ), which protects the fibres from high alkali attack. AR glass is the most popular glass fibre used in cement-based composites. Disadvantages of glass fibres include low resistance to sustained loads and cyclic loads (Li, 2011).

Extended exposure of glass fibre reinforced concrete (GFRC) to natural weather conditions result in changes in mechanical properties. Furthermore, exposure of GFRC to normal

natural weathering cycles result in cyclical volumetric dimension changes. Most commercially manufactured GFRC composites experience a reduction in tensile strength, flexural strength, and ductility with age if exposed to an outdoor environment. The strength of fully-aged GFRC composites decreases to about 40% of the initial strength prior to aging. However, strain capacity (ductility or toughness) decreases to about 20% of the initial strain capacity prior to aging. This loss in strain capacity is referred to as composite embrittlement (ACI 544.1R-96, 2002).

#### **2.2.1.4 BASALT FIBRE**

Basalt fibres are manufactured in a single-stage process by melting crushed volcanic basalt rock. They are environmentally safe, non-toxic, possess high heat stability, and insulating characteristics, and have an elastic structure. Basalt fibres are extremely strong and durable and hence, it is an ideal material for structural and other construction related applications. It provides unique mechanical properties when used in composite materials. The mechanical characteristics of roving depend on the diameter of the elemental fibres. Elemental fibres with smaller diameter show higher tensile strength and modulus of elasticity than those of elemental fibres with larger diameter. The fibres can easily be processed into fabric. Continuous roving basalt fibre can be used to produce a wide range of composite materials with high reliability (Brik, 1997).

The physical and chemical properties of various fibres used in concrete are listed in Table 2.1.

**Table 2.1: Comparison of physical and chemical properties of fibres used in concrete**

(ACI 544.1R-96, 2002 and Parnas et al., 2007)

| Properties                                | FIBRE TYPE  |           |            |             |             |
|---|-------------|-----------|------------|-------------|-------------|
|   | STEEL       | POLYMERIC | CARBON     | GLASS       | BASALT      |
| Filament diameter ( $\mu\text{m}$ )       | 250 - 1000  | 10 - 1000 | 8 - 18     | 6 - 21      | 9 - 23      |
| Mass Density ( $\text{g}/\text{cm}^3$ )   | 7.8         | 0.9 - 1.4 | 1.6 - 2.15 | 2.46 - 2.74 | 2.6 - 2.7   |
| Tensile strength (MPa)                    | 1000 - 3000 | 75 - 2900 | 480 - 4000 | 2500 - 3500 | 4150 - 4800 |
| Modulus of elasticity (GPa)               | 200         | 3.5 - 115 | 27 - 480   | 65 - 80     | 90 - 110    |
| Ultimate elongation (%)                   | 0.5 - 35    | 3 - 150   | 0.5 - 2.4  | 2.5 - 4.8   | 2.5 - 3.15  |
| Adhesiveness in matrix                    | Low         | Low       | Low        | Good        | Good        |
| Chemical stability                        | Average     | High      | High       | High        | High        |
| Thermal resistance ( $^{\circ}\text{C}$ ) | 650 to 800  | 70 to 280 | -60 to 500 | 300 to 2300 | -260 to 700 |

## 2.2.2 CLASSIFICATION BASED ON FIBRE VOLUME

The amount of fibre added has a significant influence on the mechanical properties and failure mode of fibre reinforced concrete. Based on how much fibre is added, fibre-reinforced cementitious composites can be classified into the following three groups.

### 2.2.2.1 LOW FIBRE VOLUME (< 1%)

Concrete mix with low fibre volume are used to reduce shrinkage cracking. These fibres are used in slabs and pavements that have a large exposed surface area. Dispersed fibres offer the following (Mehta and Monteiro, 2006).

- Fibres are uniformly distributed in three-dimensions making an efficient load distribution
- Fibres are less corrosive than reinforcing steel bars
- Fibres can reduce the labor cost of placing the bars, and wire-mesh.

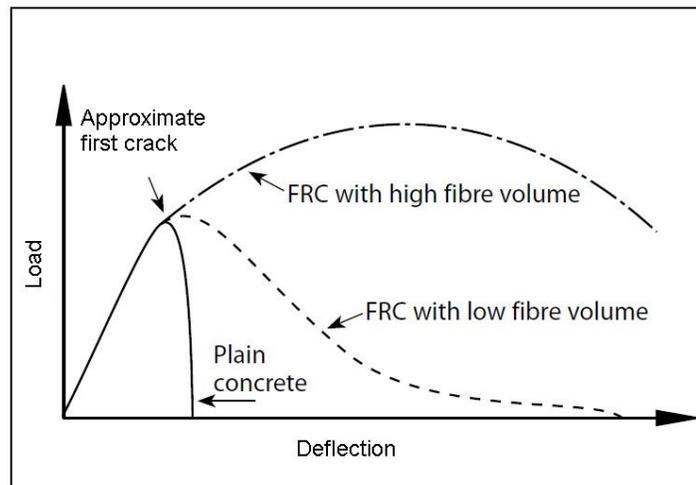
### 2.2.2.2 MODERATE FIBRE VOLUME (1% – 2%)

Fibre reinforced concrete with moderate fibre volume fractions (between 1% and 2%) exhibit improved mechanical properties including modulus of rupture, fracture toughness, and impact resistance. The fibres in this class of fibre reinforced concrete can be used as secondary reinforcement in structural members such as in partial replacement of shear steel stirrups or for crack width control in structures (Li, 2011).

### 2.2.2.3 HIGH FIBRE VOLUME (> 2%)

The fibres used at this level lead to strain-hardening of the composites. These composites are often referred as high performance fibre reinforced composites (HPFRC) because of this improved behavior. In the last decade, even better composites were developed and are referred as ultra-high-performance fibre-reinforced concretes (Mehta and Monteiro, 2006).

It is evident from Figure 2.2, that increasing the volume of fibres to concrete greatly increases the toughness of the material. Hence, fibre reinforced concrete sustains loads at deflections much greater than the load at which the first cracking appears. Toughness is defined as the area under a load-deflection curve (CCI, 2010).



**Figure 2.2: Load-deflection curves for plain concrete and fibre reinforced concrete**  
(CCI, 2010)

In cement based composites, fibres carry the additional load after the first crack. The minimum fibre volume required for the composite to sustain the load after the matrix fracture is called critical fibre volume. The critical fibre volume in concrete is calculated to be approximately 0.31%, 0.40%, and 0.75% for steel, glass, and polypropylene fibres (Beaudoin, 1990). It was found through research that flexural fibre strengthening can occur for practical composites between fibre volumes of about 0.3% to 1.3 %, depending on the aspect ratio and orientation (Hannant, 1978).

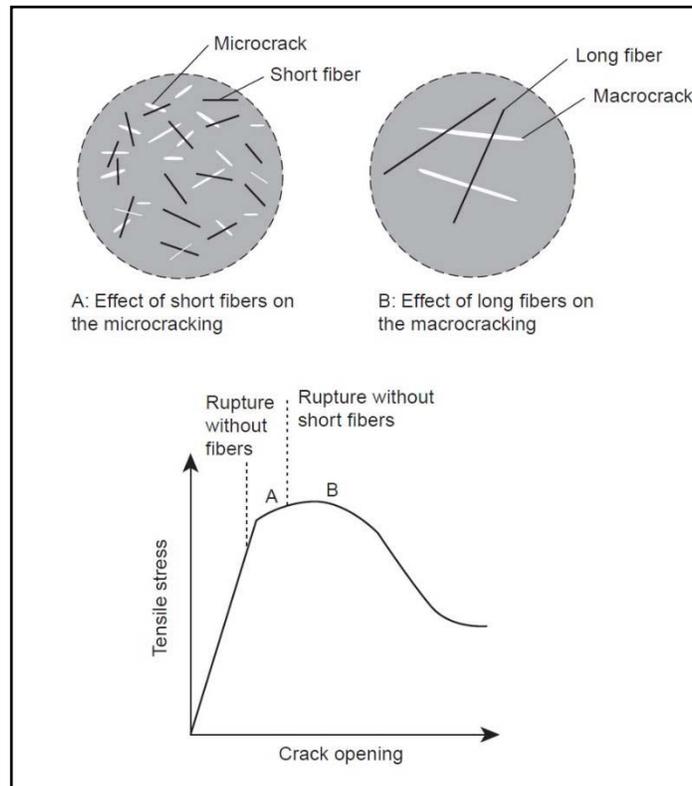
## **2.2.3 CLASSIFICATION BASED ON FIBRE GEOMETRY**

### **2.2.3.1 SHORT AND LONG FIBRES**

Concrete carries flaws and micro-cracks both in the material and at the interfaces even before an external load is applied. These defects and micro-cracks emanate from excess water, bleeding, plastic settlement, thermal and shrinkage strains, and stress concentrations imposed by external restraints. Under an applied load, distributed micro-cracks propagate, coalesce, and align themselves to produce macro-cracks. Conditions of critical crack growth are attained at the tips of the macro-cracks when loads are further increased resulting in unstable and catastrophic failure. The micro-cracks can be favorably bridged by adding short, randomly distributed fibres of various suitable materials. Fibres not only suppress the formation of cracks, but also abate their propagation and growth (Banthia, 2008).

Long fibres are needed to bridge discrete *macro-cracks* at high loads. However, the volume of long fibres required to bridge macro-cracks can be much smaller than the volume of short fibres. The presence of long fibres significantly reduces the workability of the mix. The influence of short and long fibres on the behaviour of the composite under tension is shown in Figure 2.3 (Mehta and Monteiro, 2006).

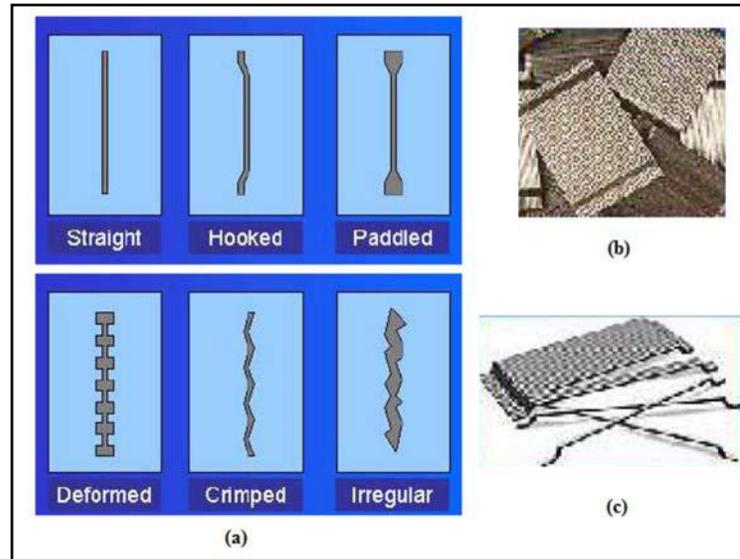
Pull-out or sliding of the fibre occurs if the fibre is shorter than a certain critical length. The critical fibre length is calculated based on fibre diameter, ultimate tensile strength of the fibre, and the interfacial shear strength (Beaudoin, 1990).



**Figure 2.3: Influence of fibres in different stages of concrete tensile cracking**  
(Mehta and Monteiro, 2006)

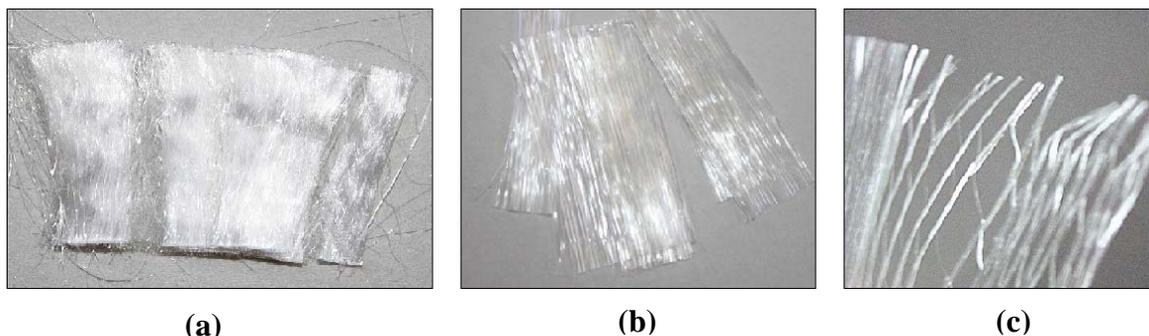
### 2.2.3.2 FIBRE SHAPE

The shape of fibre has significant effect on the bond characteristics in the concrete matrix. Steel fibres used in concrete are of different shapes and sizes as shown in Figure 2.4. Typical steel fibre types used in concrete are: a) straight, smooth drawn wire steel fibres, b) deformed (crimped) wire steel fibres, c) variable cross section steel fibres, and d) glued bundles of steel fibres with crimped ends (Nemati, 2013).



**Figure 2.4: Shapes of steel fibre**  
**(a) Shapes of steel fibre (b) Steel fibre glued together (c) Fibres separate during mixing to ensure uniform distribution (Nemati, 2013)**

Polypropylene fibres are available in two different geometries: (a) Monofilament and (b) Fibrillated (Figure 2.5). Monofilament polypropylene fibres are produced by an extrusion process, in which the polypropylene resin is hot drawn through a die of circular cross section. A number of continuous filaments (tows) are produced at one time. They are then cut to the appropriate lengths. Fibrillated polypropylene fibres are also produced by an extrusion process. However, the material is drawn through a rectangular die. It consists of a complex microstructure of amorphous material and crystalline micro-fibrils. Fibrillated fibres are intended to improve the bonding with the matrix by providing an interlocking effect (Bentur and Mindess, 2007).



**Figure 2.5: Polypropylene fibres**  
**(a) Monofilament (b) Fibrillated (c) Magnified fibrillated (Nycon, 2014)**

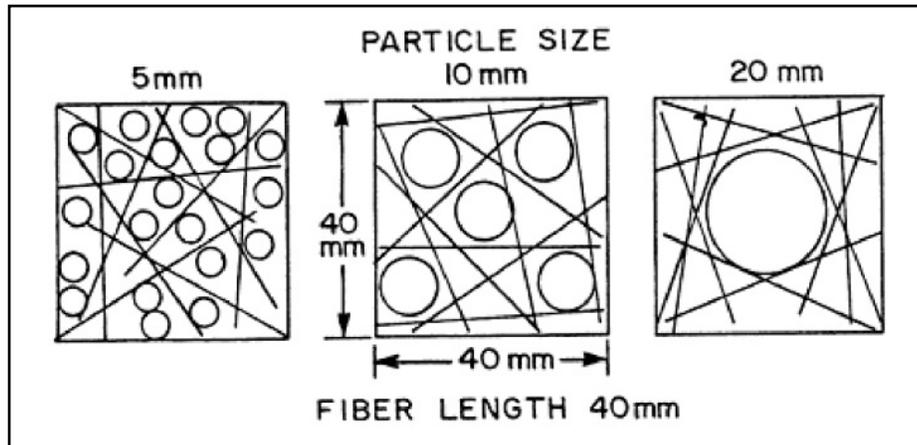
## **2.3 EFFECT OF FIBRE IN CONCRETE**

Introduction of fibres into concrete results in changes in post-elastic properties and the changes range from subtle to substantial, depending upon a number of factors, including matrix strength, fibre type, fibre modulus, fibre aspect ratio, fibre strength, fibre surface bonding characteristics, fibre content, fibre orientation, and aggregate size. The most significant enhancement from the fibres is the post-cracking composite response. This is most commonly evaluated and controlled through flexural toughness testing which is a measurement of the area under the load-deformation curve (ACI 544.1R-96, 2002).

A high fibre tensile strength is essential for a substantial reinforcing action. The tensile strength of the fibres decreases as their length increases. A high ratio of fibre modulus of elasticity to matrix modulus of elasticity, facilitates stress transfer from the matrix to the fibre. The load is transferred through the matrix to the fibre by shear deformation at the fibre-matrix interface. Fibres having large values of failure strain provide high extensibility in the composites (Beaudoin, 1990).

### **2.3.1 WORKABILITY**

Short fibres of aspect ratio (length/diameter) less than 50 easily disperse in the concrete mix. Long thin fibres, on the other hand, of aspect ratio greater than 100, tend to interlock which is very difficult to separate even by vibration. Movement of fibres is restricted in the matrix with large aggregates. This leads to lumping of fibres around large aggregates as shown in Figure 2.6. Workability reduces when the volume of fibre, aspect ratio of the fibre, or maximum size of the aggregate increases (Hannant, 1978). The greater the amount of cement paste (the volume fraction of the fluid phase) within which the fibres can move, the greater the workability (Johnston, 2000).



**Figure 2.6: Effect of aggregate size on fibre distribution for fibre length 40 mm**  
(Hannant, 1978)

### 2.3.2 STRENGTH

The role of fibres in hardened FRC is primarily to promote crack distribution and reduce crack widths. Prior to the start of visible and continuous cracking, fibres at the concentrations that are commonly used in FRC (less than 1 % by volume of concrete) have little effect on the mechanical properties. However, micro-cracking does occur as the FRC is loaded and there are characteristic levels of load and deformation at which the FRC eventually starts to exhibit cracks that are significant in continuity, visibility, total length, and width. At this stage, the micro-cracks have become macro-cracks. This condition is termed as “first crack”, and is clearly identifiable for direct tension and flexure by a sharp reduction in stiffness (Tatnall et al., 2006).

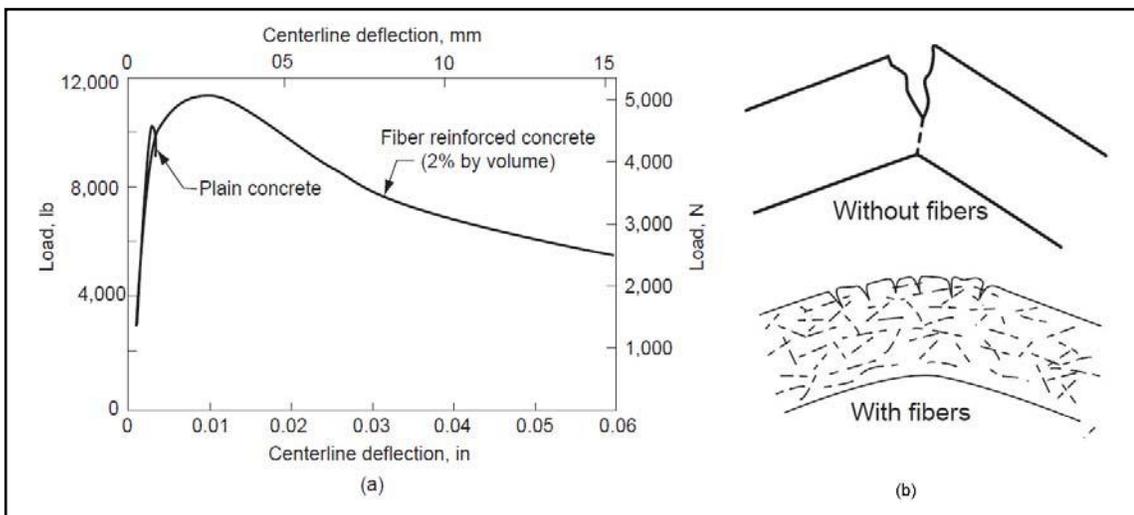
Improvement in the flexural, split tensile, and compressive strengths of concrete because of the addition of fibre is governed by: (a) aspect ratio ( $l/d$ ) of the fibre, (b) volume of fibre, and (c) the bond characteristic of the fibre. There is a limit to the quantity of fibre which can be introduced into a mix of specific proportions and water-cement ratio without causing balling and interlocking of fibres. Increasing the sand content or the cementitious content of the mix, allows an increase in the fibre content. Increasing the fibre content or the aspect ratio of the fibre causes reduction in workability and increased balling of fibres during mixing as explained in Section 2.3.1. Deformed fibres possess higher bond strength than straight fibres and smooth fibres (Narayanan and Palanjian, 1984).

Steel fibres are often found to have a much greater effect on the flexural strength of SFRC than on either the compressive or tensile strengths (Bentur and Mindess, 2007).

### 2.3.3 FLEXURAL TOUGHNESS

Flexural toughness or energy absorbing capability, imparted by fibres in fibre reinforced concrete, can be quantified by calculating the area under load-deflection curve after the first crack of the specimen (Hannant, 1978).

Typical load-deflection curves of four-point bending tests for plain concrete and fibre reinforced concrete are shown in Figure 2.7a. The load in this curve is the point load applied at the middle third of the beam specimen and deflection is measured at the mid-span of the beam specimen. The plain concrete beam specimen fails suddenly once the deflection corresponding to the ultimate flexural strength is exceeded. The fibre reinforced concrete beam specimen, on the other hand, continues to sustain considerable loads even at deflections in excess of the fracture deflection of plain concrete. Figure 2.7b shows the mechanism of an increase in flexure toughness of concrete with fibres (Mehta and Monteiro, 2006).

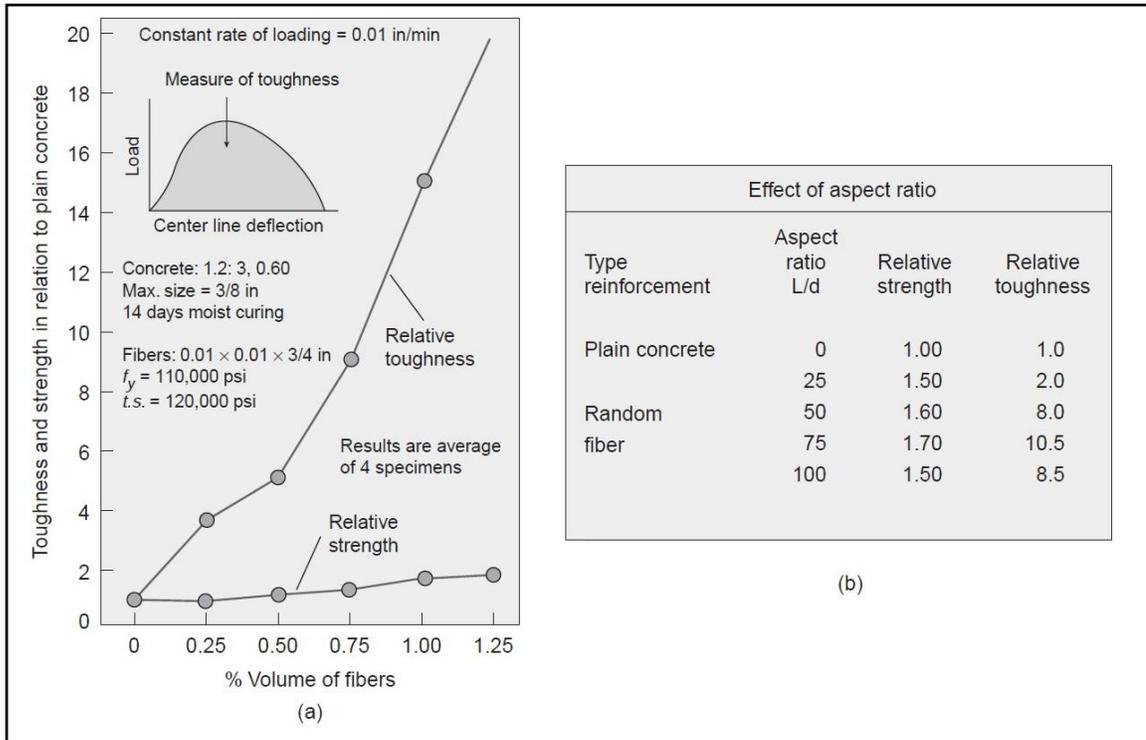


**Figure 2.7: Flexural toughness**  
**(a) Load-deflection behavior of plain and FRC (Mehta and Monteiro, 2006)**  
**(b) mechanism of increase in flexure toughness (Neville, 1976)**

The important factors governing the toughness of fibre reinforced concrete are fibre efficiency, position of the crack, fibre type, aspect ratio, volume fraction, and the distribution of fibres. If fibres are aligned and are parallel to the direction of applied stress, the efficiency factor is unity. Swamy et al. (1974) found that the fibres which are parallel or nearly parallel to the tensile stress trajectories are effective in crack control. Fibre efficiency is controlled by the resistance of the fibre from being pulled-out from the concrete matrix, which is developed as a result of the bond strength at the fibre-matrix interface. The advantage of a pull-out type of failure is that it is gradual and ductile. Rapid and catastrophic failures may occur if the fibres are brittle and thus, they fail in tension with little or no elongation (Ramakrishnan et al., 1998).

Fibres with better bond characteristics (i.e. deformed fibres or fibres with greater aspect ratios) exhibit higher toughness than smooth, straight fibres at the same volume concentrations (Bentur and Mindess, 2007).

The most important contribution of fibre (low and moderate fibre content) in concrete is not the flexural strength, rather it is the flexural toughness of the material. It is evident from the curve in Figure 2.8a that increasing the volume of fibres enhanced both the flexural strength and the toughness. The load in the load-deflection curve (Figure 2.8a) is the point load applied at the middle third of the beam specimen and deflection is measured at the mid-span of the beam specimen. However, the increase in toughness was as much as 20 times for 1.25% volume of fibres. The increase in flexural strength was less than two fold for the same volume of fibres (Mehta and Monteiro, 2006).



**Figure 2.8: Factors affecting properties of FRC**  
**(a) Influence of increasing fibre volume (b) Influence of increasing aspect ratio**

(Mehta and Monteiro, 2006)

### 2.3.4 CREEP AND SHRINKAGE

Uncontrolled shrinkage of concrete can produce severe cracking. Shrinkage of concrete is dependent on mix variables, degree of hydration, volume fraction of fibres, and relative humidity of the environment (Beaudoin, 1990). The addition of steel fibres does not reduce the creep strains of the composite. The shrinkage of concrete is also unaffected by the presence of steel fibres (Hannant, 1978).

Tensile creep reduced slightly, however, flexural creep substantially reduced when very stiff carbon fibres were used. However, in most studies because of the low volume, the fibres simply acted as rigid inclusions in the matrix without producing much effect on the dimensional stability of the composite (Mehta and Monteiro, 2006).

### **2.3.5 DURABILITY**

The benefits of adding fibres in concrete depend on the nature of the fibres incorporated and have long-term effects on the performance of the composite. The following factors affect the durability of fibre reinforced concrete (Bentur and Mindess, 2007).

- Fibre degradation due to chemical attack
- Fibre matrix interfacial physical interactions
- Fibre matrix interfacial chemical interactions
- Volume instability and cracking

Degradation of fibres by chemical attack result from two types of processes: a) direct attack by the cementitious matrix due to reactions with the highly alkaline pore water (occurs with glass fibres and natural fibres) or b) attack by external agents which penetrate through the cementitious matrix into the fibre (corrosion in steel fibres). Chloride penetration and carbonation are the primary reasons for corrosion of steel fibre (Bentur and Mindess, 2007).

Changes of properties over time can occur due to microstructural changes at the fibre matrix interface. The microstructure is prone to changes over time due to continued hydration and densification. The influences of these microstructural changes are large in case of thin filaments (micro fibres) whose surface area is rather large. Many of the long-term performance problems are induced by volume changes in the material resulting from temperature and humidity changes. Volume changes which are induced in natural exposure due to wetting and drying may cause internal damage due to micro-cracking (Bentur and Mindess, 2007).

### **2.4 PRODUCTION ASPECTS OF FIBRE REINFORCED CONCRETE**

High aspect ratio fibres are more effective in improving the post-peak performance of conventionally mixed steel fibre reinforced concrete (SFRC) because of their high resistance to pullout from the matrix. A detrimental effect of using high aspect ratio fibres is the tendency of the fibres to ball-up during mixing. This can be avoided by careful selection of fibre dimensions and by appropriate mix designs. Techniques for retaining

high pullout resistance while reducing fibre aspect ratio include enlarging or hooking the ends of the fibres, roughening their surface texture, or crimping to produce a wavy rather than straight fibre profile (ACI 544.1R-96, 2002).

Aggregates larger than 19 mm are not recommended for use by *ACI 544.3R (2008)* in steel-fibre concrete. Proper workability in mixtures containing fibres are met by the use of air entraining agents, plasticizing admixtures, higher cement paste content (with or without a pozzolan), and the use of glued-together fibres (bundled fibres) (Mehta and Monteiro, 2006).

Glass fibre reinforced concretes (GFRC) are produced by either the spray-up process or the premix process. In the spray-up process, glass fibres are chopped and simultaneously deposited with a sprayed cement/sand slurry onto forms producing relatively thin panels ranging from 13 mm to 20 mm thick. Synthetic fibre reinforced concretes (SNFRC) are generally mixed in batch processes (ACI 544.1R-96, 2002).

## **2.5 APPLICATIONS OF FIBRE REINFORCED CONCRETE**

The most significant properties of SFRC are the improved flexural toughness (such as the ability to absorb energy after cracking), impact resistance, and flexural fatigue endurance (ACI 544.1R-96, 2002). Hence, SFRC found its application in highways and air field pavement overlays. SFRC is useful in resisting cavitation, erosion, and impact damage in hydraulic structures such as sluiceways and spillways. Warehouse and factory floors are applications which utilize the increased impact resistance and post-cracking ductility of steel fibre concrete. It is used in mining, tunneling, and rock slope stabilization for the stabilization of rock or loose surfaces by shotcrete. The major benefit is a considerable reduction in labor cost. SFRC is also found successful in precast components such as manhole covers, slabs, refractories, and non-pressure pipes (Hannant, 1978)

GFRC is used extensively for architectural cladding panels due to its light weight and economical cost. Other uses include shell structures, prefabricated windows, pipes, channels, permanent formwork, floor slabs, and the rendering of masonry construction to

enhance strength and stability. In all these applications, it is particularly attractive since it can readily be produced in various complex shapes (due to the strength and flexibility) and be made as a thin component. It can thus, provide a basis for making various lightweight precast units (Bentur and Mindes, 2007).

Polypropylene fibre reinforced concrete is utilized in numerous non load-bearing applications, particularly where impact resistance is an important consideration. Typical uses include the following: cladding, flat and corrugated cement sheets, cavity panels, tunnel lining materials, foundation and facing piles, under-water pipe, floating units, river walls, and thin shell concrete roofing material (Beaudoin, 1990).

## **2.6 BASALT ROCK**

Basalt is a dark-colored, fine grained, igneous rock. The name “basalt” is usually given to a wide variety of dark-brown to black volcanic rocks which are formed when molten lava from deep in the earth's crust rises up and solidifies (Subramanian, 2010).

Basalt is a fine grained rock with higher content of iron and magnesium than granite. The ocean floor is almost completely made up of basalt. Most of the basalt found on Earth was produced in three rock-forming environments: a) oceanic divergent boundaries, b) oceanic hotspots, and c) mantle plumes and hotspots beneath continents. Basalt rock has long been known for its thermal properties, strength, and durability. The density of basalt rock is between  $2.8 \text{ g/cm}^3$ , and  $2.9 \text{ g/cm}^3$ . Crushed basalt is used in road base, concrete aggregate, asphalt pavement aggregate, railroad ballast, and filter stone in drain fields. Polished, thin basalt slabs are used as floor tiles, building veneer, and in monuments due to its superior abrasion resistance (Subramanian, 2010).

## **2.7 BASALT FIBRE CHARACTERISTICS**

Basalt filaments are made by melting crushed volcanic basalt rock to about  $1400^\circ\text{C}$  to  $1700^\circ\text{C}$  for about 6 hours. The molten material is then extruded through special platinum bushings to produce continuous filaments of basalt fibre. The three main manufacturing

techniques of basalt filaments are centrifugal-blowing, centrifugal-multiroll, and die-blowing. The fibres cool into hexagonal chains resulting in a resilient structure substantially stronger than steel or glass fibres. Its production creates no environmental waste (Subramanian, 2010).

Basalt roving (Figure 2.9) is a bundle of continuous mono-directional complex basalt fibres. Basalt fibre has electrical insulating properties 10 times better than glass and has better chemical resistance than glass fibre, especially in strong alkalis. It reduces the risk of environment pollution unlike glass fibre which produces high-toxic metals and oxides during its production. Furthermore, basalt fibre has higher stiffness and strength than glass



**Figure 2.9: Basalt fibre rovings**  
(Kamenny Vek, 2013)

fibre. Roving is extremely hard: 8-9 on the Moh scale. Chopped basalt fibres are made from a continuous roving using drum chopping machines (Parnas et al., 2007). The density of basalt fibre ( $2.6 \text{ g/cm}^3$ ) is lesser than the density of steel fibre ( $7.8 \text{ g/cm}^3$ ). Hence, the addition of basalt fibre does not increase the dead load of FRC compared to steel fibre. Basalt fibres are corrosion resistant unlike steel fibres. In addition, basalt fibre also has excellent temperature resistance ( $-260^\circ\text{C}$  to  $700^\circ\text{C}$ ), anti-oxidation, and anti-radiation characteristics (Fibres Unlimited, 2013).

Sim et al. (2005) investigated the applicability of basalt fibre as a strengthening material for structural concrete members through various experimental works for durability and mechanical properties. The basalt fibre used in the test had a density of  $2.593 \text{ g/cm}^3$  and a diameter of  $10.6 \mu\text{m}$ . It exhibited a tensile strength of 1000 MPa which is about 30% of that of carbon fibres and 60% of that of high strength glass (S-glass) fibres. The basalt fibre had better resistance to the accelerated weathering test than the glass fibre. The basalt fibre maintained about 90% of the normal temperature strength after exposure at  $600^\circ\text{C}$  for 2 hours whereas, the carbon and the glass fibres did not maintain their volumetric integrity.

Following are some of the characteristics of basalt fibre (Fibres Unlimited, 2013 and Sudaglass, 2013)

- High tensile strength, high thermal conductivity, high modulus of elasticity, high sound absorption, high friction, frost, heat, and moisture resistance
- Chemical resistance to acids/alkalis, and aggressive chemicals
- No carcinogenic risk or other health hazards
- Completely inert with no environmental risks (eco-friendly)
- Good fatigue resistance
- Electro-magnetic resistance
- Resistance to ultraviolet radiation
- Dielectric characteristics
- Light weight

## **2.8 CONCRETE REINFORCEMENT WITH CHOPPED BASALT FIBRE**

Basalt fibre is an effective reinforcing additive component to concrete because it improves the thermal and mechanical properties of concrete. Basalt fibre has good adhesion with the cement matrix. The main factor for chemical stability of basalt fibre in concrete is the presence of heavy metal oxides in its molecular structure ( $Al_2O_3$  and  $Fe_2O_3$ ), which prevents disintegration of basalt fibres in a highly alkaline concrete environment (Basalt Fibres Ltd., 2013).

### **2.8.1 TESTS ON CHOPPED BASALT FIBRE REINFORCED CONCRETE**

This section discusses the previous research conducted using chopped basalt fibres in concrete.

#### **2.8.1.1 STRENGTH, TOUGHNESS AND IMPACT RESISTANCE**

Ramakrishnan et al. (1998) conducted tests using basalt fibres 12  $\mu m$  in diameter and 13 mm in length. The fibre dosage varied from 0.1% - 0.5% by volume. The water-cement ratio was kept at 0.5 for all the mixes.

Based on this research the following points are concluded.

- Satisfactory workability can be maintained with addition of basalt fibres up to 0.5% by volume.
- Large quantities of basalt fibres could be added without causing any balling or segregation.
- There was little or no variation in compressive strength for basalt fibre reinforced concrete.
- Difference in the number of blows from first crack to failure increased from 4 (for plain concrete) to 34 (for 0.5% by volume of fibre), which indicates that there was considerable increase in impact strength.
- Toughness indices ( $I_5$ ,  $I_{10}$ ,  $I_{20}$ ) are dimensionless parameters which are defined on the basis of three service levels identified as the multiples of the first crack deflection. The index  $I_5$  is computed by dividing the area under the load-deflection curve (flexural test using third-point loading) up to three times the first crack deflection divided by the area up to first crack deflection. Likewise,  $I_{10}$  and  $I_{20}$  are the indices up to 5.5 and 10.5 times the first crack deflection, respectively. Residual strength factor ( $R_{5,10}$ ) is derived directly from toughness indices  $I_5$  and  $I_{10}$ . Residual strength is calculated using Equation 2.1 and Equation 2.2.

$$R_{M,N} = C(I_N - I_M) \quad (2.1)$$

$$C = \frac{100}{(N - M)} \quad (2.2)$$

Hence,  $R_{5,10} = 20(I_{10}-I_5)$ . An  $R_{5,10}$  value of 100 indicates good post-crack strength (good elastic behavior). This study (Ramakrishnan et al., 1998) shows that the residual strength index ( $R_{5,10}$ ) increased from 82 (for 0.1% by volume of fibre) to 137 (for 0.5% by volume of fibre) which indicates that there was considerable increase in the toughness (post-crack strength) with the increase in fibre dosage.

- The most important contribution of fibres, is the change of mode of failure from a brittle to ductile when subjected to compression, bending, and impact.

The study recommended to increase the fibre length from 13 mm to 50 mm for better performance based on the previous research conducted using polypropylene fibres.

#### **2.8.1.2 FLEXURAL STRENGTH OF BEAM**

Tests were conducted on concrete specimens reinforced with 16  $\mu\text{m}$  basalt filaments of three different lengths (12 mm, 24 mm, and 50 mm) with varying fibre content (1%, 2% and 3% by weight). The results showed that the plain concrete and 12 mm basalt fibre reinforced specimens were brittle, regardless of the fibre content. The disintegration of the specimen occurred simultaneously with the formation of first crack. The first crack was formed at 0.75 to 0.85 of the breaking load. The axial and flexural strength of the specimens reinforced with 24 mm and 50 mm filaments (1% - 3% by weight) were found to be 1.79 to 2.24 times more than that of the unreinforced specimens, respectively (Klimov and Piskun, 2009).

#### **2.8.1.3 FLEXURAL STRENGTH OF SLAB**

Load testing on quadrate slabs (120 mm thick) containing 24 mm basalt fibres at 3.5  $\text{kg}/\text{m}^3$ , resulted in an effective bending strength of 0.31  $\text{N}/\text{mm}^2$ , which is slightly less (0.38  $\text{N}/\text{mm}^2$ ) than similar slab reinforced with steel fibre at 40  $\text{kg}/\text{m}^3$  (Beitzel, 2010). This study did not compare the performance of basalt fibre slabs with plain concrete.

#### **2.8.1.4 COMPRESSIVE AND FLEXURAL STRENGTH**

Flexural and compressive strength tests were conducted with 16  $\mu\text{m}$  diameter and 24 mm long basalt fibre reinforced concrete by KNUCA (2011) for Technobasalt-Invest LLC. The results showed that the flexural strength and the compressive strength increased by 29% and 14%, respectively from plain concrete specimens by adding 5  $\text{kg}/\text{m}^3$  of 16  $\mu\text{m}$  diameter and 24 mm long basalt fibre to 29 MPa concrete. Adding 4  $\text{kg}/\text{m}^3$  of 16  $\mu\text{m}$  diameter and 24 mm long basalt fibre to 35 MPa concrete, increased the flexural strength up to 29% and compressive strength by 9% from plain concrete specimens.

### **2.8.1.5 LONG TERM DURABILITY IN ALKALINE ENVIRONMENT**

Tests conducted by Rock-composites (2012) on 16 micron basalt chopped fibre and 12mm basalt rebar showed that the basalt products have better alkali resistance than E-glass, aramid, and poly fibre. It did not corrode like steel. The basalt fibre and basalt rebar were subjected to an alkali solution with a pH range of 13.7 to 13.9. This range is harsher than the range recommended by ACI 440.1R (2006). The aging temperature was between 76°C to 80°C and lasted over 20 days which correlates to 100 years of accelerated exposure. The results showed that the basalt chopped fibre and basalt rebar had minimum degradation which were less than 0.0001%. Hence, basalt products are minimally affected by the high alkaline concrete environment.

### **2.8.1.6 STRENGTH**

Fibres Unlimited (2013) conducted tests using basalt fibres 17 µm in diameter and 12 mm in length at 1 kg/m<sup>3</sup> dosage (Mix 1); and also with basalt fibres 15 µm in diameter and 18 mm in length at 3 kg/m<sup>3</sup> dosage (Mix 2). The results showed that the compressive strength increased by 7%, the flexural strength increased by 8.6%, the split tensile strength increased by 3%, coefficient of impermeability increased by 43%, from Mix 1 to Mix 2. However, the results (compressive, flexural, split tensile strength) of BFRC Mix 1 and BFRC Mix 2 were not compared with that of plain concrete.

### **2.8.1.7 BOND WITH CONCRETE**

In addition to the technical advantages, it is also important to note that much more elementary basalt fibres are spread out in concrete matrix contributing to the binding process than in the case of other types of fibres. Research has shown that the presence of 300 million basalt fibres in 1 m<sup>3</sup> of concrete provides better binding than other type of fibres as shown in Table 2.2 (Basalt Fibres Ltd., 2013).

**Table 2.2: Dispersion of fibres in concrete**

(Basalt Fibres Ltd., 2013)

| Fibre properties                            | Steel fibre |                    | Polypropylene fibre |                   | Basalt fibre |                   |
|---|-------------|--------------------|---------------------|-------------------|--------------|-------------------|
|   | Length      | 24 mm              | Length              | 24 mm             | Length       | 24 mm             |
|   | Diameter    | 0.62 mm            | Diameter            | 0.52 mm           | Diameter     | 14 $\mu\text{m}$  |
|   | Amount      | 30 $\text{kg/m}^3$ | Amount              | 7 $\text{kg/m}^3$ | Amount       | 3 $\text{kg/m}^3$ |
| Amount of fibres in 1 $\text{m}^3$ concrete | 0.6 million |                    | 1.7 million         |                   | 300 million  |                   |

### **2.8.1.8 MECHANICAL AND THERMAL PROPERTIES**

Borhan (2013) investigated the thermal and mechanical properties of basalt fibre reinforced concrete using fibres 13  $\mu\text{m}$  in diameter and 25.4 mm in length. The following volume fractions of basalt fibre were used: 0.1%, 0.2%, 0.3%, and 0.5%. Results indicated that the compressive strength and the split tensile strength increase with the increase in fibre content until 0.3% by volume, then there is a slight reduction for 0.5% by volume. There was up to a 10% increase in split tensile strength for 0.3% by volume of basalt fibre and 4% reduction in split tensile strength for 0.5% by volume of basalt fibre, with respect to plain concrete. Similarly, there was up to 15% increase in compressive strength for 0.3% by volume of fibre and 10% reduction in compressive strength for 0.5% by volume of fibre, with respect to plain concrete.

### **2.9 APPLICATIONS OF BASALT FIBRE REINFORCED CONCRETE**

Basalt-based materials, including basalt roving chopped basalt fibre strands and basalt composite rebar can be used for enhancing radioactive waste isolation during the storage and disposal phases and maintaining it during a significant portion of the post-closure phase. Concrete reinforced with chopped basalt fibre strands has high durability, high abrasion resistance, high shock resistance, high frost-resistance, high corrosion resistance, and high water resistance. Another key advantage of basalt fibres is its low cost and its use does not significantly affect the construction cost of nuclear power facilities (Gulik and Biland, 2012).

Basalt has high chemical and thermal stability, good thermal, electrical, and sound insulating properties. Hence, it is used in fire protection. Basalt has good electrical insulating properties and chemical resistance, especially in strong alkalis. Hence, basalt composite pipes can be used to transport corrosive liquids and gases (Parnas et al., 2007).

Field application of basalt fibre reinforcement include concrete (molding blocks, beams, fire resistant concrete, and pre-stressed concrete), industrial concrete floors, runways in airports, motorway, industrial floors in shops where heavy equipment is used, internal reinforcement of tunnels and channels, slope stabilization, repair and reconstruction of buildings, concrete water channels, fire retardant construction, and military installations (Baytrade, 2013).

## **2.10 CONCLUSIONS**

Literature review shows that there are three main factors which influence the strength and toughness of fibre reinforced concrete.

- Aspect ratio of the fibre
- Volume of the fibre
- Bond strength of the fibre

Low to moderate fibre content improves the flexural toughness of fibre reinforced concrete, whereas, the improvement in the flexural strength is relatively low. The flexural toughness and strength (flexure, compressive, and split tensile) show an increasing trend for a particular fibre type and mix until an optimum fibre length and fibre volume are attained. Large aspect ratio fibres at high volume fraction cause workability issues. Short fibres help in bridging micro-cracks however, they do not significantly improve the flexural strength. Long fibres help in bridging macro-cracks and thus, improve the post-elastic behaviour. The cracks in the matrix propagate with the increase in load until either the fibre fails in tension or fibre pull-out from the matrix occurs.

The test results from the research conducted by Ramakrishnan et al. (1998) using basalt fibres 12  $\mu\text{m}$  in diameter and 13 mm long shows that there was no improvement in the compressive strength and the flexural strength of BFRC with the addition of basalt fibres (0.1% to 0.5% by volume of basalt fibres). However, there was considerable improvement in the impact strength and flexural toughness of BFRC specimens (for 0.5% by volume of fibre) from plain concrete.

The test results from the research conducted by Borhan (2013) using basalt fibres 13  $\mu\text{m}$  in diameter and 25.4 mm long shows that the compressive strength and the split tensile strength increase with the increase in fibre content up to 0.3% by volume of basalt fibres. However, there was slight reduction in the compressive strength and the split tensile strength for 0.5% by volume of basalt fibres.

The test results from similar research conducted by KNUCA (2011) using basalt fibres 16  $\mu\text{m}$  in diameter and 24 mm long showed that the flexural strength and the compressive strength increased by 29% and 14%, respectively from plain concrete specimens by adding 5  $\text{kg}/\text{m}^3$  to 29 MPa plain concrete.

Literature review found how various types of fibres used in concrete improve the mechanical properties of plain concrete, and the advantages and disadvantages of using these fibres in concrete. There have been some research in the past using basalt filaments to improve the performance of plain concrete. However, the literature review showed that no research has been conducted in the past using basalt bundled fibres.

The current research aims to find the optimum fibre length and volume of basalt fibres (bundles and filaments) required to improve the flexural strength, compressive strength, and split tensile strength of BFRC from plain concrete. The research also compares the performance of bundled fibres with basalt filaments of various lengths (12 mm, 36 mm, and 50 mm) at various fibre dosages (4  $\text{kg}/\text{m}^3$ , 8  $\text{kg}/\text{m}^3$ , and 12  $\text{kg}/\text{m}^3$ ).

### **3. EXPERIMENTAL PROGRAM**

#### **3.1 SCOPE OF THE RESEARCH**

This project is a part of continuous effort to develop a smart and greener concrete. To achieve this goal, research projects were conducted at the University of Windsor to determine an optimum basalt fibre quantity for a given plain concrete mix, using chopped basalt fibres of various lengths (12 mm to 50 mm) and forms (filaments and bundles). The weight ratio for the concrete mix for this research was chosen at 1:1.4:2.8 (cement: fine aggregate: coarse aggregate) with water-cement ratio of 0.5. This water-cement ratio was decided based on the previous research completed at the University of Windsor.

The scope of this project included a) preparing Basalt Fibre Reinforced Concrete (BFRC) mixes using fibres of varying lengths and forms, b) preparing beam specimens (150 mm x 150 mm in cross section and 600 mm long) and cylinder specimens (100 mm diameter and 200 mm high), c) curing these specimens for twenty eight days, d) testing them with required instrumentation and data acquisition system, and (e) analyzing the test data.

The aim of this project was to determine the physical properties such as compressive strength, split tensile strength, and modulus of rupture of Basalt Fibre Reinforced Concrete (BFRC) made with bundled and filament chopped basalt fibres. For each fibre length (12 mm, 36 mm, and 50 mm) and form (bundle and filament), the fibre amount used were 0 kg/m<sup>3</sup>, 4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>. These results were compared against representative steel fibre and macro synthetic fibre mixes.

The test results from this project were then used to evaluate the performance of BFRC mixes which are used in concrete pavements and repairing damaged building and bridge components. It is believed that BFRC will revolutionize the construction industry because it is cheaper, greener, lighter, and eliminates the problem of corrosion of reinforcement bar and corrosion led damages in the steel reinforced concrete structures.

## 3.2 MATERIALS

### 3.2.1 FIBRES

Two types of chopped basalt fibres (bundles and filaments) of various lengths, steel fibres, and macro synthetic fibres were used for this research.

#### 3.2.1.1 BASALT FIBRE

The following basalt fibres were used. These fibres were obtained from Sudaglass Fiber Technology, Inc. in the USA.

1. Bundles (Figure 3.1a)  
Length: 12 mm, 36 mm, and 50 mm  
Diameter: 16 micron
2. Filaments (Figure 3.1b)  
Length: 12 mm, 36 mm, and 50 mm  
Diameter: 16 micron



(a)



(b)

**Figure 3.1: Basalt fibres**  
**(a) Basalt bundles (b) Basalt filaments**

Filament fibres especially of longer length ( $\geq 36$  mm) tend to lump at higher dosage ( $\geq 8$  kg/m<sup>3</sup>) during mixing. In order to prevent lumping of fibres at high dosages, the fibres were added slowly at a constant rate, while the mix was still dry and the concrete mixer was in motion. Bundled fibres mix uniformly even for longer length and at high dosages.

However, as the dry mixing progresses, the bundled fibres separate and disperse as individual filaments in the concrete mix.

### **3.2.1.2 STEEL FIBRE**

Hooked end, cold drawn steel fibres were used in this study (Figure 3.2). These fibres were obtained from Nycon Corporation in the USA.

Diameter: 0.9 mm

Length: 38 mm



**Figure 3.2: Steel fibres**

### **3.2.1.3 POLYOLEFIN FIBRE**

STRUX 90/40, which is a Polyolefin and monofilament fibre, was used (Figure 3.3). These fibres were obtained from Grace Construction Products in Canada.

Length: 40 mm

Aspect ratio: 90



**Figure 3.3: Polyolefin fibres**

### **3.2.2 CEMENT**

Type 10 General Use Portland Limestone cement conforming to CSA A3001 (2008) was used. The cement was supplied by St. Marys Cement, St. Marys, Ontario.

### **3.2.3 COARSE AGGREGATE**

Well graded, normal weight gravel called *Lafarge gravel* supplied by Santerra Stonecraft located in Windsor, Ontario was used. The maximum size of the aggregate used was 20 mm (nominal size was 19 mm). The gravel was spread in a single layer in the lab and left to air dry for a week before the mix. In order to minimize fine powdery material in the gravel which absorbs the water, the dried gravel was heaped conically, and shoveled from the surface. This process eliminated most of the fine powder in the gravel.

### **3.2.4 FINE AGGREGATE**

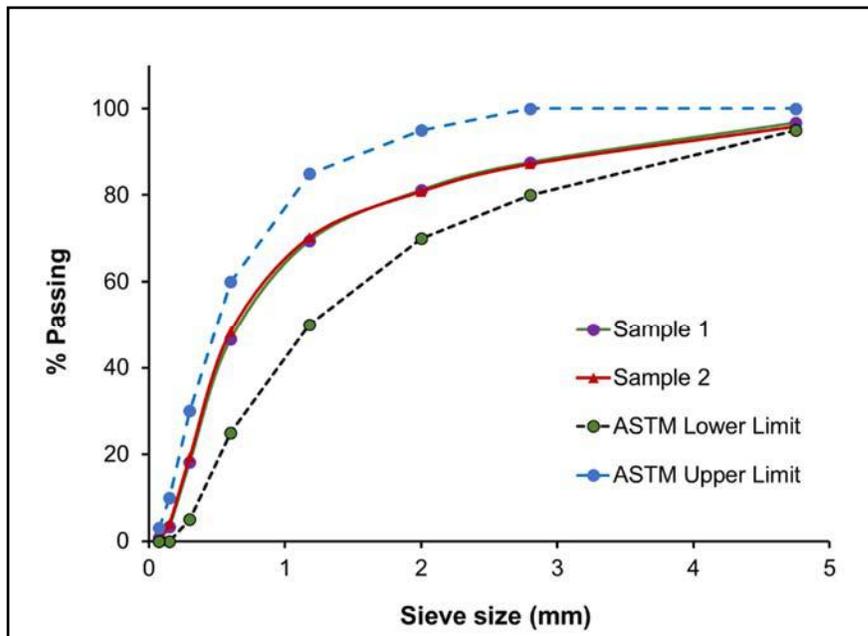
Well graded, normal weight sand supplied by Santerra Stonecraft located in Windsor, Ontario was used. The sand was spread in a single layer in the lab and left to air dry for a week before the mix.

### **3.2.5 GRADING OF AGGREGATE**

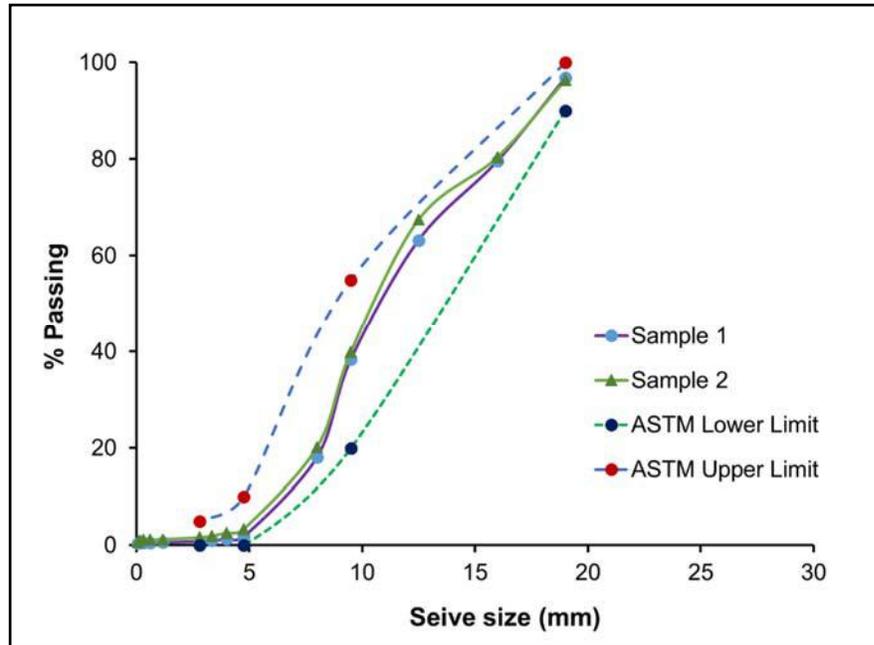
The coarse and fine aggregates conformed to the grading requirements of CSA A23.1 (2009a) and ASTM C33 (2013). Sieve analysis was performed. The sample sizes for coarse aggregate and fine aggregate were 5 kg and 500 g, respectively. Each sample was then placed on the topmost sieve in a stack of sieves and then placed in the sieve shaker (Figure 3.4). The shaker was then turned on for a few minutes, allowing the sample to pass through the sieves. Varying quantities of the sample were retained on each sieve, based on the mesh size and individual grain size. The results along with the upper and lower limits recommended in CSA A23.1 Table 10 (sand) and Table 11 (gravel) (2009a) / ASTM C33 Table 1 (sand), and Table 3 (gravel) (2013) are shown in Figures 3.5 and 3.6.



**Figure 3.4: Sieve shaker**



**Figure 3.5: Sieve analysis – Fine aggregate or sand**



**Figure 3.6: Sieve analysis – Coarse aggregate or gravel**

### **3.2.6 WATER**

The water used for all the concrete mixes was normal drinking water at the University of Windsor.

### **3.3 QUANTITY ESTIMATE**

The quantities for each concrete batch, considering 20% wastage, were calculated based on the determined proportions of the concrete mix, as explained in section 3.1. Each batch was done in two mixes due to the limitation of the mixer's capacity which is only 0.1 m<sup>3</sup>. The quantities used for each mix are listed below in Table 3.1. The water-cement ratio was usually kept at 0.5 for all the mixes. In one mix (BB 50-4), the water-cement ratio was reduced to 0.4 to maintain the slump less than 200 mm. This caused very high compressive strength and flexural strength. As a result this mix and related tests were repeated with water-cement ratio of 0.5.

**Table 3.1: Quantity estimates per mix of 159 kg**

| Material         | Quantity (kg) | Ratio |
|------------------|---------------|-------|
| Cement           | 27.9          | 1     |
| Fine Aggregate   | 39.05         | 1.4   |
| Coarse Aggregate | 78.15         | 2.8   |
| Water            | 13.95         | 0.5   |



**Figure 3.7: Concrete mixer**



**Figure 3.8: Quantities for a mix**

### 3.4 MIXING PROCEDURE

The concrete mixer of 0.1 m<sup>3</sup> capacity at the University of Windsor lab was used for all the mixes (Figure 3.7). The required quantities of coarse aggregate, fine aggregate, cement, basalt fibre, and water were measured before each mix (Figure 3.8). The mixer was rinsed with water and drained before the first mix of each day so that it did not absorb water from the mix. The coarse and fine aggregates were mixed dry for 3 minutes before adding cement. The cement was added and mixed for another 2 minutes. Fibre was added slowly at a constant rate, while the mix was still dry and the concrete mixer was in motion to eliminate lumping of fibres in the mix as shown in Figure 3.9. At higher fibre dosages, the mixer had to be stopped a few times and the dry concrete mix was agitated manually with a trowel several times to remove the fibres lumped around the mixer blades. The lumping of fibres was found to be more evident in case of basalt filaments compared to basalt bundled fibres. The dry mixing process continued until all the fibres dispersed uniformly. Basalt bundled fibres dispersed evenly as individual strands in the dry mix even at high volume fraction (0.46% by volume). Finally after the fibre had mixed thoroughly, water was added and the mixer was run for another 5 minutes as shown in Figure 3.10. The mixer was thoroughly cleaned with water after each mix. This also helped in maintaining consistency between the mixes to a certain extent, as this eliminated cross contamination between the mixes. The same mixing procedure was repeated for all the mixes.

For macro synthetic fibre (polyolefin) mix, the fibre dosage started at 3 kg/m<sup>3</sup> and then it was increased at a rate of 0.5 kg/m<sup>3</sup> till a maximum workable dosage of 4.5 kg/m<sup>3</sup> was achieved. It was felt that the addition of more fibre would cause lumping. The water-cement ratio of 0.5 provided the mix adequate workability (Average slump of 194 mm).

For steel fibre mix, the fibre dosage started at 30 kg/m<sup>3</sup> and increased at a rate of 5 kg/m<sup>3</sup> till a maximum workable dosage of 40 kg/m<sup>3</sup> was achieved. The water-cement ratio of 0.5 provided the mix adequate workability (Average slump of 216 mm).

The water-cement ratio was kept at 0.5 for the mixes, to achieve test specimens of comparable strengths at different fibre volume fractions. Workability was reduced due to the addition of fibres. At high fibre volume fractions, however, a very small amount of superplasticiser (25 ml to 55 ml) Rheobuild 1000 (supplied by BASF, Canada) was added to achieve adequate workability (slump  $\geq 100$  mm) without adding additional water.



**Figure 3.9: Dry mix with fibre**



**Figure 3.10: Wet mix with fibre**

### **3.5. TEST MATRIX**

The test matrix as shown in Table 3.2 was considered in this project. In each batch, 8 cylinders were prepared for compression tests (4 cylinders each for 7 day and 28 day test), 4 cylinders were prepared for split tensile tests and 6 beams were cast for flexural tests.

Each specimen in Table 3.2 was named based on the fibre type and fibre volume. The first term denotes the type of fibre (PC: Plain Concrete; SF: Steel Fibre; PP: Polyolefin; BB: Basalt Bundle; and BF: Basalt Filament), the following number denotes the length of fibre in mm and the last number denotes the amount of fibre in  $\text{kg/m}^3$  of concrete used in the mix (% by weight). Table 3.3 explains the naming scheme.

For example,

PC – Specimen without fibre or plain concrete

SF 38-40 – Steel Fibre 38 mm long at  $40 \text{ kg/m}^3$

PP 40-4.5 – Polyolefin fibre 40 mm long at 4.5 kg/m<sup>3</sup>

BF 12-4 – B- Basalt, F - Filament, 12 mm long at 4 kg/m<sup>3</sup>

BB 36-8 – B- Basalt, B - Bundle, 36 mm long at 8 kg/m<sup>3</sup>

**Table 3.2: Test matrix**

| Specimen name | Fibre length (mm) | Fibre quantity       |          | Number of cylinders for 7 day compression test | Number of cylinders for 28 day compression test | Number of cylinders for 28 day split tensile test | Number of beam specimens |
|---------------|-------------------|----------------------|----------|--|---|---|--------------------------|
|               |                   | (kg/m <sup>3</sup> ) | % volume |  |   |   |                          |
| PC            | NA                | 0                    | 0        | 4  | 4   | 4   | 6                        |
| BF 12-4       | 12                | 4                    | 0.15     | 4  | 4   | 4   | 6                        |
| BF 12-8       | 12                | 8                    | 0.31     | 4  | 4   | 4   | 6                        |
| BF 12-12      | 12                | 12                   | 0.46     | 4  | 4   | 4   | 6                        |
| BB 12-4       | 12                | 4                    | 0.15     | 4  | 4   | 4   | 6                        |
| BB 12-8       | 12                | 8                    | 0.31     | 4  | 4*  | 4*  | 6                        |
| BB 12-12      | 12                | 12                   | 0.46     | 4  | 4   | 4   | 6                        |
| BF 36-4       | 36                | 4                    | 0.15     | 4  | 4   | 4   | 6                        |
| BF 36-8       | 36                | 8                    | 0.31     | 4  | 4   | 4   | 6                        |
| BF 36-12      | 36                | 12                   | 0.46     | 4  | 4   | 4   | 6                        |
| BB 36-4       | 36                | 4                    | 0.15     | 4  | 4*  | 4*  | 6                        |
| BB 36-8       | 36                | 8                    | 0.31     | 4  | 4   | 4   | 6                        |
| BB 36-12      | 36                | 12                   | 0.46     | 4  | 4   | 4   | 6                        |
| BF 50-4       | 50                | 4                    | 0.15     | 4  | 4   | 4   | 6                        |
| BF 50-8       | 50                | 8                    | 0.31     | 4  | 4   | 4   | 6                        |
| BF 50-12      | 50                | 12                   | 0.46     | 4  | 4*  | 4*  | 6                        |
| BB 50-4       | 50                | 4                    | 0.15     | 4  | 4*  | 4*  | 6*                       |
| BB 50-8       | 50                | 8                    | 0.31     | 4  | 4   | 4   | 6                        |
| BB 50-12      | 50                | 12                   | 0.46     | 4  | 4   | 4   | 6                        |
| PP 40-4.5     | 40                | 4.5                  | 0.49     | 4  | 4   | 4   | 6                        |
| SF 38-40      | 38                | 40                   | 0.51     | 4  | 4   | 4   | 6                        |

\* - Specimens were mixed and cast twice for the following reasons.

(a) Slump for the mix was less than 100 mm for higher fibre dosages.

(b) To keep the water-cement ratio constant at 0.5 for all the mixes.

**Table 3.3: Specimen Nomenclature**

| <b>Term</b> | <b>Symbol</b>   | <b>Meaning</b>                              |
|-------------|-----------------|---|
| 1           | B               | Basalt                                      |
|             | PP              | Polyolefin                                  |
|             | SF              | Steel Fibre                                 |
| 2           | B               | Bundle                                      |
|             | F               | Filament                                    |
| 3           | 12//36/38/40/50 | Length of fibre (mm)                        |
| 4           | 0/4/4.5/8/12/40 | Percentage of fibre (by weight ) in the mix |

### **3.6 SLUMP TEST**

A slump test is generally used to assess the workability and horizontal free flow of self-compacting concrete (SCC) in the absence of obstructions. It measures the consistency of the plastic concrete of a specific batch. It refers to the ease with which the concrete flows. It indicates the degree of wetness. Workability of concrete is mainly affected by consistency, i.e. wetter mixes are more workable than drier mixes. However, concrete of the same consistency may vary in workability (CSA A23.2-5C, 2009a) / (ASTM C143, 2012a).

A truncated cone (Abrams cone), 300 mm in height, and 100 mm diameter at the top, and 200 mm diameter at the bottom, was used for the slump test (Figure 3.11). The slump cone was filled with fresh concrete mix in three equal layers. Each layer was compacted a by 16 mm tamping rod (25 strokes for each layer). The strokes were uniformly distributed over the cross section. The second and third layers were compacted throughout the depth of the layer and penetrating 25 mm into the underlying layer (CSA A23.2-5C, 2009a) / (ASTM C143, 2012a).

The excess concrete was removed with a screeding rolling motion of the tamping rod after the top layer was compacted. The slump cone was carefully raised immediately at a constant rate (by counting from 1001 to 1005), in the vertical direction by steady upward lift ensuring no lateral or torsional movement to the concrete. The entire operation from start of filling to the removal of slump cone was completed without interruption in

2 minutes. The slump was determined immediately by measuring the difference in height of the mould and the average height of the top surface of concrete after subsidence as shown in Figure 3.12. The slump often varied considerably between the mixes of similar fibre dosage and length. This could be due to the presence of varying amounts of fine powder in gravel. More powdery material result in higher absorption of water. There was no segregation of the aggregates even at slumps greater than 200 mm. Test results show that the variation in slump (slump between 100 mm to 200 mm) has little effect on compressive or flexural strengths as long as the water-cement ratio is kept constant. The workability was improved by adding Rheobuild 1000 superplasticizer for mixes when slump was found to be less than 100 mm. Rheobuild 1000 superplasticizer (55 ml) was added for BF 50-12 mix for which the slump was less than 100 mm before the addition of superplasticizer. The slump values obtained for the basalt bundled fibre specimens and the basalt filament fibre specimens are shown in Appendix D.



**Figure 3.11: Slump cone**



**Figure 3.12: Slump test**

### 3.6.1 INTERPRETATION OF RESULTS

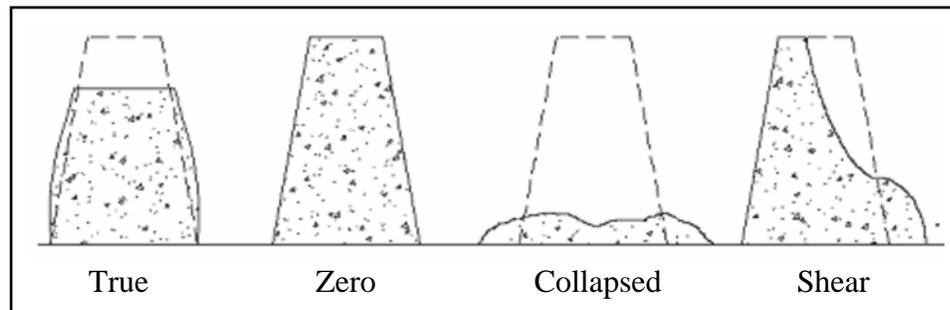
The slumped concrete takes various shapes and according to the profile of slumped concrete, the slump is termed as true slump, zero slump, shear slump or collapsed slump (Figure 3.13). A collapsed slump indicates a mix with high workability. ACI 211.1-91 Table 6.3.1 (2009), recommends the following slumps as listed in Table 3.4.

**Table 3.4: Recommended slumps for various types of construction**

(ACI 211.1-91 Table 6.3.1, 2009)

| Types of construction                            | Slump (mm) |         |
|--|------------|---------|
|  | Maximum*   | Minimum |
| Reinforced foundation walls and footings         | 75         | 25      |
| Plain footings, caissons, and substructure walls | 75         | 25      |
| Beams and reinforced walls                       | 100        | 25      |
| Building columns                                 | 100        | 25      |
| Pavements and slabs                              | 75         | 25      |
| Mass concrete                                    | 75         | 25      |

*\*May be increased by 25 mm for consolidation by rodding.*



**Figure 3.13: Four Types of Slump**  
(ICAR 105-1, 2003)

### **3.7 PREPARATION OF TEST SPECIMENS**

#### **3.7.1 FORMS FOR COMPRESSION TEST AND SPLIT TENSILE TEST SPECIMENS**

Plastic cylindrical forms (clear dimensions are: 100 mm diameter x 200 mm high) having a nonabsorbent surface were used (CSA A23.2-3C Clause 4.1, 2009a). The forms were lightly coated with form release oil before use.

#### **3.7.2 FORMS FOR FLEXURAL TEST SPECIMENS**

The forms were made of polycarbonate and had clear dimensions of 150 mm x 150 mm in internal cross section and 600 mm in length, conforming to CSA A23.2-3C Clause 4.2 (2009a). The forms were cleaned and lightly coated with form release oil before use (Figure 3.14).



**Figure 3.14: Polycarbonate form**

#### **3.7.3 COMPRESSION TEST SPECIMENS**

The specimens were cylindrical with length equal to twice their diameter (100 mm diameter x 200 mm high) conforming to CSA A23.2-3C Clause 7 (2009a). Four specimens were made from each batch for compression testing. The average of three consistent results was taken as the compression strength of the batch.

### **3.7.4 METHOD OF CONSOLIDATION**

#### **3.7.4.1 RODDING – FOR COMPRESSION AND SPLIT TENSILE TEST SPECIMENS**

As the slump was greater than 40 mm for all the mixes. Rodding was used for compaction of the cylinders, as per CSA A23.2-3C Clause 6, and Clause 7.2.1 (2009a). The concrete was filled in the mould in three equal layers. Each layer was compacted with a 10 mm diameter rod, 20 strokes uniformly distributed over the cross section of the mould. The bottom layer was rodded throughout its depth. For each of the upper layer, rodding was allowed to penetrate at least to a depth of 25 mm into the underlying layer. Sufficient care was taken to avoid any air voids. The top surface was leveled with the tamping rod after compaction. For mixes with slump greater than 180 mm, the number of strokes for consolidation for each layer was reduced to 8 strokes in accordance with CSA A23.2-3C Clause 7.2.1.2 (2009a).

#### **3.7.4.2 INTERNAL VIBRATION – FOR FLEXURAL TEST SPECIMEN**

Internal vibrator with flexible shaft powered by electric motor and with vibration frequency 120 Hz or higher was used. Vibrator was inserted at 150 mm intervals along the length of the specimen (CSA A23.2-3C Clause 4.4.1 and Clause 8.2.4, 2009a). Sufficient care was taken to avoid the vibrator from touching the form (Figure 3.15).



**Figure 3.15: Two beam specimens**

### **3.7.5 LABORATORY CURING OF SPECIMENS**

The specimens were removed from the form after attaining initial strength (20 hours  $\pm$  4 hours after casting) and left for air curing in the lab (CSA A23.2-3C Clause 7.3.1, 2009a).

### **3.7.6 PLANENESS AND PERPENDICULARITY OF COMPRESSION TEST SPECIMEN**

The ends of the compression test specimens shall not depart from a plane by more than 0.05 mm as per CSA A23.2-9C Clause 4.1.3 and 4.1.4 (2009a). The compression test specimen also shall not depart from perpendicularity to the axis by more than 0.5 degree. The compression test specimens were cut at the ends using wet saw with 500 mm diameter blades and capped using a sulphur capping compound to achieve planeness and perpendicularity (Figure 3.16).



**Figure 3.16: Wet saw for surfacing the cylinders**

### 3.7.7 CAPPING COMPOUND

Forney Hi-Cap™ was used for capping (Figure 3.17). This was preferred over the other brands as it melts fast, sets fast, and has lower fumes than other brands. Hi-Cap™ has a melting range of 240°F to 290°F (115 to 143 °C) and comes in easy-melt thin flake form. It meets the requirements of ASTM C617 (2012b).



**Figure 3.17: Capping compound**  
**(a) Capping compound (Forney Hi-Cap™) (b) Molten capping compound**

#### 3.7.7.1 CAPPING PROCEDURE

The capping compound was melted in a pot with automatic temperature control, capable of maintaining molten sulphur. The sulphur caps were formed against a machined metal plate with a recessed area in a shallow dish shape for receiving molten sulphur. The recess depth was about 5 mm. The metal plate was oiled before pouring the molten capping material. Immediately after



**Figure 3.18: Capping procedure**

the molten capping material was poured in the recess, the cylinder specimen was slowly lowered into the molten liquid, ensuring that no pressure was applied from the top and

perpendicularity was maintained (Figure 3.18). Figures 3.19 and 3.20 show specimens with caps before and after compression testing.



**Figure 3.19: Capped cylinders**



**Figure 3.20: Tested cylinders**

### **3.8 STRENGTH TEST**

In the experimental program, three basic tests for mechanical properties of concrete which are tests for modulus of rupture, compressive strength, and split tensile strength were conducted. The compressive strength of concrete cylinders was tested on the 7<sup>th</sup> day and 28<sup>th</sup> day. The modulus of rupture and split tensile strength were tested on the 28<sup>th</sup> day.

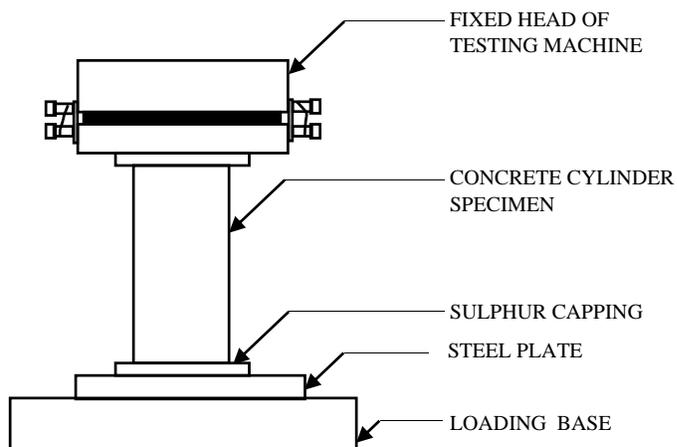
#### **3.8.1 TEST SETUP**

##### **3.8.1.1 COMPRESSIVE STRENGTH OF CONCRETE**

The compressive strength test was carried out at ages of 7 days and 28 days to determine the development of compressive strength of the concrete. Test Mark high capacity series compression testing machine with a maximum capacity of 2,224 kN (500,000 lbs.) was used for testing the compressive strength and the split tensile strength of concrete. Figure 3.21 shows the schematics of the compression test setup and a photo of the compression test setup is shown in Figure 3.22. The diameter and the length of the cylindrical specimen were entered in the machine. The machine calculated the cross sectional area of the specimen. Loading rate option in the machine was set as 'MPa/s'. The test option was selected as 'Cylinder in compression'. In accordance with CSA A23.2-9C (2009a) / ASTM C39 (2012c), load was applied on the cylinder at a constant rate of 0.25 MPa/s ( $\pm$

0.05 MPa/s) without shock until the specimen failed. The loading rate was adjusted manually using the hydraulic valve in the machine. The load at failure and the stress at failure were recorded.

The stress-strain curve of concrete subjected to uniaxial compression is linear up to 30% of the ultimate stress. The cracks begin to propagate at stress levels between 30% and 75% of the ultimate stress. However, no cracking occurs in the mortar matrix and the crack propagation is stable. The stress level of 75% of the ultimate stress represents the onset of unstable crack propagation and is called *critical stress*. At stress levels above 75% of the ultimate stress, complete fracture of the test specimen may occur (Mehta and Monteiro, 2006). Hence, for this research 65% of the ultimate stress was used as the stress at failure for all compression test specimens. The ‘Sample break’ (in percentage) option in the Test Mark machine was set to 35%. Sample break is defined as a percentage of the ultimate stress. Hence, the stress at failure recorded by the machine was 65% of the ultimate stress and this was used in the analysis.



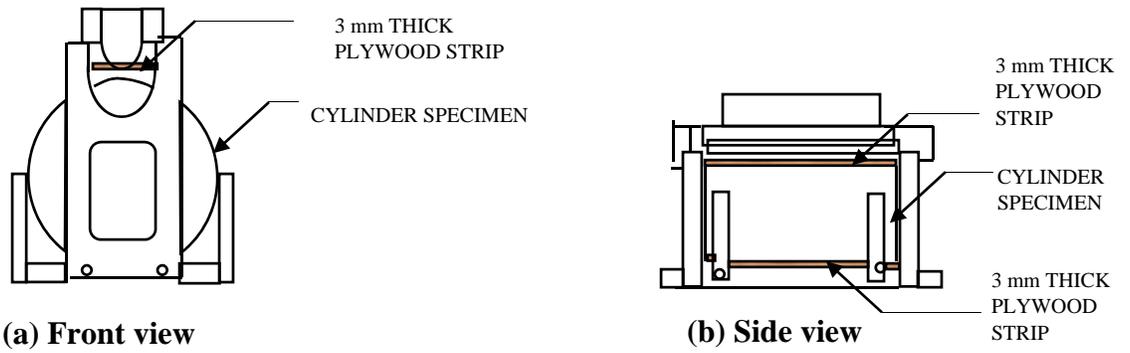
**Figure 3.21: Schematics: Compression test setup**



**Figure 3.22: Compression test setup**

### **3.8.1.2 SPLIT TENSILE STRENGTH**

The test option in the Test Mark compression machine was selected as 'Cylinder in Split Tension'. The loading rate was set to 'MPa/min'. The test cylinder was placed horizontally between two bearing strips of 3 mm thick plywood and approximately 25 mm wide. The length of the plywood was equal to that of the specimen. For positioning the bearing strip and test cylinder, an aligning jig was used as shown in Figure 3.23 and Figure 3.24. In accordance with CSA A23.2-13C (2009a) / ASTM C496 (2011), load was applied on the cylinder at a constant rate of 1.05 MPa/min ( $\pm 0.35$  MPa/min) without shock until the specimen failed (Figure 3.25). The loading rate was adjusted manually using the hydraulic valve in the machine. The load at failure and the stress at failure were recorded. For this research 65% of the ultimate stress was used as the stress at failure for all the split tensile test specimens which is similar to compressive strength test as explained in Section 3.8.1.1.



**Figure 3.23: Schematics: Split tensile test setup**



**(a) Front view**



**(b) Side view**



**(c) Overall view**

**Figure 3.24: Jig for aligning concrete cylinder and bearing strip**



**Figure 3.25: Tested cylinder**

### **3.8.1.3 FLEXURAL TEST SETUP**

The test measures the flexural strength or modulus of rupture of concrete, which is commonly used in the design of pavements or slab on grade. The testing machine conforming to the requirements of CSA A23.2-8C (2009a) / ASTM C78 (2010), clauses 5.1.1, 5.1.7 and 5.3, was used for the test. The third-point loading method, employing bearing plates with roller supports, was used as shown below in Figure 3.26 and Figure 3.27. This was done to ensure that the vertical forces were applied to the beam specimen without any eccentricity. The centerline, positions of support, and the loading points were marked on the beam specimens. The test specimen was turned on its side with respect to its position as molded. An aluminum strip was glued at the mid-span of each specimen for measuring the mid-span deflection. A 5 mm stroke KYOWA made Linear Displacement Transducer (LDT) was used to record this deflection.

The load was applied at a constantly increasing rate until rupture occurred such that the increase in flexural stress was 1.05 MPa/min ( $\pm 0.15$  MPa/min), as per CSA A23.2-8C (2009a) / ASTM C78 (2010). This provides an average loading rate of 110 N/s to 150 N/s. The loading rate was controlled by measuring the instantaneous load recorded every 10 seconds using a stop watch. Load and corresponding deflection were recorded every second during the test using the software of data acquisition system. The maximum load at failure of the specimen was used for the calculation of modulus of rupture unlike compression and split tensile tests.

### 3.8.1.3.1 MODULUS OF RUPTURE

If the fracture occurs within the middle third of the span length, Modulus of rupture is calculated as follows (CSA A23.2-8C, 2009a).

$$R = \frac{Pl}{bd^2} \quad (3.1)$$

where;

R = Modulus of rupture, MPa

P = Maximum applied load, N

l = Span length, mm

b = average width of the specimen, mm

d = average depth of the specimen, mm

If the fracture occurs outside the middle third of the span length by not more than 5% of the span length, then the modulus of rupture is calculated as follows:

$$R = \frac{3Pa}{bd^2} \quad (3.2)$$

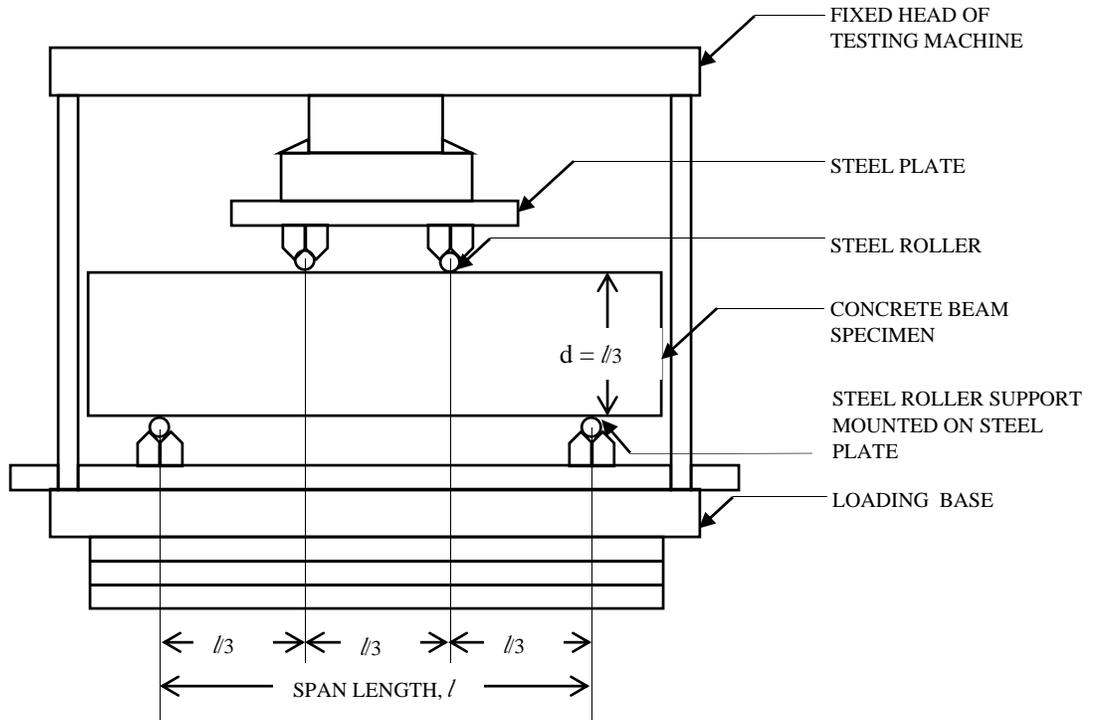
where;

a = distance between the line of fracture and the nearest support measured along the centerline of the bottom surface of the beam, mm.

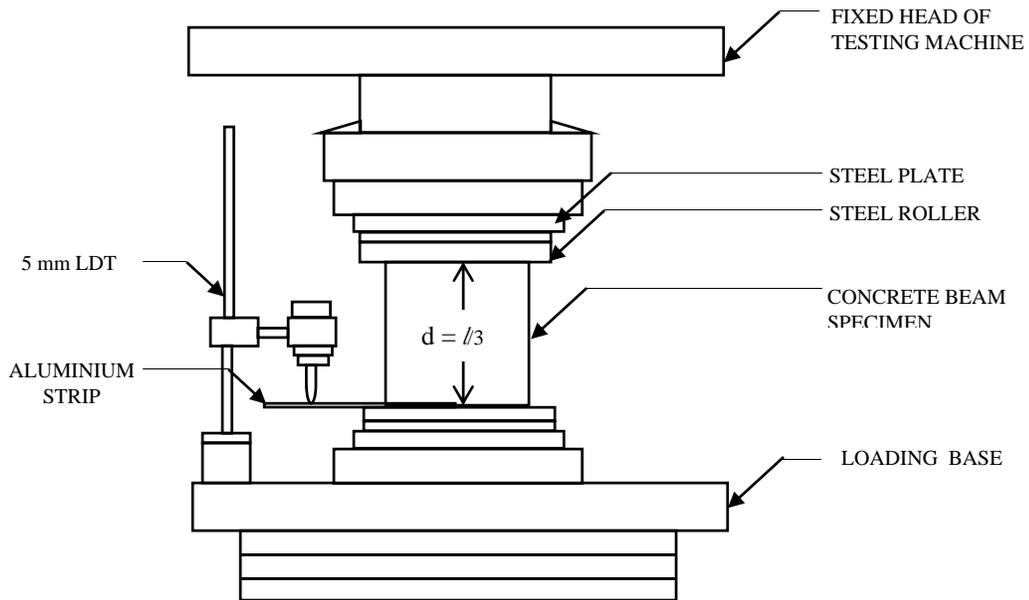
If the fracture occurs outside of the middle third of the span length by more than 5% of the span length, the result of the test is discarded.

For all the test specimens in this project, fracture occurred within the middle third.

Schematics of the test setup are shown in Figures 3.26(a) and 3.26(b). A photo of the test setup is shown in Figure 3.27.

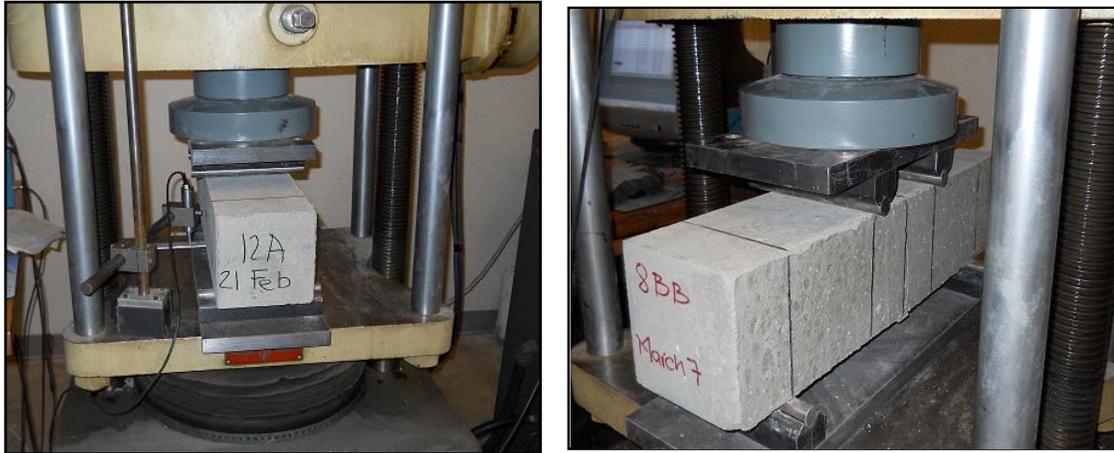


(a) Side view - Flexural test setup



(b) Front view - Flexural test setup

Figure 3.26: Schematics: Flexural test setup



**Figure 3.27: Flexural test setup**

### **3.9 SUMMARY**

This chapter described the procedure followed in casting and testing beam and cylinder specimens containing randomly dispersed fibres. The cylinders were tested in compression on the 7<sup>th</sup> day and 28<sup>th</sup> day after casting. The flexural strength of the beam specimens and the split tensile strength of the cylinder specimens were tested on the 28<sup>th</sup> day after casting.

#### **4. STATISTICAL ANALYSIS**

Variations in the properties or proportions of the constituent materials, and variations in compaction, sampling, curing, and testing procedures, lead to variations in strength of the test specimens.

The concrete strength can be estimated with reasonable accuracy only when an adequate number of tests are conducted in accordance with standard practices and test methods. For the statistical procedures to be valid, the data should be derived from samples obtained by means of a *random* sampling. Random sampling means that each possible sample has an equal chance of being selected. Statistical procedures provide a sound basis for determining the potential quality and strength of the concrete (ACI 214R, 2011).

##### **4.1 VARIATIONS IN STRENGTH**

Variation in the measured strengths can cause significant shift in fundamental statistical characteristics, such as mean, standard deviation, coefficient of variation, or other statistical measures. Table 4.1 summarizes the principal sources of strength variation (ACI 214R, 2011).

**Table 4.1: Principal sources of strength variation**

(ACI 214R, 2011)

| <b>Variations due to the properties of concrete</b>   | <b>Variations due to testing methods</b>  |
|---|---|
| Changes in water-cement ratio caused by:<br>-Poor control of water<br>-Excessive variation of moisture in aggregate or variable aggregate moisture measurements<br>-Re-tempering  | Variations due to fabrication techniques:<br>-Handling, storing, and curing of newly made cylinders<br>-Poor quality, damaged, or distorted molds                     |
| Variations in water requirement caused by:<br>-Changes in aggregate grading, absorption, particle shape<br>-Changes in cementitious and admixture properties<br>-Changes in air content<br>-Delivery time and temperature changes | Changes in curing:<br>-Temperature variation<br>-Variable moisture control<br>-Delays in bringing cylinders to the laboratory<br>-Delays in beginning standard curing |
| Variations in characteristics and proportions of ingredients:<br>-Aggregates<br>-Cementitious materials, including pozzolans<br>-Admixtures   | Poor testing procedures:<br>-Specimen preparation<br>-Test procedure<br>-Un-calibrated testing equipment  |
| Variations in mixing, transporting, placing, and consolidation  | Improper sampling procedures  |
| Variations in concrete temperature and curing   |   |

The first criterion for producing concrete of consistent strength, is to keep control over the water-cement ratio. The water requirement of concrete is strongly influenced by the characteristics of the aggregates, variations in aggregate grading, cement, and admixtures used in the concrete, as well as the desired consistency, in terms of workability. Water demand also varies with air content and can increase with temperature. (ACI 214R, 2011).

Hence, for this research, sufficient care was taken to use dry aggregates and a constant water-cement ratio of 0.5 for all the concrete batches. This kind of quality control is difficult to maintain in the field. Sieve analysis for both coarse and fine aggregates were conducted to ensure that the aggregates met CSA A23.1 (2009a) / ASTM C33 (2013) standards. Sand and gravel were spread in a single layer in the lab and left to air dry for a week before each mix. There was often considerable variations in workability of the mix in spite of maintaining measures to control the water-cement ratio, like making the mixer and the wheel barrow moist before each mix so that they do not absorb the water from the mix. This was mainly due to the presence of fine powdery material in the coarse aggregate that varied from mix to mix, which absorbed water, and thus, resulted in varying workability. Although these powdery materials could be removed by sieving, it is not practical to eliminate this in the field. Hence, sieving of coarse aggregate was not done to remove the fine powdery material in the gravel.

Variations in strength are also influenced by air content. The entrained air content influences both water requirement and strength. There is an inverse relationship between strength and air content. The air content of a specific concrete mixture varies depending on variations in constituent materials, extent of mixing, and ambient site conditions (ACI 214R, 2011). Care was taken to remove entrapped air in the specimens by using proper vibration techniques for the beams, and performing adequate hand compaction for the cylinders as recommended by the Canadian standard, CSA A23.2-3C (2009a).

The temperature of fresh concrete affects both the amount of water needed to achieve the proper consistency and the entrained air content. In addition, the concrete temperature during the first 24 hours of curing can have a significant effect on the later-age strengths of the concrete. Concrete cylinders that are not protected from temperatures outside the range as specified in ASTM C31 (2012d) may not accurately reflect the potential strength of the concrete (ACI 214R, 2011).

Admixtures can contribute to variability in the concrete mix. Hence, for this research, super-plasticizer was added only when the mix was not workable (when slump < 100 mm).

## 4.2 STATISTICAL FUNCTIONS

Concrete strength tests typically follow a normal distribution curve. Strength test results are defined as the average strength of all specimens of the same age, fabricated from a sample taken from a single batch of concrete (ACI 214R, 2011). Canadian standard, CSA A23.1 Clause 4.4.6.4 (2009a) recommends a minimum of two test cylinders from each batch, for average compressive strength determination. However, for this study, in each batch, four cylinders were cast for 28 day compression strength test and the average of three consistent test values was used.

The normal distribution can be fully defined mathematically by two statistical parameters: Mean ( $\bar{X}$ ), and Standard deviation (s).

### 4.2.1 MEAN ( $\bar{X}$ )

The sample mean,  $\bar{X}$ , is the arithmetic average of all observations (n) in a sample. The sample of observations are randomly selected from a larger population of observations (Montgomery and Runger, 2010). The sample mean is calculated using Equation 4.1.

$$\bar{X} = \frac{\sum_{i=1}^n X_i}{n} = \frac{1}{n} \sum X_i = \frac{1}{n} (X_1 + X_2 + X_3 + \dots + X_n) \quad (4.1)$$

where;  $X_i$  is the  $i^{\text{th}}$  strength test result.  $X_1$  is the first strength test result,  $\sum X_i$  is the sum of all strength test results and n is the number of tests (ACI 214R, 2011).

#### 4.2.2 STANDARD DEVIATION (s)

The sample standard deviation,  $s$ , is the most generally recognized measure of dispersion of the individual test data from their average. The *sample standard deviation* ( $s$ ) is obtained by Equation 4.2.

$$s = \sqrt{\frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n - 1}} = \sqrt{\frac{(X_1 - \bar{X})^2 + (X_2 - \bar{X})^2 + \dots + (X_n - \bar{X})^2}{n - 1}} \quad (4.2)$$

where  $s$  is the sample standard deviation,  $n$  is the number of strength test results (number of samples),  $\bar{X}$  is the sample mean.

The *pooled standard deviation* ( $\bar{s}$ ) is the statistical average standard deviation of two separate sample groups (for example, PC and BB 12-4 in Table 4.15). The statistical average standard deviation of two sample groups is calculated as shown in Equation 4.3.

$$\bar{s} = \sqrt{\frac{(n_A - 1)(s_A)^2 + (n_B - 1)(s_B)^2}{(n_A + n_B - 2)}} \quad (4.3)$$

where  $\bar{s}$  is the pooled standard deviation, determined from two sample groups,  $s_A$  and  $s_B$  are the standard deviations of sample group A and sample group B, respectively, and  $n_A$  and  $n_B$  are the number of tests in sample group A and sample group B, respectively (ACI 214R, 2011).

#### 4.2.3 COEFFICIENT OF VARIATION (CV)

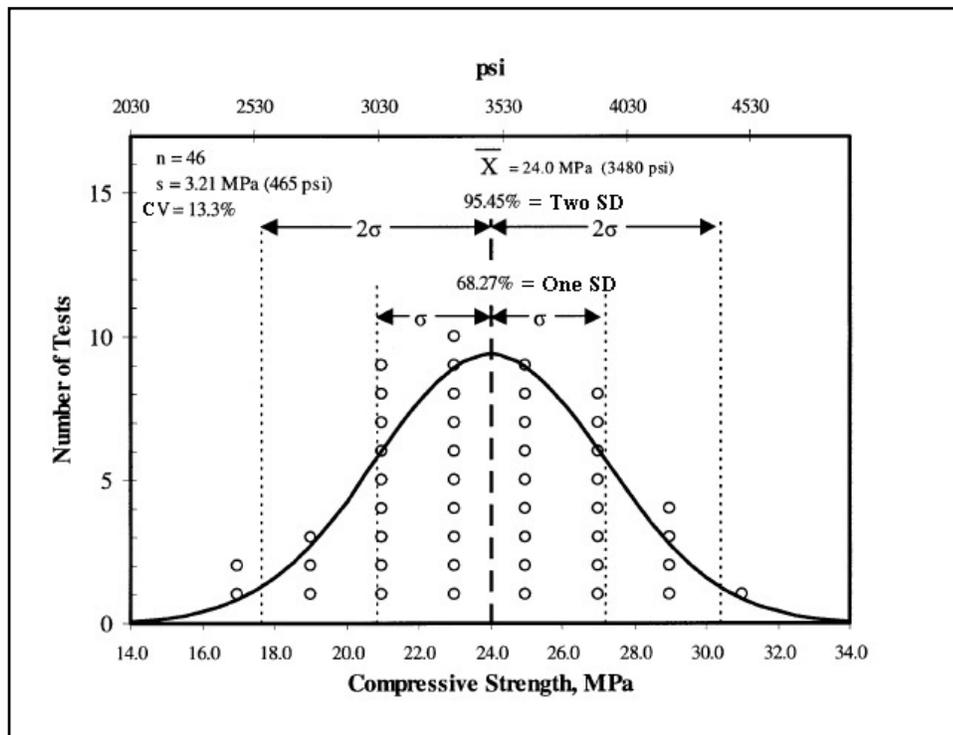
The coefficient of variation, CV, is the ratio of the standard deviation to the mean of a group of values. It is expressed in percentage (Steele et al., 2006).

$$CV = \frac{s}{\bar{X}} * 100 \quad (4.4)$$

where; CV is the coefficient of variation,  $s$  is the sample standard deviation, and  $\bar{X}$  is the sample mean.

The normal distribution curve of concrete strength tests is symmetrical about the mean value of the data as illustrated in Figure 4.1. Approximately 68% of the area under the normal distribution curve lies within  $\pm 1\sigma$  of the mean, and 95% lies within  $\pm 2\sigma$  of the mean (ACI 214R, 2011).

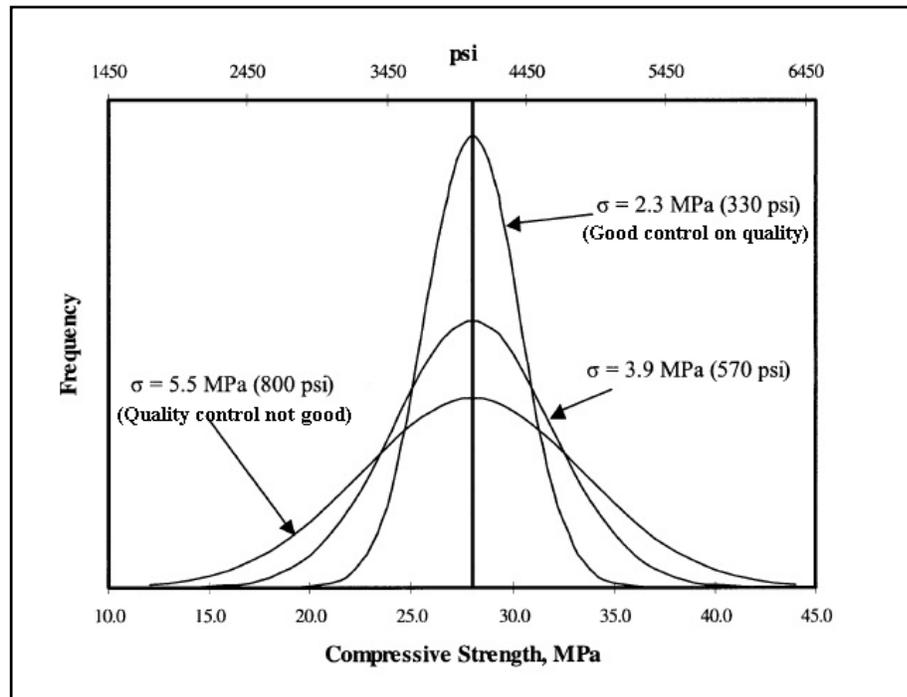
Eurocode, BS EN 1990 (2002) recommends a confidence interval of  $\pm 1.64\sigma$  (90% of the area under normal distribution curve) for field conditions. The Canadian standard, CSA A23.1 Annex C Clause C.1.2 (2009b) recommends a tolerance limit (confidence interval) of 90% for field conditions. ACI 214R (2011) recommends a confidence interval of  $\pm 1.28\sigma$  (80% of the area under normal distribution curve) for field conditions.



**Figure 4.1: Frequency distribution of strength data and corresponding assumed normal distribution**  
(ACI 214R, 2011)

The strength test values tend to cluster near to the average value, that is, the histogram of test results is tall and narrow, when there is good control. As variation in strength results

increases, the spread in the data increases, and the normal distribution curve becomes lower, and wider as illustrated in Figure. 4.2 (ACI 214R, 2011).



**Figure 4.2: Normal frequency curves for three different distributions with same mean and different standard deviation**  
(ACI 214R, 2011)

Notations used in Figure 4.1, and Figure 4.2

$n$  = number of samples

$\bar{X}$  = sample mean

$s$  = sample standard deviation

$\sigma$  = population standard deviation

CV = coefficient of variation

### 4.3 ONE SAMPLE T-TEST

*One sample t-test* is a hypothesis test on the mean of a population, where the data is a random sample from a normal distribution (Montgomery and Runger, 2010).

For using one sample t-test the following are to be followed.

- The sample should be randomly picked from the population
- The population distribution is at least approximately normal
- The mean of the population should be known
- The samples should be independent

One-sample t-test, also known as the *goodness of fit test*, shows whether the collected data is useful in making a prediction about the population. The t-value is calculated using Equation 4.5, and t-value is determined using standard t-distribution table shown in Appendix A.

$$t = \frac{\bar{X} - \mu_0}{s} \sqrt{n} \quad (4.5)$$

where,

$\bar{X}$  = the mean of the measured values

$\mu_0$  = the assumed mean value

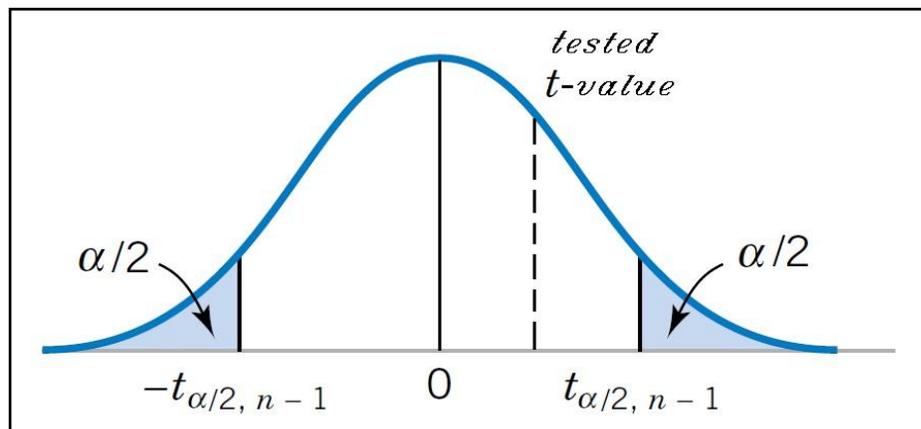
$s$  = the sample standard deviation of the measured values, determined using Equation 4.2.

$n$  = the number of specimens in the sample

Degrees of freedom are defined as the number of values in a sample that are free to vary. The degrees of freedom for one sample t-test, with  $n$  number of specimens in the sample, is  $n-1$ . The t percentage points  $-t_{\frac{\alpha}{2}, n-1}$  and  $t_{\frac{\alpha}{2}, n-1}$ , also known as  $-t_{\text{critical}}$  and  $t_{\text{critical}}$ , mark

the boundaries of the critical region as shown in Figure 4.3 (Montgomery and Runger, 2010).

In this study, the *level of significance* for the t-test,  $\alpha$ , was taken to be 0.05 which corresponds to a *confidence level* of 95%. As the values fall on either side of the bell curve, a two-tailed t-test was used, and  $\alpha/2 = 0.025$  was used to determine the  $t_{\text{critical}}$  values (Appendix A). The tested t-value is compared with  $t_{\text{critical}}$ . The t-test results are interpreted using two types of hypothesis which are *null hypothesis*,  $H_0$  and *alternative hypothesis*,  $H_1$ . Null hypothesis assumes that there is no significant difference between the population mean, and the assumed sample mean (that is,  $\bar{X} = \mu_0$ ) whereas, the alternative hypothesis assumes that there is a significant difference between the population mean and assumed sample mean. If  $-t_{\text{critical}} < \text{tested t-value} < t_{\text{critical}}$ , then, the null hypothesis is accepted. If the tested t-value falls outside  $t_{\text{critical}}$  boundaries, then the null hypothesis is rejected. The criteria for accepting null hypothesis,  $H_0$ , and alternative hypothesis,  $H_1$ , is shown in Table 4.2.



**Figure 4.3: The reference distribution for  $H_0$  with critical region for  $H_1$**   
(Montgomery and Runger, 2010)

**Table 4.2: Criterion for one sample t-test conclusion**

| <b>Criterion</b>   | <b>Conclusion</b>                                |
|--|--|
| <b>t-value comparison</b>  |  |
| $ t  < t_{\text{crit}, \frac{\alpha}{2}}$  | Accept $H_0 (\bar{X} = \mu_0)$ , Reject $H_1$    |
| $ t  > t_{\text{crit}, \frac{\alpha}{2}}$  | Accept $H_1 (\bar{X} \neq \mu_0)$ , Reject $H_0$ |
| <i>In Figure 4.3, the shaded area represents the region where <math>H_0</math> is rejected, and the unshaded region represents the confidence interval where <math>H_0</math> is accepted.</i> |  |

Table 4.3 shows a sample calculation of one sample t-test for modulus of rupture (specimen BB 12-4). The sample size is 3, and degree of freedom is  $3-1 = 2$ . The calculated mean modulus of rupture ( $\bar{X}$ ) is 4.02 MPa and the assumed modulus of rupture ( $\mu_0$ ) is 4.00 MPa. The tested t-value calculated using Equation 4.5 is 0.20, which is less than  $t_{\text{crit}, \alpha/2} = 4.303$  for degree of freedom 2, and 95% confidence interval found from Appendix A. Hence, null hypothesis,  $H_0(\bar{X} = \mu_0)$  is accepted which means that the calculated mean modulus of rupture and the assumed mean modulus of rupture are not statistically different (Table 4.4). It indicates that the calculated modulus of rupture is within 95% confidence interval (CI) of the assumed mean modulus of rupture.

**Table 4.3: Modulus of rupture (MOR): One sample t-test**

Sample calculation – BB 12-4

| Parameters   | Values    |
|--|-----------|
| Modulus of rupture of specimen 1 $X_1$ (MPa)         | 3.87      |
| Modulus of rupture of specimen 2 $X_2$ (MPa)         | 4.16      |
| Modulus of rupture of specimen 3 $X_3$ (MPa)         | 4.03      |
| Mean Modulus of rupture ( $\bar{X}$ ) (Equation 4.1) | 4.02      |
| Assumed Modulus of rupture $\mu_0$ (MPa)             | 4.00      |
| Standard deviation (s) (Equation 4.2)                | 0.14      |
| Degree of freedom, DF ( $n - 1$ )                    | $3-1 = 2$ |
| Tested t-value (Equation 4.5)                        | 0.20      |
| $t_{crit, \frac{\alpha}{2}}$ (Appendix A)            | 4.303     |
| Confidence interval, CI (%)                          | 95        |
| Coefficient of variation, CV (%) (Equation 4.4)      | 3.57      |

**Table 4.4: Statistical conclusion for One sample t-test**

| t-value comparison                                | Conclusion                                       |
|---|--|
| $ t  = 0.20 < t_{crit, \frac{\alpha}{2}} = 4.303$ | Accept $H_0$ ( $\bar{X} = \mu_0$ ), reject $H_1$ |

### 4.3.1 ONE SAMPLE T-TEST – BASALT BUNDLE SPECIMENS

#### 4.3.1.1 STATISTICAL COMPARISON OF MEAN MODULUS OF RUPTURE

Table 4.5 shows the test results of one sample t-test of modulus of rupture of basalt bundled beam specimens. Null hypothesis  $H_0(\bar{X} = \mu_0)$  is accepted in all cases which means that there is no significant difference between the assumed modulus of rupture, and the calculated mean modulus of rupture at 95% confidence level.

**Table 4.5: Basalt bundles: Modulus of rupture (MOR): One sample t-test**

| Test specimen | Mean MOR (MPa) | Assumed mean MOR (MPa) | SD (s) | Tested t-value (Eqn. 4.5) | Null hypothesis ( $H_0$ ) 95% CI | CV (%) |
|---------------|----------------|------------------------|--------|---------------------------|----------------------------------|--------|
| BB 12-4       | 4.02           | 4.00                   | 0.14   | 0.20                      | Accept                           | 3.57   |
| BB 12-8       | 4.30           | 4.00                   | 0.35   | 1.46                      | Accept                           | 8.21   |
| BB 12-12      | 4.63           | 4.60                   | 0.02   | 3.03                      | Accept                           | 0.34   |
| BB 36-4       | 4.39           | 4.50                   | 0.20   | -0.95                     | Accept                           | 4.58   |
| BB 36-8       | 4.70           | 4.75                   | 0.04   | -1.92                     | Accept                           | 0.93   |
| BB 36-12      | 4.93           | 5.00                   | 0.31   | -0.41                     | Accept                           | 6.23   |
| BB 50-4       | 4.40           | 4.50                   | 0.10   | -1.78                     | Accept                           | 2.27   |
| BB 50-8       | 4.89           | 4.50                   | 0.20   | 3.42                      | Accept                           | 4.06   |
| BB 50-12      | 5.11           | 5.00                   | 0.16   | 1.17                      | Accept                           | 3.21   |

Degree of freedom  $(n-1) = 2$ , and  $t_{crit, \frac{\alpha}{2}} = \pm 4.303$  at 95% confidence level (Appendix A) for all the above test specimens.

#### 4.3.1.2 STATISTICAL COMPARISON OF MEAN COMPRESSIVE STRENGTH

Table 4.6 shows the test results of one sample t-test of 28 day cylinder compressive strength of basalt bundled specimens. Null hypothesis  $H_0(\bar{X} = \mu_0)$  is accepted in all cases which means that there is no significant difference between the assumed mean compressive strength, and the calculated mean compressive strength at 95% confidence level.

**Table 4.6: Basalt bundles: 28 day Compressive strength: One sample t-test**

| Test specimen | Mean compressive strength (MPa) | Assumed mean compressive strength (MPa) | SD (s) | Tested t-value (Eqn. 4.5) | Null hypothesis (H <sub>0</sub> ) 95% CI | CV (%) |
|---------------|---------------------------------|---|--------|---------------------------|--|--------|
| BB 12-4       | 36.85                           | 37                                      | 0.99   | -0.26                     | Accept                                   | 2.68   |
| BB 12-8       | 35.81                           | 35                                      | 1.37   | 1.02                      | Accept                                   | 3.84   |
| BB 12-12      | 39.06                           | 40                                      | 1.01   | -1.61                     | Accept                                   | 2.58   |
| BB 36-4       | 37.49                           | 40                                      | 1.12   | -3.90                     | Accept                                   | 2.98   |
| BB 36-8       | 43.42                           | 43                                      | 0.53   | 1.35                      | Accept                                   | 1.23   |
| BB 36-12      | 44.95                           | 45                                      | 0.15   | -0.62                     | Accept                                   | 0.33   |
| BB 50-4       | 38.78                           | 40                                      | 0.84   | -2.51                     | Accept                                   | 2.17   |
| BB 50-8       | 43.01                           | 44                                      | 2.90   | -0.59                     | Accept                                   | 6.75   |
| BB 50-12      | 44.40                           | 44                                      | 2.85   | 0.24                      | Accept                                   | 6.41   |

Degree of freedom (n-1) = 2, and  $t_{crit, \frac{\alpha}{2}} = \pm 4.303$  at 95% confidence level (Appendix A) for all the above test specimens.

#### 4.3.1.3 STATISTICAL COMPARISON OF MEAN SPLIT TENSILE STRENGTH

Table 4.7 shows the test results of one sample t-test of 28 day split tensile strength of basalt bundled cylinder specimens. Null hypothesis  $H_0(\bar{X} = \mu_0)$  is accepted in all cases which means that there is no significant difference between the assumed mean split tensile strength and the calculated mean split tensile strength at 95% confidence level.

**Table 4.7: Basalt bundles: Split tensile strength: One sample t-test**

| Test specimen | Mean split tensile strength (MPa) | Assumed mean split tensile strength (MPa) | SD (s) | Tested t-value (Eqn. 4.5) | Null hypothesis (H <sub>0</sub> ) 95% CI | CV (%) |
|---------------|-----------------------------------|---|--------|---------------------------|--|--------|
| BB 12-4       | 3.91                              | 4.00                                      | 0.50   | -0.32                     | Accept                                   | 12.79  |
| BB 12-8       | 3.76                              | 4.00                                      | 0.41   | -1.02                     | Accept                                   | 10.86  |
| BB 12-12      | 3.56                              | 4.00                                      | 0.37   | -2.09                     | Accept                                   | 10.31  |
| BB 36-4       | 3.84                              | 4.00                                      | 0.21   | -1.30                     | Accept                                   | 5.42   |
| BB 36-8       | 3.96                              | 4.00                                      | 0.73   | -0.09                     | Accept                                   | 18.33  |
| BB 36-12      | 4.38                              | 4.00                                      | 0.51   | 1.30                      | Accept                                   | 11.57  |
| BB 50-4       | 3.77                              | 3.50                                      | 0.28   | 1.70                      | Accept                                   | 7.30   |
| BB 50-8       | 3.92                              | 4.00                                      | 0.40   | -0.33                     | Accept                                   | 10.23  |
| BB 50-12      | 4.31                              | 4.00                                      | 0.82   | 0.65                      | Accept                                   | 19.04  |

Degree of freedom (n-1) = 2, and  $t_{crit, \frac{\alpha}{2}} = \pm 4.303$  at 95% confidence level (Appendix A) for all the above test specimens.

### 4.3.2 ONE SAMPLE T-TEST – BASALT FILAMENT SPECIMENS

#### 4.3.2.1 STATISTICAL COMPARISON OF MEAN MODULUS OF RUPTURE

Table 4.8 shows the test results of one sample t-test of modulus of rupture of basalt filament specimens. Null hypothesis  $H_0(\bar{X} = \mu_0)$  is accepted in all cases which means that there is no significant difference between the assumed mean modulus of rupture and the calculated mean modulus of rupture at 95% confidence level.

**Table 4.8: Basalt filaments: Modulus of rupture (MOR): One sample t-test**

| Test specimen | Mean MOR (MPa) | Assumed mean MOR (MPa) | SD (s) | Tested t-value (Eqn. 4.5) | Null hypothesis ( $H_0$ ) 95% CI | CV (%) |
|---------------|----------------|------------------------|--------|---------------------------|----------------------------------|--------|
| BF 12-4       | 3.97           | 4.00                   | 0.22   | -0.27                     | Accept                           | 5.54   |
| BF 12-8       | 4.40           | 4.50                   | 0.08   | -1.99                     | Accept                           | 1.89   |
| BF 12-12      | 4.72           | 4.75                   | 0.08   | -0.60                     | Accept                           | 1.62   |
| BF 36-4       | 4.59           | 4.50                   | 0.29   | 0.54                      | Accept                           | 6.38   |
| BF 36-8       | 4.99           | 5.00                   | 0.05   | -0.45                     | Accept                           | 1.00   |
| BF 36-12      | 4.80           | 5.00                   | 0.19   | -1.81                     | Accept                           | 3.93   |
| BF 50-4       | 4.01           | 4.00                   | 0.25   | 0.09                      | Accept                           | 6.30   |
| BF 50-8       | 4.98           | 5.00                   | 0.13   | -0.31                     | Accept                           | 2.51   |
| BF 50-12      | 4.91           | 4.75                   | 0.15   | 1.91                      | Accept                           | 2.96   |

Degree of freedom  $(n-1) = 2$ , and  $t_{\text{crit}, \frac{\alpha}{2}}$  at 95% confidence level (Appendix A) for all the above test specimens.

#### 4.3.2.2 STATISTICAL COMPARISON OF MEAN COMPRESSIVE STRENGTH

Table 4.9 shows the test results of one sample t-test of 28 day cylinder compressive strength of basalt filament specimens. Null hypothesis  $H_0(\bar{X} = \mu_0)$  is accepted in all cases which means that there is no significant difference between the assumed mean compressive strength and the calculated mean compressive strength at 95% confidence level.

**Table 4.9: Basalt filaments: 28 day Compressive strength: One sample t-test**

| Test specimen | Mean compressive strength (MPa) | Assumed mean compressive strength (MPa) | SD (s) | Tested t-value (Eqn. 4.5) | Null hypothesis (H <sub>0</sub> ) 95% CI | CV (%) |
|---------------|---------------------------------|---|--------|---------------------------|--|--------|
| BF 12-4       | 35.74                           | 35                                      | 0.99   | 1.30                      | Accept                                   | 2.77   |
| BF 12-8       | 37.33                           | 37                                      | 1.60   | 0.36                      | Accept                                   | 4.28   |
| BF 12-12      | 37.36                           | 37                                      | 0.57   | 1.10                      | Accept                                   | 1.52   |
| BF 36-4       | 36.38                           | 40                                      | 4.01   | -1.56                     | Accept                                   | 11.02  |
| BF 36-8       | 38.73                           | 39                                      | 0.26   | -1.81                     | Accept                                   | 0.67   |
| BF 36-12      | 37.25                           | 40                                      | 1.67   | -2.85                     | Accept                                   | 4.49   |
| BF 50-4       | 38.23                           | 40                                      | 2.15   | -1.42                     | Accept                                   | 5.62   |
| BF 50-8       | 38.11                           | 40                                      | 2.48   | -1.32                     | Accept                                   | 6.50   |
| BF 50-12      | 41.05                           | 40                                      | 1.38   | 1.32                      | Accept                                   | 3.35   |

Degree of freedom (n-1) = 2, and  $t_{crit, \frac{\alpha}{2}} = \pm 4.303$  at 95% confidence level (Appendix A) for all the above test specimens.

#### 4.3.2.3 STATISTICAL COMPARISON OF MEAN SPLIT TENSILE STRENGTH

Table 4.10 shows the test results of one sample t-test of 28 day split tensile strength of basalt filament cylinder specimens. Null hypothesis  $H_0(\bar{X} = \mu_0)$  is accepted in all cases which means that there is no significant difference between the assumed mean split tensile strength and the calculated mean split tensile strength at 95% confidence level.

**Table 4.10: Basalt filaments: Split tensile strength: One sample t-test**

| Test specimen | Mean split tensile strength (MPa) | Assumed mean split tensile strength (MPa) | SD (s) | Tested t-value (Eqn. 4.5) | Null hypothesis (H <sub>0</sub> ) 95% CI | CV (%) |
|---------------|-----------------------------------|---|--------|---------------------------|--|--------|
| BF 12-4       | 3.71                              | 3.75                                      | 0.03   | -2.62                     | Accept                                   | 0.71   |
| BF 12-8       | 3.87                              | 4.00                                      | 0.29   | -0.77                     | Accept                                   | 7.53   |
| BF 12-12      | 4.14                              | 4.00                                      | 0.33   | 0.76                      | Accept                                   | 7.88   |
| BF 36-4       | 3.68                              | 3.00                                      | 0.54   | 2.19                      | Accept                                   | 14.63  |
| BF 36-8       | 3.59                              | 3.50                                      | 0.09   | 1.80                      | Accept                                   | 2.49   |
| BF 36-12      | 3.50                              | 3.50                                      | 0.29   | 0.02                      | Accept                                   | 8.21   |
| BF 50-4       | 3.45                              | 3.50                                      | 0.13   | -0.62                     | Accept                                   | 3.78   |
| BF 50-8       | 3.59                              | 4.00                                      | 0.32   | -2.25                     | Accept                                   | 8.78   |
| BF 50-12      | 3.94                              | 4.00                                      | 0.40   | -0.24                     | Accept                                   | 10.21  |

Degree of freedom (n-1) = 2, and  $t_{crit, \frac{\alpha}{2}} = \pm 4.303$  at 95% confidence level (Appendix A) for all the above test specimens.

### 4.3.3 ONE SAMPLE T-TEST – CONTROL SPECIMENS

#### 4.3.3.1 STATISTICAL COMPARISON OF MEAN MODULUS OF RUPTURE

Table 4.11 shows the test results of one sample t-test of modulus of rupture of control specimens. Null hypothesis  $H_0(\bar{X} = \mu_0)$  is accepted in all cases which means that there is no significant difference between the assumed mean modulus of rupture and the calculated mean modulus of rupture at 95% confidence level.

**Table 4.11: Control specimens: Modulus of rupture (MOR): One sample t-test**

| Test specimen | Mean MOR (MPa) | Assumed mean MOR (MPa) | SD (s) | Tested t-value (Eqn. 4.5) | Null hypothesis ( $H_0$ ) 95% CI | CV (%) |
|---------------|----------------|------------------------|--------|---------------------------|----------------------------------|--------|
| PC            | 4.05           | 4                      | 0.10   | 0.94                      | Accept                           | 2.47   |
| SF 38-40      | 5.28           | 5                      | 0.12   | 3.94                      | Accept                           | 2.33   |
| PP 40-4.5     | 5.09           | 5                      | 0.11   | 1.42                      | Accept                           | 2.07   |

Degree of freedom  $(n-1) = 2$ , and  $t_{crit, \frac{\alpha}{2}} = \pm 4.303$  at 95% confidence level (Appendix A) for all the above test specimens.

#### 4.3.3.2 STATISTICAL COMPARISON OF MEAN COMPRESSIVE STRENGTH

Table 4.12 shows the test results of one sample t-test of 28 day cylinder compressive strength of control specimens. Null hypothesis  $H_0(\bar{X} = \mu_0)$  is accepted in all cases which means that there is no significant difference between the assumed mean compressive strength and the calculated mean compressive strength at 95% confidence level.

**Table 4.12: Control specimens: 28 day Compressive strength: One sample t-test**

| Test specimen | Mean compressive strength (MPa) | Assumed mean compressive strength (MPa) | SD (s) | Tested t-value (Eqn. 4.5) | Null hypothesis ( $H_0$ ) 95% CI | CV (%) |
|---------------|---------------------------------|---|--------|---------------------------|----------------------------------|--------|
| PC            | 31.21                           | 30                                      | 1.40   | 1.49                      | Accept                           | 4.49   |
| SF 38-40      | 43.13                           | 44                                      | 1.15   | -1.31                     | Accept                           | 2.67   |
| PP 40-4.5     | 37.06                           | 40                                      | 2.26   | -2.25                     | Accept                           | 6.11   |

Degree of freedom  $(n-1) = 2$ , and  $t_{crit, \frac{\alpha}{2}} = \pm 4.303$  at 95% confidence level (Appendix A) for all the above test specimens.

### 4.3.3.3 STATISTICAL COMPARISON OF MEAN SPLIT TENSILE STRENGTH

Table 4.13 shows the test results of one sample t-test of 28 day split tensile strength of control cylinder specimens. Null hypothesis  $H_0(\bar{X} = \mu_0)$  is accepted in all cases which means that there is no significant difference between the assumed mean split tensile strength and the calculated mean split tensile strength at 95% confidence level.

**Table 4.13: Control specimens: Split tensile strength: One sample t-test**

| Test specimen | Mean split tensile strength (MPa) | Assumed mean split tensile strength (MPa) | SD (s) | Tested t-value (Eqn. 4.5) | Null hypothesis ( $H_0$ ) 95% CI | CV (%) |
|---------------|-----------------------------------|---|--------|---------------------------|----------------------------------|--------|
| PC            | 3.45                              | 3.50                                      | 0.03   | -2.51                     | Accept                           | 0.93   |
| SF 38-40      | 3.67                              | 3.50                                      | 0.16   | 1.87                      | Accept                           | 4.38   |
| PP 40-4.5     | 3.52                              | 3.50                                      | 0.18   | 0.16                      | Accept                           | 5.01   |

Degree of freedom  $(n-1) = 2$ , and  $t_{crit, \frac{\alpha}{2}} = \pm 4.303$  at 95% confidence level (Appendix A) for all the above test specimens.

#### 4.4 INDEPENDENT SAMPLE T-TEST

*Independent sample t-test*, also known as *two-sample t-test* or *paired t-test*, occurs when the observations on the two populations of interest are collected in pairs. Each pair (or sample groups) of observations; for example BB 12-4, and BF 12-4, are taken under conditions that may change from one pair to another. The test procedure consists of analyzing the differences between the sample groups. If there is no difference between the sample groups, the difference between the means should be zero. This test procedure is called the independent sample t-test (Montgomery and Runger, 2010).

The principle of the independent sample t-test is similar to the one sample t-test. However, it is used to compare two sample groups while one sample t-test compares only one group with the expected (estimated) population mean. The t-value of independent sample t-test can be calculated using the Equation 4.6.

$$t = \frac{\mu_1 - \mu_2}{\bar{s} \sqrt{\frac{1}{n_A} + \frac{1}{n_B}}} \quad (4.6)$$

where;

$\bar{s}$  is the statistical average standard deviation, or pooled standard deviation, determined from Equation 4.3.

$\mu_1$  is the mean for sample group A

$\mu_2$  is the mean for sample group B

$n_A$  and  $n_B$  are the number of tests in sample group A and B, respectively.

For this statistical analysis, a confidence level of 95% was chosen which corresponds to two-sigma limit ( $\pm 2\sigma$ ). The confidence level of 90% was also considered to analyze the cases where the tested t-value is close to  $t_{\text{crit}, \frac{\alpha}{2}}$  at 95% confidence level. The 90% tolerance limit (confidence interval) is recommended by both CSA A23.1 Annex C Clause C.1.2 (2009b) and Eurocode, BS EN 1990 (2002). The criteria for accepting null hypothesis,  $H_0$ ,

and alternative hypothesis,  $H_1$ , are shown in Table 4.14. The acceptance of null hypothesis indicates that the mean of the two groups are not statistically different.

**Table 4.14: Criterion for paired t-test conclusion**

| <b>Criterion</b>                          | <b>Conclusion</b>                            |
|---|--|
| <b>t-value comparison</b>                 |  |
| $ t  < t_{\text{crit}, \frac{\alpha}{2}}$ | Accept $H_0 \mu_1 = \mu_2$ , Reject $H_1$    |
| $ t  > t_{\text{crit}, \frac{\alpha}{2}}$ | Accept $H_1 \mu_1 \neq \mu_2$ , Reject $H_0$ |

Table 4.15 shows a sample calculation for independent sample t-test for mean modulus of rupture between PC and BB 12-4. Sample size for both PC and BB 12-4 is 3. Pooled standard deviation ( $\bar{s}$ ) is calculated using Equation 4.3. The tested t-value is calculated using Equation 4.6. Based on the criterion for t-test conclusion shown in Table 4.14, null hypothesis  $H_0 (\mu_1 = \mu_2)$  is accepted as the tested t-value is less than  $t_{\text{crit}, \alpha/2}$  at 95%, and 90% confidence level as per criteria set in Table 4.14. Table 4.15 shows an example of independent sample t-test applied to compare specimens BB 12-4, and PC. This test (Table 4.16) shows that the mean modulus of rupture of PC and BB 12-4 specimens are not statistically different both at 90% and 95% confidence intervals. In other words, there is no significant improvement in flexural strength of BB 12-4 compared to PC.

**Table 4.15: Modulus of rupture (MOR): Independent sample t-test**

Sample calculation (PC: BB 12-4)

| Parameters   | Values          |
|--|-----------------|
| Average Modulus of rupture of PC ( $\mu_1$ )                       | 4.05            |
| Standard deviation of PC ( $s_A$ )                                 | 0.10            |
| Average Modulus of rupture for BB 12-4 ( $\mu_2$ )                 | 4.02            |
| Standard deviation of BB 12-4 ( $s_B$ )                            | 0.14            |
| Number of PC specimens tested ( $n_A$ )                            | 3               |
| Number of BB 12-4 specimens tested ( $n_B$ )                       | 3               |
| Pooled Standard deviation ( $\bar{s}$ ) (Equation 4.3)             | 0.12            |
| Degree of freedom ( $n_A + n_B - 2$ )                              | $3 + 3 - 2 = 4$ |
| Tested t-value (Equation 4.6)                                      | 0.37            |
| $t_{crit, \frac{\alpha}{2}}$ for 95% confidence level (Appendix A) | 2.776           |
| $t_{crit, \frac{\alpha}{2}}$ for 90% confidence level (Appendix A) | 2.132           |

**Table 4.16: Statistical conclusion for Independent sample t-test**

| t-value comparison                                | Conclusion                                     |
|---|--|
| $ t  = 0.37 < t_{crit, \frac{\alpha}{2}} = 2.776$ | Accept $H_0$ ( $\mu_1 = \mu_2$ ), Reject $H_1$ |
| $ t  = 0.37 < t_{crit, \frac{\alpha}{2}} = 2.132$ | Accept $H_0$ ( $\mu_1 = \mu_2$ ), Reject $H_1$ |

#### **4.4.1 INDEPENDENT SAMPLE T-TEST – BASALT BUNDLE SPECIMENS**

##### **4.4.1.1 STATISTICAL COMPARISON OF MEAN MODULUS OF RUPTURE**

Table 4.17 compares the mean modulus of rupture (MOR) of bundled basalt beam specimens with that of control specimens (plain concrete or PC, steel fibre or SF 38-40, and macro synthetic fibre or PP 40-4.5 specimens). It was observed from hypothesis testing, that BB12-4, and BB12-8 are not statistically different from PC both at 90%, and 95% confidence levels, which means that there is no significant change in the mean modulus of rupture (MOR) between PC and the above specimens. The mean MOR of BB 36-4 is statistically different from PC at 90% confidence level though it is statistically similar to PC if 95% confidence interval is considered. This indicates that there is a change in flexural strength between these samples at 90% confidence level. Similarly, BB 36-12 and BB 50-12 are statistically similar to SF 38-40 at both confidence intervals. Hence, BB 36-12 and BB 50-12 provide similar flexural strength as SF 38-40. Further, BB 36-12, BB 50-8, and BB 50-12 are statistically similar to PP 40-4.5. The independent t-test indicates that there is no significant difference in the mean modulus of rupture between sample group 1 and 2 when the null hypothesis ( $H_0$ ) is accepted.

**Table 4.17: Basalt bundles vs. Control specimens: MOR: Independent sample t-test**

| Sample    |                 | Pooled SD ( $\bar{s}$ ) | Tested t-value<br>(Eqn. 4.6) | Null hypothesis ( $H_0$ ) |               |
|-----------|-----------------|-------------------------|------------------------------|---------------------------|---------------|
| Group 1   | Group 2         |                         |                              | 95% CI                    | 90% CI        |
| PC        | <b>BB 12-4</b>  | 0.12                    | 0.37                         | <b>Accept</b>             | <b>Accept</b> |
| PC        | <b>BB 12-8</b>  | 0.26                    | -1.15                        | <b>Accept</b>             | <b>Accept</b> |
| PC        | BB 12-12        | 0.07                    | -9.81                        | Reject                    | Reject        |
| PC        | <b>BB 36-4</b>  | 0.16                    | -2.59                        | <b>Accept</b>             | Reject        |
| PC        | BB 36-8         | 0.08                    | -10.26                       | Reject                    | Reject        |
| PC        | BB 36-12        | 0.23                    | -4.69                        | Reject                    | Reject        |
| PC        | BB 50-4         | 0.10                    | -4.21                        | Reject                    | Reject        |
| PC        | BB 50-8         | 0.16                    | -6.52                        | Reject                    | Reject        |
| PC        | BB 50-12        | 0.14                    | -9.51                        | Reject                    | Reject        |
| SF 38-40  | BB 12-4         | 0.13                    | 11.57                        | Reject                    | Reject        |
| SF 38-40  | BB 12-8         | 0.26                    | 4.55                         | Reject                    | Reject        |
| SF 38-40  | BB 12-12        | 0.09                    | 9.10                         | Reject                    | Reject        |
| SF 38-40  | BB 36-4         | 0.17                    | 6.55                         | Reject                    | Reject        |
| SF 38-40  | BB 36-8         | 0.09                    | 7.67                         | Reject                    | Reject        |
| SF 38-40  | <b>BB 36-12</b> | 0.23                    | 1.84                         | <b>Accept</b>             | <b>Accept</b> |
| SF 38-40  | BB 50-4         | 0.11                    | 9.65                         | Reject                    | Reject        |
| SF 38-40  | BB 50-8         | 0.17                    | 2.87                         | Reject                    | Reject        |
| SF 38-40  | <b>BB 50-12</b> | 0.15                    | 1.43                         | <b>Accept</b>             | <b>Accept</b> |
| PP 40-4.5 | BB 12-4         | 0.13                    | 10.41                        | Reject                    | Reject        |
| PP 40-4.5 | BB 12-8         | 0.26                    | 3.71                         | Reject                    | Reject        |
| PP 40-4.5 | BB 12-12        | 0.08                    | 7.47                         | Reject                    | Reject        |
| PP 40-4.5 | BB 36-4         | 0.16                    | 5.32                         | Reject                    | Reject        |
| PP 40-4.5 | BB 36-8         | 0.08                    | 5.85                         | Reject                    | Reject        |
| PP 40-4.5 | <b>BB 36-12</b> | 0.23                    | 0.85                         | <b>Accept</b>             | <b>Accept</b> |
| PP 40-4.5 | BB 50-4         | 0.10                    | 8.23                         | Reject                    | Reject        |
| PP 40-4.5 | <b>BB 50-8</b>  | 0.16                    | 1.50                         | <b>Accept</b>             | <b>Accept</b> |
| PP 40-4.5 | <b>BB 50-12</b> | 0.14                    | -0.21                        | <b>Accept</b>             | <b>Accept</b> |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{crit, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{crit, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

Table 4.18 shows the effect of fibre length of bundled fibres on mean MOR. The following is the summary of observations.

- For fibre dosage of 4 kg/m<sup>3</sup>, the change in MOR is statistically significant when the length of bundled fibre increases from 12 mm to 36 mm at 90% confidence interval, however, it is not statistically significant at 95% CI. The change in MOR is statistically significant when the length of bundled fibre increases from 12 mm to 50 mm at both 90% and 95% confidence intervals.
- For fibre dosage of 8 kg/m<sup>3</sup>, the change in MOR is statistically insignificant when the length of bundled fibre increases from 12 mm to 36 mm at both 90% and 95% confidence intervals. The change in MOR is statistically significant when the length of bundled fibre increases from 12 mm to 50 mm at 90% CI, however, it is not statistically significant at 95% CI.
- For fibre dosage of 12 kg/m<sup>3</sup>, the change in MOR is not statistically significant when the length of bundled fibre increases from 12 mm to 36 mm at both 90% and 95% confidence intervals. However, the change in MOR is statistically significant when the length of bundled fibre increases from 12 mm to 50 mm at both 90% and 95% CIs.
- The change in MOR due to increase in bundled fibre length from 36 mm to 50 mm for all fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>) is statistically insignificant at both 90% and 95% confidence intervals.

**Table 4.18: Basalt bundles: Effect of fibre length: MOR: Independent sample t-test**

| Sample          |                 | Pooled SD ( $\bar{s}$ ) | Tested t-value (Eqn. 4.6) | Null hypothesis ( $H_0$ ) |               |
|-----------------|-----------------|-------------------------|---------------------------|---------------------------|---------------|
| Group 1         | Group 2         |                         |                           | 95% CI                    | 90% CI        |
| <b>BB 12-4</b>  | <b>BB 36-4</b>  | 0.17                    | -2.61                     | <b>Accept</b>             | Reject        |
| BB 12-4         | BB 50-4         | 0.12                    | -3.77                     | Reject                    | Reject        |
| <b>BB 12-8</b>  | <b>BB 36-8</b>  | 0.25                    | -1.97                     | <b>Accept</b>             | <b>Accept</b> |
| <b>BB 12-8</b>  | <b>BB 50-8</b>  | 0.29                    | -2.54                     | <b>Accept</b>             | Reject        |
| <b>BB 12-12</b> | <b>BB 36-12</b> | 0.22                    | -1.69                     | <b>Accept</b>             | <b>Accept</b> |
| BB 12-12        | BB 50-12        | 0.12                    | -5.07                     | Reject                    | Reject        |
| <b>BB 36-4</b>  | <b>BB 50-4</b>  | 0.16                    | -0.06                     | <b>Accept</b>             | <b>Accept</b> |
| <b>BB 36-8</b>  | <b>BB 50-8</b>  | 0.14                    | -1.62                     | <b>Accept</b>             | <b>Accept</b> |
| <b>BB 36-12</b> | <b>BB 50-12</b> | 0.25                    | -0.91                     | <b>Accept</b>             | <b>Accept</b> |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{crit, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{crit, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

Table 4.19 shows the effect of fibre quantity of basalt bundled fibres on mean MOR. The following is the summary of observations.

- For short (12 mm) bundled fibres, the change in MOR is not statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> at both 90% and 95% confidence intervals. However, the change in MOR is statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> at both 90% and 95% confidence intervals.
- For medium length (36 mm) bundled fibres, the change in MOR is not statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> at 95% confidence interval (CI). However, it is statistically significant at 90% CI.
- For long (50 mm) bundled fibres, the change in MOR is statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> at both 90% and 95% confidence intervals.
- The change in MOR due to increase in fibre dosage from 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> for all fibre lengths (12 mm, 36 mm, and 50 mm) is statistically insignificant at both 90% and 95% confidence intervals.

**Table 4.19: Basalt bundles: Effect of fibre quantity: MOR: Independent sample t-test**

| Sample         |                 | Pooled SD ( $\bar{s}$ ) | Tested t-value (Eqn. 4.6) | Null hypothesis ( $H_0$ ) |               |
|----------------|-----------------|-------------------------|---------------------------|---------------------------|---------------|
| Group 1        | Group 2         |                         |                           | 95% CI                    | 90% CI        |
| <b>BB 12-4</b> | <b>BB 12-8</b>  | 0.27                    | -1.28                     | <b>Accept</b>             | <b>Accept</b> |
| BB 12-4        | BB 12-12        | 0.10                    | -7.32                     | Reject                    | Reject        |
| <b>BB 36-4</b> | <b>BB 36-8</b>  | 0.15                    | -2.63                     | <b>Accept</b>             | Reject        |
| <b>BB 36-4</b> | <b>BB 36-12</b> | 0.26                    | -2.54                     | <b>Accept</b>             | Reject        |
| BB 50-4        | BB 50-8         | 0.16                    | -3.85                     | Reject                    | Reject        |
| BB 50-4        | BB 50-12        | 0.14                    | -6.43                     | Reject                    | Reject        |
| <b>BB 12-8</b> | <b>BB 12-12</b> | 0.25                    | -1.62                     | <b>Accept</b>             | <b>Accept</b> |
| <b>BB 36-8</b> | <b>BB 36-12</b> | 0.22                    | -1.27                     | <b>Accept</b>             | <b>Accept</b> |
| <b>BB 50-8</b> | <b>BB 50-12</b> | 0.18                    | -1.47                     | <b>Accept</b>             | <b>Accept</b> |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{crit, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{crit, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

#### **4.4.1.2 STATISTICAL COMPARISON OF MEAN COMPRESSIVE STRENGTH**

Table 4.20 compares the 28 day compressive strength of bundled basalt beam specimens with that of control specimens (plain concrete or PC, steel fibre or SF 38-40, and macro synthetic fibre or PP 40-4.5 specimens). It is observed from hypothesis testing that all the basalt bundle specimens are statistically different from PC at both 90%, and 95% CIs. Specimens BB 36-8, BB 36-12, BB 50-8, and BB 50-12 are statistically similar to SF 38-40 at 95% CI. However, they are statistically different from PP 40-4.5 at 95% CI. Hence, it was found that all three fibre dosages ( $4 \text{ kg/m}^3$ ,  $8 \text{ kg/m}^3$ , and  $12 \text{ kg/m}^3$ ), and all three fibre lengths (12 mm, 36 mm, and 50 mm) of basalt bundled fibres have significant effect on the 28 day compressive strength when compared with PC. Short bundled fibres (12 mm) at all dosages ( $4 \text{ kg/m}^3$ ,  $8 \text{ kg/m}^3$ , and  $12 \text{ kg/m}^3$ ), and 36 mm and 50 mm bundled fibres at low fibre dosage ( $4 \text{ kg/m}^3$ ) provide similar compressive strength as PP 40-4.5 specimen. The medium length (36 mm) and long (50 mm) bundled fibres at  $8 \text{ kg/m}^3$  and  $12 \text{ kg/m}^3$  have significant influence on the 28 day compressive strength compared with PC and provide compressive strength similar to SF 38-40.

**Table 4.20: Basalt bundles vs. Control specimens: Compressive strength:  
Independent sample t-test**

| Sample           |                 | Pooled SD ( $\bar{s}$ ) | Tested<br>t-value<br>(Eqn. 4.6) | Null hypothesis (H <sub>0</sub> ) |               |
|------------------|-----------------|-------------------------|---------------------------------|-----------------------------------|---------------|
| Group 1          | Group 2         |                         |                                 | 95% CI                            | 90% CI        |
| PC               | BB 12-4         | 1.21                    | -5.70                           | Reject                            | Reject        |
| PC               | BB 12-8         | 1.39                    | -4.06                           | Reject                            | Reject        |
| PC               | BB 12-12        | 1.22                    | -7.88                           | Reject                            | Reject        |
| PC               | BB 36-4         | 1.27                    | -6.07                           | Reject                            | Reject        |
| PC               | BB 36-8         | 1.06                    | -14.09                          | Reject                            | Reject        |
| PC               | BB 36-12        | 1.00                    | -16.88                          | Reject                            | Reject        |
| PC               | BB 50-4         | 1.16                    | -8.03                           | Reject                            | Reject        |
| PC               | BB 50-8         | 2.28                    | -6.34                           | Reject                            | Reject        |
| PC               | BB 50-12        | 2.24                    | -7.20                           | Reject                            | Reject        |
| SF 38-40         | BB 12-4         | 1.07                    | 7.16                            | Reject                            | Reject        |
| SF 38-40         | BB 12-8         | 1.27                    | 7.07                            | Reject                            | Reject        |
| SF 38-40         | BB 12-12        | 1.08                    | 4.60                            | Reject                            | Reject        |
| SF 38-40         | BB 36-4         | 1.13                    | 6.09                            | Reject                            | Reject        |
| <b>SF 38-40</b>  | <b>BB 36-8</b>  | 0.90                    | -0.40                           | <b>Accept</b>                     | <b>Accept</b> |
| <b>SF 38-40</b>  | <b>BB 36-12</b> | 0.82                    | -2.71                           | <b>Accept</b>                     | Reject        |
| SF 38-40         | BB 50-4         | 1.01                    | 5.27                            | Reject                            | Reject        |
| <b>SF 38-40</b>  | <b>BB 50-8</b>  | 2.21                    | 0.06                            | <b>Accept</b>                     | <b>Accept</b> |
| <b>SF 38-40</b>  | <b>BB 50-12</b> | 2.17                    | -0.72                           | <b>Accept</b>                     | <b>Accept</b> |
| <b>PP 40-4.5</b> | <b>BB 12-4</b>  | 1.75                    | 0.15                            | <b>Accept</b>                     | <b>Accept</b> |
| <b>PP 40-4.5</b> | <b>BB 12-8</b>  | 1.87                    | 0.82                            | <b>Accept</b>                     | <b>Accept</b> |
| <b>PP 40-4.5</b> | <b>BB 12-12</b> | 1.75                    | -1.40                           | <b>Accept</b>                     | <b>Accept</b> |
| <b>PP 40-4.5</b> | <b>BB 36-4</b>  | 1.78                    | -0.29                           | <b>Accept</b>                     | <b>Accept</b> |
| PP 40-4.5        | BB 36-8         | 1.64                    | -4.73                           | Reject                            | Reject        |
| PP 40-4.5        | BB 36-12        | 1.60                    | -6.02                           | Reject                            | Reject        |
| <b>PP 40-4.5</b> | <b>BB 50-4</b>  | 1.71                    | -1.24                           | <b>Accept</b>                     | <b>Accept</b> |
| PP 40-4.5        | BB 50-8         | 2.60                    | -2.80                           | Reject                            | Reject        |
| PP 40-4.5        | BB 50-12        | 2.57                    | -3.49                           | Reject                            | Reject        |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{crit, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{crit, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

Table 4.21 shows the effect of fibre length of bundled fibres on 28 day cylinder compressive strength. The following is the summary of observations.

- For fibre dosage of 4 kg/m<sup>3</sup>, the change in compressive strength is not statistically significant when the length of bundled fibre increases from 12 mm to 36 mm at both 90% and 95% confidence intervals. The change in compressive strength is statistically significant when the length of bundled fibre increases from 12 mm to 50 mm at 90% confidence interval, however, it is not statistically significant at 95% CI.
- For fibre dosage of 8 kg/m<sup>3</sup>, the change in compressive strength is statistically significant when the length of bundled fibre increases from 12 mm to 36 mm or 12 mm to 50 mm at both 90% and 95% confidence intervals.
- For fibre dosage of 12 kg/m<sup>3</sup>, the change in compressive strength is statistically significant when the length of bundled fibre increases from 12 mm to 36 mm or 12 mm to 50 mm at both 90% and 95% confidence intervals.
- However, the change in compressive strength due to increase in bundled fibre length from 36 mm to 50 mm for all fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>) is statistically insignificant at both 90% and 95% confidence intervals.

**Table 4.21: Basalt bundles: Effect of fibre length: Compressive strength: Independent sample t-test**

| Sample          |                 | Pooled SD ( $\bar{s}$ ) | Tested t-value (Eqn. 4.6) | Null hypothesis ( $H_0$ ) |               |
|-----------------|-----------------|-------------------------|---------------------------|---------------------------|---------------|
| Group 1         | Group 2         |                         |                           | 95% CI                    | 90% CI        |
| <b>BB 12-4</b>  | <b>BB 36-4</b>  | 1.05                    | -0.74                     | <b>Accept</b>             | <b>Accept</b> |
| <b>BB 12-4</b>  | <b>BB 50-4</b>  | 0.92                    | -2.58                     | <b>Accept</b>             | <b>Reject</b> |
| BB 12-8         | BB 36-8         | 1.04                    | -8.94                     | Reject                    | Reject        |
| BB 12-8         | BB 50-8         | 2.27                    | -3.88                     | Reject                    | Reject        |
| BB 12-12        | BB 36-12        | 0.72                    | -10.00                    | Reject                    | Reject        |
| BB 12-12        | BB 50-12        | 2.14                    | -3.06                     | Reject                    | Reject        |
| <b>BB 36-4</b>  | <b>BB 50-4</b>  | 0.99                    | -1.61                     | <b>Accept</b>             | <b>Accept</b> |
| <b>BB 36-8</b>  | <b>BB 50-8</b>  | 2.09                    | 0.24                      | <b>Accept</b>             | <b>Accept</b> |
| <b>BB 36-12</b> | <b>BB 50-12</b> | 2.02                    | 0.33                      | <b>Accept</b>             | <b>Accept</b> |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{crit, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{crit, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

Table 4.22 shows the effect of fibre quantity of bundled fibres on 28 day compressive strength. The following is the summary of observations.

- For short (12 mm) bundled fibres, the change in compressive strength is not statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> at both 90% and 95% confidence intervals. The change in compressive strength is statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> at 90% CI, however, it is statistically insignificant at 95% confidence interval.
- For medium length (36 mm) bundled fibres, the change in compressive strength is statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> at both 90% and 95% confidence intervals.
- For long (50 mm) bundled fibres, the change in compressive strength is statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> at 90% CI, however, it is not statistically significant at 95% CI. The change in compressive strength is statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> at both 90% and 95% confidence intervals.
- The change in compressive strength due to increase in fibre dosage from 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> for 12 mm and 36 mm bundled fibres are statistically significant at both 90% and 95% confidence intervals. However, it is not statistically significant for 50 mm bundled fibre at both 90% and 95% confidence intervals

**Table 4.22: Basalt bundles: Effect of fibre quantity: Compressive strength: Independent sample t-test**

| Sample         |                 | Pooled SD ( $\bar{s}$ ) | Tested t-value (Eqn. 4.6) | Null hypothesis ( $H_0$ ) |               |
|----------------|-----------------|-------------------------|---------------------------|---------------------------|---------------|
| Group 1        | Group 2         |                         |                           | 95% CI                    | 90% CI        |
| <b>BB 12-4</b> | <b>BB 12-8</b>  | 1.20                    | 1.06                      | <b>Accept</b>             | <b>Accept</b> |
| <b>BB 12-4</b> | <b>BB 12-12</b> | 1.00                    | -2.71                     | <b>Accept</b>             | Reject        |
| BB 36-4        | BB 36-8         | 0.87                    | -8.30                     | Reject                    | Reject        |
| BB 36-4        | BB 36-12        | 0.80                    | -11.48                    | Reject                    | Reject        |
| <b>BB 50-4</b> | <b>BB 50-8</b>  | 2.14                    | -2.42                     | <b>Accept</b>             | Reject        |
| BB 50-4        | BB 50-12        | 2.10                    | -3.28                     | Reject                    | Reject        |
| BB 12-8        | BB 12-12        | 1.21                    | -3.30                     | Reject                    | Reject        |
| BB 36-8        | BB 36-12        | 0.39                    | -4.77                     | Reject                    | Reject        |
| <b>BB 50-8</b> | <b>BB 50-12</b> | 2.88                    | -0.59                     | <b>Accept</b>             | <b>Accept</b> |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{crit, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{crit, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

#### **4.4.1.3 STATISTICAL COMPARISON OF MEAN SPLIT TENSILE STRENGTH**

Table 4.23 compares the split tensile strength of bundled basalt cylinder specimens with that of control specimens (plain concrete or PC, steel fibre or SF 38-40, and macro synthetic fibre or PP 40- 4.5 specimens). Based on hypothesis tests, it is observed that BB 36-4, and BB 36-12 are statistically different from PC at both 90% and 95% confidence intervals. Further, SF 38-40, and all basalt bundle specimens are statistically similar, except BB 36-12 at 90% CI. Similarly, all basalt bundle specimens, except BB 36-12, are statistically similar to PP 40-4.5 at both 90% and 95% CIs. Hence, it was found that the intermediate length (36 mm) bundled fibre at high dosage of  $12 \text{ kg/m}^3$  has significant influence on the split tensile strength when compared with PC, SF 38-40 or PP 40-4.5.

**Table 4.23: Basalt bundles vs. Control specimens: Split tensile strength:  
Independent sample t-test**

| Sample    |          | Pooled SD ( $\bar{s}$ ) | Tested<br>t-value<br>(Eqn. 4.6) | Null hypothesis ( $H_0$ ) |        |
|-----------|----------|-------------------------|---------------------------------|---------------------------|--------|
| Group 1   | Group 2  |                         |                                 | 95% CI                    | 90% CI |
| PC        | BB 12-4  | 0.35                    | -1.57                           | Accept                    | Accept |
| PC        | BB 12-8  | 0.29                    | -1.30                           | Accept                    | Accept |
| PC        | BB 12-12 | 0.26                    | -0.49                           | Accept                    | Accept |
| PC        | BB 36-4  | 0.15                    | -3.21                           | Reject                    | Reject |
| PC        | BB 36-8  | 0.51                    | -1.21                           | Accept                    | Accept |
| PC        | BB 36-12 | 0.36                    | -3.16                           | Reject                    | Reject |
| PC        | BB 50-4  | 0.20                    | -1.98                           | Accept                    | Accept |
| PC        | BB 50-8  | 0.28                    | -2.02                           | Accept                    | Accept |
| PC        | BB 50-12 | 0.58                    | -1.81                           | Accept                    | Accept |
| SF 38-40  | BB 12-4  | 0.37                    | -0.77                           | Accept                    | Accept |
| SF 38-40  | BB 12-8  | 0.31                    | -0.34                           | Accept                    | Accept |
| SF 38-40  | BB 12-12 | 0.28                    | 0.50                            | Accept                    | Accept |
| SF 38-40  | BB 36-4  | 0.19                    | -1.12                           | Accept                    | Accept |
| SF 38-40  | BB 36-8  | 0.53                    | -0.67                           | Accept                    | Accept |
| SF 38-40  | BB 36-12 | 0.38                    | -2.30                           | Accept                    | Reject |
| SF 38-40  | BB 50-4  | 0.23                    | -0.53                           | Accept                    | Accept |
| SF 38-40  | BB 50-8  | 0.31                    | -1.00                           | Accept                    | Accept |
| SF 38-40  | BB 50-12 | 0.59                    | -1.32                           | Accept                    | Accept |
| PP 40-4.5 | BB 12-4  | 0.37                    | -1.27                           | Accept                    | Accept |
| PP 40-4.5 | BB 12-8  | 0.31                    | -0.95                           | Accept                    | Accept |
| PP 40-4.5 | BB 12-12 | 0.29                    | -0.17                           | Accept                    | Accept |
| PP 40-4.5 | BB 36-4  | 0.19                    | -2.07                           | Accept                    | Accept |
| PP 40-4.5 | BB 36-8  | 0.53                    | -1.03                           | Accept                    | Accept |
| PP 40-4.5 | BB 36-12 | 0.38                    | -2.79                           | Reject                    | Reject |
| PP 40-4.5 | BB 50-4  | 0.23                    | -1.34                           | Accept                    | Accept |
| PP 40-4.5 | BB 50-8  | 0.31                    | -1.61                           | Accept                    | Accept |
| PP 40-4.5 | BB 50-12 | 0.59                    | -1.64                           | Accept                    | Accept |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{crit, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{crit, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

Table 4.24 shows the effect of fibre length of basalt bundled specimens on the split tensile strength. The following is the summary of observations.

- For fibre dosage of 4 kg/m<sup>3</sup>, the change in split tensile strength is not statistically significant when the length of bundled fibre increases from 12 mm to 36 mm or 12 mm to 50 mm at both 90% and 95% confidence intervals.
- For fibre dosage of 8 kg/m<sup>3</sup>, the change in split tensile strength is not statistically significant when the length of bundled fibre increases from 12 mm to 36 mm or 12 mm to 50 mm at both 90% and 95% confidence intervals.
- For fibre dosage of 12 kg/m<sup>3</sup>, the change in split tensile strength is statistically significant when the length of bundled fibre increases from 12 mm to 36 mm at 90% CI, however, it is not statistically significant at 95% CI. The change in split tensile strength is not statistically significant when the length of bundled fibre increases from 12 mm to 50 mm at both 90% and 95% confidence intervals.
- However, the change in split tensile strength due to increase in bundled fibre length from 36 mm to 50 mm for all fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>) is not statistically significant at both 90% and 95% confidence intervals.

**Table 4.24: Basalt bundles: Effect of fibre length: Split tensile strength: Independent sample t-test**

| Sample   |          | Pooled SD ( $\bar{s}$ ) | Tested t-value (Eqn. 4.6) | Null hypothesis ( $H_0$ ) |        |
|----------|----------|-------------------------|---------------------------|---------------------------|--------|
| Group 1  | Group 2  |                         |                           | 95% CI                    | 90% CI |
| BB 12-4  | BB 36-4  | 0.38                    | 0.20                      | Accept                    | Accept |
| BB 12-4  | BB 50-4  | 0.40                    | 0.41                      | Accept                    | Accept |
| BB 12-8  | BB 36-8  | 0.59                    | -0.42                     | Accept                    | Accept |
| BB 12-8  | BB 50-8  | 0.40                    | -0.49                     | Accept                    | Accept |
| BB 12-12 | BB 36-12 | 0.44                    | -2.28                     | Accept                    | Reject |
| BB 12-12 | BB 50-12 | 0.64                    | -1.45                     | Accept                    | Accept |
| BB 36-4  | BB 50-4  | 0.24                    | 0.37                      | Accept                    | Accept |
| BB 36-8  | BB 50-8  | 0.59                    | 0.08                      | Accept                    | Accept |
| BB 36-12 | BB 50-12 | 0.68                    | 0.13                      | Accept                    | Accept |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{crit, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{crit, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

Table 4.25 shows the effect of fibre quantity of basalt bundled fibres on the split tensile strength. The following is the summary of observations.

- For short (12 mm) bundled fibres, the change in split tensile strength is not statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> at both 90% and 95% confidence intervals.
- For medium length (36 mm) bundled fibres, the change in split tensile strength is not statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> at both 90% and 95% confidence intervals.
- For long (50 mm) bundled fibres, the change in split tensile strength is not statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> at both 90% and 95% confidence intervals.
- The change in split tensile strength due to increase in fibre dosage from 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> for all fibre lengths (12 mm, 36 mm, and 50 mm) is not statistically significant at both 90% and 95% confidence intervals.

**Table 4.25: Basalt bundles: Effect of fibre quantity: Split tensile strength: Independent sample t-test**

| Sample  |          | Pooled SD ( $\bar{s}$ ) | Tested t-value (Eqn. 4.6) | Null hypothesis (H <sub>0</sub> ) |        |
|---------|----------|-------------------------|---------------------------|-----------------------------------|--------|
| Group 1 | Group 2  |                         |                           | 95% CI                            | 90% CI |
| BB 12-4 | BB 12-8  | 0.46                    | 0.39                      | Accept                            | Accept |
| BB 12-4 | BB 12-12 | 0.44                    | 0.98                      | Accept                            | Accept |
| BB 36-4 | BB 36-8  | 0.53                    | -0.27                     | Accept                            | Accept |
| BB 36-4 | BB 36-12 | 0.39                    | -1.70                     | Accept                            | Accept |
| BB 50-4 | BB 50-8  | 0.34                    | -0.55                     | Accept                            | Accept |
| BB 50-4 | BB 50-12 | 0.61                    | -1.08                     | Accept                            | Accept |
| BB 12-8 | BB 12-12 | 0.39                    | 0.64                      | Accept                            | Accept |
| BB 36-8 | BB 36-12 | 0.63                    | -0.81                     | Accept                            | Accept |
| BB 50-8 | BB 50-12 | 0.65                    | -0.73                     | Accept                            | Accept |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{crit, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{crit, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

## **4.4.2 INDEPENDENT SAMPLE T-TEST – BASALT FILAMENT SPECIMENS**

### **4.4.2.1 STATISTICAL COMPARISON OF MEAN MODULUS OF RUPTURE**

Table 4.26 compares mean modulus of rupture (MOR) of basalt filament beam specimens with control specimens (plain concrete or PC, steel fibre or SF 38-40, and macro synthetic fibre or PP 40-4.5 specimens). It was observed from hypothesis testing, that BF 12-4, and BF 50-4 are statistically similar to PC at both 90% and 95% confidence intervals. All basalt filament specimens are statistically different from SF 38-40 at both 90% and 95% CIs. Specimens BF 36-4, BF 36-8, BF 36-12, BF 50-8, and BF 50-12 are statistically similar to PP 40-4.5 at 95% CI. Hence, it was found that the short (12 mm), and long (50 mm) filaments at low fibre dosage of 4 kg/m<sup>3</sup> have no statistical influence on the flexural strength when compared with PC. None of the basalt filament specimens have similar flexural strength as SF 38-40 specimen. The 36 mm filament at 8 kg/m<sup>3</sup>, and 50 mm filament at 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup> provide similar flexural strength as PP 40-4.5 specimen.

**Table 4.26: Basalt filaments vs. Control specimens: MOR: Independent sample t-test**

| Sample           |                 | Pooled SD ( $\bar{s}$ ) | Tested t-value<br>(Eqn. 4.6) | Null hypothesis ( $H_0$ ) |               |
|------------------|-----------------|-------------------------|------------------------------|---------------------------|---------------|
| Group 1          | Group 2         |                         |                              | 95% CI                    | 90% CI        |
| <b>PC</b>        | <b>BF 12-4</b>  | 0.17                    | 0.64                         | <b>Accept</b>             | <b>Accept</b> |
| PC               | BF 12-8         | 0.09                    | -4.65                        | Reject                    | Reject        |
| PC               | BF 12-12        | 0.09                    | -9.20                        | Reject                    | Reject        |
| PC               | BF 36-4         | 0.22                    | -3.01                        | Reject                    | Reject        |
| PC               | BF 36-8         | 0.08                    | -14.46                       | Reject                    | Reject        |
| PC               | BF 36-12        | 0.15                    | -6.06                        | Reject                    | Reject        |
| <b>PC</b>        | <b>BF 50-4</b>  | 0.19                    | 0.26                         | <b>Accept</b>             | <b>Accept</b> |
| PC               | BF 50-8         | 0.11                    | -9.99                        | Reject                    | Reject        |
| PC               | BF 50-12        | 0.12                    | -8.40                        | Reject                    | Reject        |
| SF 38-40         | BF 12-4         | 0.18                    | 9.04                         | Reject                    | Reject        |
| SF 38-40         | BF 12-8         | 0.11                    | 10.20                        | Reject                    | Reject        |
| SF 38-40         | BF 12-12        | 0.10                    | 6.65                         | Reject                    | Reject        |
| SF 38-40         | BF 36-4         | 0.22                    | 3.76                         | Reject                    | Reject        |
| SF 38-40         | BF 36-8         | 0.09                    | 3.82                         | Reject                    | Reject        |
| SF 38-40         | BF 36-12        | 0.16                    | 3.66                         | Reject                    | Reject        |
| SF 38-40         | BF 50-4         | 0.20                    | 7.81                         | Reject                    | Reject        |
| SF 38-40         | BF 50-8         | 0.12                    | 2.98                         | Reject                    | Reject        |
| SF 38-40         | BF 50-12        | 0.13                    | 3.36                         | Reject                    | Reject        |
| PP 40-4.5        | BF 12-4         | 0.17                    | 7.97                         | Reject                    | Reject        |
| PP 40-4.5        | BF 12-8         | 0.09                    | 8.80                         | Reject                    | Reject        |
| PP 40-4.5        | BF 12-12        | 0.09                    | 4.83                         | Reject                    | Reject        |
| <b>PP 40-4.5</b> | <b>BF 36-4</b>  | 0.22                    | 2.76                         | <b>Accept</b>             | Reject        |
| <b>PP 40-4.5</b> | <b>BF 36-8</b>  | 0.08                    | 1.48                         | <b>Accept</b>             | <b>Accept</b> |
| <b>PP 40-4.5</b> | <b>BF 36-12</b> | 0.15                    | 2.27                         | <b>Accept</b>             | Reject        |
| PP 40-4.5        | BF 50-4         | 0.19                    | 6.79                         | Reject                    | Reject        |
| <b>PP 40-4.5</b> | <b>BF 50-8</b>  | 0.12                    | 1.15                         | <b>Accept</b>             | <b>Accept</b> |
| <b>PP 40-4.5</b> | <b>BF 50-12</b> | 0.13                    | 1.70                         | <b>Accept</b>             | <b>Accept</b> |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{crit, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{crit, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

Table 4.27 shows the effect of fibre length of basalt filaments on mean MOR. The following is the summary of observations.

- For fibre dosage of 4 kg/m<sup>3</sup>, the change in MOR is statistically significant when length of the filament increases from 12 mm to 36 mm at both 90% and 95% CIs. However, the change in MOR is not statistically significant when length of the filament increases from 12 mm to 50 mm at both 90% and 95% confidence intervals.
- For fibre dosage of 8 kg/m<sup>3</sup>, the change in MOR is statistically significant when length of the filament increases from 12 mm to 36 mm or 12 mm to 50 mm at both 90% and 95% confidence intervals.
- For fibre dosage of 12 kg/m<sup>3</sup>, the change in MOR is not statistically significant when length of the filament increases from 12 mm to 36 mm or 12 mm to 50 mm at both 90% and 95% confidence intervals.
- The change in MOR due to increase in filament length from 36 mm to 50 mm for 4 kg/m<sup>3</sup> is statistically significant at 90% CI, however, it is not statistically significant at 95% CI. The change in MOR due to increase in filament length from 36 mm to 50 mm for 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup> is statistically insignificant at both 90% and 95% CIs.

**Table 4.27: Basalt filaments: Effect of fibre length: MOR: Independent sample t-test**

| Sample          |                 | Pooled SD ( $\bar{s}$ ) | Tested t-value (Eqn. 4.6) | Null hypothesis ( $H_0$ ) |               |
|-----------------|-----------------|-------------------------|---------------------------|---------------------------|---------------|
| Group 1         | Group 2         |                         |                           | 95% CI                    | 90% CI        |
| BF 12-4         | BF 36-4         | 0.26                    | -2.96                     | Reject                    | Reject        |
| <b>BF 12-4</b>  | <b>BF 50-4</b>  | 0.24                    | -0.24                     | <b>Accept</b>             | <b>Accept</b> |
| BF 12-8         | BF 36-8         | 0.07                    | -10.40                    | Reject                    | Reject        |
| BF 12-8         | BF 50-8         | 0.11                    | -6.61                     | Reject                    | Reject        |
| <b>BF 12-12</b> | <b>BF 36-12</b> | 0.14                    | -0.67                     | <b>Accept</b>             | <b>Accept</b> |
| <b>BF 12-12</b> | <b>BF 50-12</b> | 0.12                    | -1.97                     | <b>Accept</b>             | <b>Accept</b> |
| <b>BF 36-4</b>  | <b>BF 50-4</b>  | 0.27                    | 2.59                      | <b>Accept</b>             | Reject        |
| <b>BF 36-8</b>  | <b>BF 50-8</b>  | 0.10                    | 0.12                      | <b>Accept</b>             | <b>Accept</b> |
| <b>BF 36-12</b> | <b>BF 50-12</b> | 0.17                    | -0.78                     | <b>Accept</b>             | <b>Accept</b> |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{\text{crit}, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{\text{crit}, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

Table 4.28 shows the effect of fibre quantity of basalt filaments on mean MOR. The following is the summary of observations.

- For short (12 mm) filaments, the change in MOR is statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> at both 90% and 95% confidence intervals.
- For medium length (36 mm) filaments, the change in MOR is statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> at 90% CI, however, it is not statistically significant at 95% CI. The change in MOR is statistically insignificant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> at both 90% and 95% CIs.
- For long (50 mm) filaments, the change in MOR is statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> at both 90% and 95% confidence intervals.
- The change in MOR due to increase in fibre dosage from 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> for 12 mm filament is statistically significant at both 90% and 95% confidence intervals. However, it is not statistically significant for 36 mm and 50 mm filaments at both 90% and 95% confidence intervals.

**Table 4.28: Basalt filaments: Effect of fibre quantity: MOR: Independent sample**

**t-test**

| Sample         |                 | Pooled SD ( $\bar{s}$ ) | Tested t-value (Eqn. 4.6) | Null hypothesis ( $H_0$ ) |               |
|----------------|-----------------|-------------------------|---------------------------|---------------------------|---------------|
| Group 1        | Group 2         |                         |                           | 95% CI                    | 90% CI        |
| BF 12-4        | BF 12-8         | 0.17                    | -3.23                     | Reject                    | Reject        |
| BF 12-4        | BF 12-12        | 0.16                    | -5.65                     | Reject                    | Reject        |
| <b>BF 36-4</b> | <b>BF 36-8</b>  | 0.21                    | -2.31                     | <b>Accept</b>             | Reject        |
| <b>BF 36-4</b> | <b>BF 36-12</b> | 0.25                    | -1.05                     | <b>Accept</b>             | <b>Accept</b> |
| BF 50-4        | BF 50-8         | 0.20                    | -5.93                     | Reject                    | Reject        |
| BF 50-4        | BF 50-12        | 0.21                    | -5.33                     | Reject                    | Reject        |
| BF 12-8        | BF 12-12        | 0.08                    | -4.89                     | Reject                    | Reject        |
| <b>BF 36-8</b> | <b>BF 36-12</b> | 0.14                    | 1.64                      | <b>Accept</b>             | <b>Accept</b> |
| <b>BF 50-8</b> | <b>BF 50-12</b> | 0.14                    | 0.61                      | <b>Accept</b>             | <b>Accept</b> |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{\text{crit}, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{\text{crit}, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

#### **4.4.2.2 STATISTICAL COMPARISON OF MEAN COMPRESSIVE STRENGTH**

Table 4.29 compares the 28 day compressive strength of basalt filament cylinder specimens with that of control specimens (plain concrete or PC, steel fibre or SF 38-40, and macro synthetic fibre or PP 40-4.5 specimens). All basalt filament sample groups, except BF 36-4, are statistically different from PC at both 90% and 95% confidence intervals. Likewise, all basalt filament sample groups, except BF 50-12, are statistically different from SF 38-40 at both 90% and 95% CIs. All basalt filament sample groups, except BF 50-12, are statically similar with PP 40-4.5 at 90% CI. Hence, it was found that all basalt filament sample groups, except 36 mm filaments at 4 kg/m<sup>3</sup>, have significant effect on the 28 day compressive strength when compared with PC. Long filaments (50 mm) at high dosage of 12 kg/m<sup>3</sup> provide compressive strength similar to SF 38-40. All filament specimens, except BF 50-12, provide compressive strength similar to PP 40-4.5.

**Table 4.29: Basalt filaments vs. Control specimens: Compressive strength:  
Independent sample t-test**

| Sample           |                 | Pooled SD ( $\bar{s}$ ) | Tested<br>t-value<br>(Eqn. 4.6) | Null hypothesis (H <sub>0</sub> ) |               |
|------------------|-----------------|-------------------------|---------------------------------|-----------------------------------|---------------|
| Group 1          | Group 2         |                         |                                 | 95% CI                            | 90% CI        |
| PC               | BF 12-4         | 1.21                    | -4.58                           | Reject                            | Reject        |
| PC               | BF 12-8         | 1.50                    | -4.99                           | Reject                            | Reject        |
| PC               | BF 12-12        | 1.07                    | -7.04                           | Reject                            | Reject        |
| <b>PC</b>        | <b>BF 36-4</b>  | 3.00                    | -2.11                           | <b>Accept</b>                     | <b>Accept</b> |
| PC               | BF 36-8         | 1.01                    | -9.13                           | Reject                            | Reject        |
| PC               | BF 36-12        | 1.54                    | -4.80                           | Reject                            | Reject        |
| PC               | BF 50-4         | 1.81                    | -4.74                           | Reject                            | Reject        |
| PC               | BF 50-8         | 2.01                    | -4.20                           | Reject                            | Reject        |
| PC               | BF 50-12        | 1.39                    | -8.68                           | Reject                            | Reject        |
| SF 38-40         | BF 12-4         | 1.07                    | 8.41                            | Reject                            | Reject        |
| SF 38-40         | BF 12-8         | 1.39                    | 5.10                            | Reject                            | Reject        |
| SF 38-40         | BF 12-12        | 0.91                    | 7.77                            | Reject                            | Reject        |
| SF 38-40         | BF 36-4         | 2.95                    | 2.80                            | Reject                            | Reject        |
| SF 38-40         | BF 36-8         | 0.84                    | 6.45                            | Reject                            | Reject        |
| SF 38-40         | BF 36-12        | 1.44                    | 5.01                            | Reject                            | Reject        |
| SF 38-40         | BF 50-4         | 1.72                    | 3.48                            | Reject                            | Reject        |
| SF 38-40         | BF 50-8         | 1.93                    | 3.18                            | Reject                            | Reject        |
| <b>SF 38-40</b>  | <b>BF 50-12</b> | 1.27                    | 2.00                            | <b>Accept</b>                     | <b>Accept</b> |
| <b>PP 40-4.5</b> | <b>BF 12-4</b>  | 1.75                    | 0.92                            | <b>Accept</b>                     | <b>Accept</b> |
| <b>PP 40-4.5</b> | <b>BF 12-8</b>  | 1.96                    | -0.17                           | <b>Accept</b>                     | <b>Accept</b> |
| <b>PP 40-4.5</b> | <b>BF 12-12</b> | 1.65                    | -0.22                           | <b>Accept</b>                     | <b>Accept</b> |
| <b>PP 40-4.5</b> | <b>BF 36-4</b>  | 3.25                    | 0.26                            | <b>Accept</b>                     | <b>Accept</b> |
| <b>PP 40-4.5</b> | <b>BF 36-8</b>  | 1.61                    | -1.27                           | <b>Accept</b>                     | <b>Accept</b> |
| <b>PP 40-4.5</b> | <b>BF 36-12</b> | 1.99                    | -0.12                           | <b>Accept</b>                     | <b>Accept</b> |
| <b>PP 40-4.5</b> | <b>BF 50-4</b>  | 2.21                    | -0.65                           | <b>Accept</b>                     | <b>Accept</b> |
| <b>PP 40-4.5</b> | <b>BF 50-8</b>  | 2.37                    | -0.54                           | <b>Accept</b>                     | <b>Accept</b> |
| <b>PP 40-4.5</b> | <b>BF 50-12</b> | 1.87                    | -2.61                           | <b>Accept</b>                     | Reject        |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{crit, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{crit, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

Table 4.30 shows the effect of fibre length of basalt filaments on 28 day compressive strength. The following is the summary of observations.

- For fibre dosage of 4 kg/m<sup>3</sup>, the change in compressive strength is not statistically significant when length of the filament increases from 12 mm to 36 mm or 12 mm to 50 mm at both 90% and 95% CIs.
- For fibre dosage of 8 kg/m<sup>3</sup>, the change in compressive strength is not statistically significant when length of the filament increases from 12 mm to 36 mm or 12 mm to 50 mm at both 90% and 95% confidence intervals.
- For fibre dosage of 12 kg/m<sup>3</sup>, the change in compressive strength is not statistically significant when length of the filament increases from 12 mm to 36 mm at both 90% and 95% confidence intervals. However, the change in compressive strength is statistically significant when length of the filament increases from 12 mm to 50 mm at both 90% and 95% confidence intervals.
- The change in compressive strength due to increase in filament length from 36 mm to 50 mm for 4 kg/m<sup>3</sup> and 8 kg/m<sup>3</sup> are statistically insignificant at both 90% and 95% confidence intervals. However, it is statistically significant for 12 kg/m<sup>3</sup> at both 90% and 95% CIs.

**Table 4.30: Basalt filaments: Effect of fibre length: Compressive strength: Independent sample t-test**

| Sample   |          | Pooled SD ( $\bar{s}$ ) | Tested t-value (Eqn. 4.6) | Null hypothesis (H <sub>0</sub> ) |        |
|----------|----------|-------------------------|---------------------------|-----------------------------------|--------|
| Group 1  | Group 2  |                         |                           | 95% CI                            | 90% CI |
| BF 12-4  | BF 36-4  | 2.92                    | -0.27                     | Accept                            | Accept |
| BF 12-4  | BF 50-4  | 1.67                    | -1.82                     | Accept                            | Accept |
| BF 12-8  | BF 36-8  | 1.14                    | -1.49                     | Accept                            | Accept |
| BF 12-8  | BF 50-8  | 2.08                    | -0.46                     | Accept                            | Accept |
| BF 12-12 | BF 36-12 | 1.25                    | 0.11                      | Accept                            | Accept |
| BF 12-12 | BF 50-12 | 1.05                    | -4.29                     | Reject                            | Reject |
| BF 36-4  | BF 50-4  | 3.22                    | -0.71                     | Accept                            | Accept |
| BF 36-8  | BF 50-8  | 1.76                    | 0.43                      | Accept                            | Accept |
| BF 36-12 | BF 50-12 | 1.53                    | -3.04                     | Reject                            | Reject |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{crit, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{crit, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

Table 4.31 shows the effect of fibre quantity of basalt filaments on 28 day compressive strength. The following is the summary of observations.

- For short (12 mm) filaments, the change in compressive strength is not statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> at both 90% and 95% confidence intervals. The change in compressive strength is statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> at 90% CI, however, it is not statistically significant at 95% CI.
- For medium length (36 mm) filaments, the change in compressive strength is not statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> at both 90% and 95% confidence intervals.
- For long (50 mm) filaments, the change in compressive strength is not statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> at both 90% and 95% confidence intervals.
- The change in compressive strength due to increase in fibre dosage from 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> for all fibre lengths (12 mm, 36 mm, and 50 mm) is not statistically significant at both 90% and 95% confidence intervals.

**Table 4.31: Basalt filaments: Effect of fibre quantity: Compressive strength: Independent sample t-test**

| Sample  |          | Pooled SD ( $\bar{s}$ ) | Tested t-value (Eqn. 4.6) | Null hypothesis ( $H_0$ ) |        |
|---------|----------|-------------------------|---------------------------|---------------------------|--------|
| Group 1 | Group 2  |                         |                           | 95% CI                    | 90% CI |
| BF 12-4 | BF 12-8  | 1.33                    | -1.46                     | Accept                    | Accept |
| BF 12-4 | BF 12-12 | 0.81                    | -2.45                     | Accept                    | Reject |
| BF 36-4 | BF 36-8  | 2.84                    | -1.01                     | Accept                    | Accept |
| BF 36-4 | BF 36-12 | 3.07                    | -0.35                     | Accept                    | Accept |
| BF 50-4 | BF 50-8  | 2.32                    | 0.07                      | Accept                    | Accept |
| BF 50-4 | BF 50-12 | 1.80                    | -1.91                     | Accept                    | Accept |
| BF 12-8 | BF 12-12 | 1.20                    | -0.03                     | Accept                    | Accept |
| BF 36-8 | BF 36-12 | 1.20                    | 1.51                      | Accept                    | Accept |
| BF 50-8 | BF 50-12 | 2.00                    | -1.80                     | Accept                    | Accept |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{crit, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{crit, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

#### **4.4.2.3 STATISTICAL COMPARISON OF MEAN SPLIT TENSILE STRENGTH**

Table 4.32 compares the split tensile strength of basalt filament cylinder specimens with control specimens (plain concrete or PC, steel fibre or SF 38-40, and macro synthetic fibre or PP 40-4.5 specimens). All basalt filament sample groups, except BF 12-4, and BF 12-12, are statistically similar to PC at both 90% and 95% confidence intervals. Similarly, all basalt filament sample groups are statistically similar to SF 38-40 at 95% CI. All basalt filament sample groups, except BF 12-12, are statistically similar to PP 40-4.5 at both 90% and 95% confidence intervals. Hence, it was found that the short filament fibres (12 mm) have significant influence on the split tensile strength when compared with PC. It was also observed that there is change in the split tensile strength between the control specimens (PC, SF 38-40, and PP 40-4.5) and 12 mm filament fibres at 12 kg/m<sup>3</sup>.

**Table 4.32: Basalt filaments vs. Control specimens: Split tensile strength:  
Independent sample t-test**

| Sample    |          | Pooled SD ( $\bar{s}$ ) | Tested<br>t-value<br>(Eqn. 4.6) | Null hypothesis (H <sub>0</sub> ) |        |
|-----------|----------|-------------------------|---------------------------------|-----------------------------------|--------|
| Group 1   | Group 2  |                         |                                 | 95% CI                            | 90% CI |
| PC        | BF 12-4  | 0.03                    | -10.68                          | Reject                            | Reject |
| PC        | BF 12-8  | 0.21                    | -2.46                           | Accept                            | Reject |
| PC        | BF 12-12 | 0.23                    | -3.64                           | Reject                            | Reject |
| PC        | BF 36-4  | 0.38                    | -0.73                           | Accept                            | Accept |
| PC        | BF 36-8  | 0.07                    | -2.55                           | Accept                            | Reject |
| PC        | BF 36-12 | 0.20                    | -0.30                           | Accept                            | Accept |
| PC        | BF 50-4  | 0.10                    | 0.00                            | Accept                            | Accept |
| PC        | BF 50-8  | 0.22                    | -0.75                           | Accept                            | Accept |
| PC        | BF 50-12 | 0.29                    | -2.10                           | Accept                            | Accept |
| SF 38-40  | BF 12-4  | 0.12                    | -0.39                           | Accept                            | Accept |
| SF 38-40  | BF 12-8  | 0.24                    | -1.02                           | Accept                            | Accept |
| SF 38-40  | BF 12-12 | 0.26                    | -2.24                           | Accept                            | Reject |
| SF 38-40  | BF 36-4  | 0.40                    | -0.02                           | Accept                            | Accept |
| SF 38-40  | BF 36-8  | 0.13                    | 0.75                            | Accept                            | Accept |
| SF 38-40  | BF 36-12 | 0.23                    | 0.89                            | Accept                            | Accept |
| SF 38-40  | BF 50-4  | 0.15                    | 1.84                            | Accept                            | Accept |
| SF 38-40  | BF 50-8  | 0.25                    | 0.41                            | Accept                            | Accept |
| SF 38-40  | BF 50-12 | 0.31                    | -1.08                           | Accept                            | Accept |
| PP 40-4.5 | BF 12-4  | 0.13                    | -1.88                           | Accept                            | Accept |
| PP 40-4.5 | BF 12-8  | 0.24                    | -1.80                           | Accept                            | Accept |
| PP 40-4.5 | BF 12-12 | 0.26                    | -2.93                           | Reject                            | Reject |
| PP 40-4.5 | BF 36-4  | 0.40                    | -0.50                           | Accept                            | Accept |
| PP 40-4.5 | BF 36-8  | 0.14                    | -0.67                           | Accept                            | Accept |
| PP 40-4.5 | BF 36-12 | 0.24                    | 0.07                            | Accept                            | Accept |
| PP 40-4.5 | BF 50-4  | 0.16                    | 0.50                            | Accept                            | Accept |
| PP 40-4.5 | BF 50-8  | 0.26                    | -0.35                           | Accept                            | Accept |
| PP 40-4.5 | BF 50-12 | 0.31                    | -1.68                           | Accept                            | Accept |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{crit, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{crit, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

Table 4.33 shows the effect of fibre length of basalt filaments on the split tensile strength. The following is the summary of observations.

- For fibre dosage of 4 kg/m<sup>3</sup>, the change in split tensile strength is not statistically significant when length of the filament increases from 12 mm to 36 mm at both 90% and 95% CIs. However, the change in split tensile strength is statistically significant when the length of filament increases from 12 mm to 50 mm at both 90% and 95% CIs.
- For fibre dosage of 8 kg/m<sup>3</sup>, the change in split tensile strength is not statistically significant when length of the filament increases from 12 mm to 36 mm or 12 mm to 50 mm at both 90% and 95% confidence intervals.
- For fibre dosage of 12 kg/m<sup>3</sup>, the change in split tensile strength is statistically significant when length of the filament increases from 12 mm to 36 mm at 90% CI, however, it is not statistically significant at 95% CI. The change in split tensile strength is not statistically significant when the length of filament increases from 12 mm to 50 mm at both 90% and 95% confidence intervals.
- The change in split tensile strength due to increase in filament length from 36 mm to 50 mm for all fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>) is not statistically significant at both 90% and 95% CIs.

**Table 4.33: Basalt filaments: Effect of fibre length: Split tensile strength: Independent sample t-test**

| Sample   |          | Pooled SD ( $\bar{s}$ ) | Tested t-value (Eqn. 4.6) | Null hypothesis ( $H_0$ ) |        |
|----------|----------|-------------------------|---------------------------|---------------------------|--------|
| Group 1  | Group 2  |                         |                           | 95% CI                    | 90% CI |
| BF 12-4  | BF 36-4  | 0.38                    | 0.10                      | Accept                    | Accept |
| BF 12-4  | BF 50-4  | 0.09                    | 3.34                      | Reject                    | Reject |
| BF 12-8  | BF 36-8  | 0.22                    | 1.57                      | Accept                    | Accept |
| BF 12-8  | BF 50-8  | 0.30                    | 1.13                      | Accept                    | Accept |
| BF 12-12 | BF 36-12 | 0.31                    | 2.55                      | Accept                    | Reject |
| BF 12-12 | BF 50-12 | 0.37                    | 0.67                      | Accept                    | Accept |
| BF 36-4  | BF 50-4  | 0.39                    | 0.71                      | Accept                    | Accept |
| BF 36-8  | BF 50-8  | 0.23                    | 0.02                      | Accept                    | Accept |
| BF 36-12 | BF 50-12 | 0.35                    | -1.54                     | Accept                    | Accept |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{\text{crit}, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{\text{crit}, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

Table 4.34 shows the effect of fibre quantity of basalt filaments on the split tensile strength. The following is the summary of observations.

- For short (12 mm) filaments, the change in split tensile strength is not statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> at both 90% and 95% confidence intervals. The change in split tensile strength is statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> at 90% CI, however, it is not statistically significant at 95% CI.
- For medium length (36 mm) filaments, the change in split tensile strength is not statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> at both 90% and 95% confidence intervals.
- For long (50 mm) filaments, the change in split tensile strength is not statistically significant when the fibre dosage increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> at both 90% and 95% confidence intervals.
- The change in split tensile strength due to increase in fibre dosage from 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> for all fibre lengths (12 mm, 36 mm, and 50 mm) is statistically insignificant at both 90% and 95% confidence intervals.

**Table 4.34: Basalt filaments: Effect of fibre quantity: Split tensile strength: Independent sample t-test**

| Sample  |          | Pooled SD ( $\bar{s}$ ) | Tested t-value (Eqn. 4.6) | Null hypothesis ( $H_0$ ) |        |
|---------|----------|-------------------------|---------------------------|---------------------------|--------|
| Group 1 | Group 2  |                         |                           | 95% CI                    | 90% CI |
| BF 12-4 | BF 12-8  | 0.21                    | -0.95                     | Accept                    | Accept |
| BF 12-4 | BF 12-12 | 0.23                    | -2.29                     | Accept                    | Reject |
| BF 36-4 | BF 36-8  | 0.39                    | 0.28                      | Accept                    | Accept |
| BF 36-4 | BF 36-12 | 0.43                    | 0.50                      | Accept                    | Accept |
| BF 50-4 | BF 50-8  | 0.24                    | -0.69                     | Accept                    | Accept |
| BF 50-4 | BF 50-12 | 0.30                    | -2.01                     | Accept                    | Accept |
| BF 12-8 | BF 12-12 | 0.31                    | -1.08                     | Accept                    | Accept |
| BF 36-8 | BF 36-12 | 0.21                    | 0.52                      | Accept                    | Accept |
| BF 50-8 | BF 50-12 | 0.36                    | -1.20                     | Accept                    | Accept |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{crit, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{crit, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

#### 4.4.3 INDEPENDENT SAMPLE T-TEST – BASALT BUNDLE vs. BASALT FILAMENT

##### 4.4.3.1 STATISTICAL COMPARISON OF MEAN MODULUS OF RUPTURE

Table 4.35 compares the mean modulus of rupture (MOR) of basalt bundle beam specimens with that of basalt filament beam specimens of same fibre length and quantity. The following is the summary of observations.

- For short (12 mm) fibres, the change in MOR between bundles and filaments for all fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>) is not statistically significant at both 90% and 95% confidence intervals.
- For medium length (36 mm) fibres, the change in MOR between bundles and filaments for 4 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup> is not statistically significant at both 90% and 95% confidence intervals. However, it is statistically significant for 8 kg/m<sup>3</sup> at both 90% and 95% confidence intervals.
- For long (50 mm) fibres, the change in MOR between bundles and filaments for 4 kg/m<sup>3</sup> is statistically significant at 90% CI, however, it is not statistically significant at 95% CI. The change in MOR between bundles and filaments for 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup> is not statistically significant at both 90% and 95% confidence intervals.

**Table 4.35: Basalt bundles vs. Basalt filaments: MOR: Independent sample t-test**

| Sample   |          | Pooled SD ( $\bar{s}$ ) | Tested t-value (Eqn. 4.6) | Null hypothesis ( $H_0$ ) |        |
|----------|----------|-------------------------|---------------------------|---------------------------|--------|
| Group 1  | Group 2  |                         |                           | 95% CI                    | 90% CI |
| BB 12-4  | BF 12-4  | 0.19                    | -0.34                     | Accept                    | Accept |
| BB 12-8  | BF 12-8  | 0.26                    | 0.51                      | Accept                    | Accept |
| BB 12-12 | BF 12-12 | 0.06                    | 2.13                      | Accept                    | Accept |
| BB 36-4  | BF 36-4  | 0.25                    | 0.98                      | Accept                    | Accept |
| BB 36-8  | BF 36-8  | 0.05                    | 7.46                      | Reject                    | Reject |
| BB 36-12 | BF 36-12 | 0.25                    | -0.60                     | Accept                    | Accept |
| BB 50-4  | BF 50-4  | 0.19                    | -2.45                     | Accept                    | Reject |
| BB 50-8  | BF 50-8  | 0.17                    | 0.63                      | Accept                    | Accept |
| BB 50-12 | BF 50-12 | 0.16                    | -1.58                     | Accept                    | Accept |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{crit, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{crit, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

#### 4.4.3.2 STATISTICAL COMPARISON OF MEAN COMPRESSIVE STRENGTH

Table 4.36 compares the 28 day compressive strength of basalt bundle cylinder specimens with that of basalt filament cylinder specimens of same fibre length and quantity. The following is the summary of observations.

- For short (12 mm) fibres, the change in compressive strength between bundles and filaments for 4 kg/m<sup>3</sup> and 8 kg/m<sup>3</sup> is not statistically significant at both 90% and 95% confidence intervals. The change in compressive strength between bundles and filaments for 12 kg/m<sup>3</sup> is statistically significant at 90% CI, however, it is not statistically significant at 95% CI.
- For medium length (36 mm) fibres, the change in compressive strength between bundles and filaments for 4 kg/m<sup>3</sup> is not statistically significant at both 90% and 95% confidence intervals. However, it is statistically significant for 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup> at both 90% and 95% confidence intervals.
- For long (50 mm) fibres, the change in compressive strength between bundles and filaments for 4 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup> is not statistically significant at both 90% and 95% CI. The change in compressive strength between bundles and filaments for 8 kg/m<sup>3</sup> is statistically significant at 90% CI, however, it is not statistically significant at 95% CI.

**Table 4.36: Basalt bundles vs. Basalt filaments: Compressive strength: Independent sample t-test**

| Sample   |          | Pooled SD ( $\bar{s}$ ) | Tested t-value (Eqn. 4.6) | Null hypothesis (H <sub>0</sub> ) |        |
|----------|----------|-------------------------|---------------------------|-----------------------------------|--------|
| Group 1  | Group 2  |                         |                           | 95% CI                            | 90% CI |
| BB 12-4  | BF 12-4  | 0.99                    | -1.37                     | Accept                            | Accept |
| BB 12-8  | BF 12-8  | 1.49                    | 1.25                      | Accept                            | Accept |
| BB 12-12 | BF 12-12 | 0.82                    | -2.54                     | Accept                            | Reject |
| BB 36-4  | BF 36-4  | 2.94                    | -0.46                     | Accept                            | Accept |
| BB 36-8  | BF 36-8  | 0.42                    | -13.65                    | Reject                            | Reject |
| BB 36-12 | BF 36-12 | 1.19                    | -7.94                     | Reject                            | Reject |
| BB 50-4  | BF 50-4  | 1.63                    | -0.41                     | Accept                            | Accept |
| BB 50-8  | BF 50-8  | 2.70                    | -2.23                     | Accept                            | Reject |
| BB 50-12 | BF 50-12 | 2.24                    | -1.83                     | Accept                            | Accept |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{crit, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{crit, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

#### 4.4.3.3 STATISTICAL COMPARISON OF MEAN SPLIT TENSILE STRENGTH

Table 4.37 compares the split tensile strength of basalt bundle cylinder specimens with that of basalt filament cylinder specimens of same fibre length and quantity. The following is the summary of observations.

- For short (12 mm) fibres, the change in split tensile strength between bundles and filaments for all fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>) is not statistically significant at both 90% and 95% confidence intervals.
- For medium length (36 mm) fibres, the change in split tensile strength between bundles and filaments for 4 kg/m<sup>3</sup> and 8 kg/m<sup>3</sup> is not statistically significant at both 90% and 95% confidence intervals. The change in split tensile strength between bundles and filaments for 12 kg/m<sup>3</sup> is statistically significant at 90% CI, however, it is not statistically significant at 95% CI.
- For long (50 mm) fibres, the change in split tensile strength between bundles and filaments for all fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>) is not statistically significant at both 90% and 95% confidence intervals.

**Table 4.37: Basalt bundles vs. Basalt filaments: Split tensile strength: Independent sample t-test**

| Sample   |          | Pooled SD ( $\bar{s}$ ) | Tested t-value (Eqn. 4.6) | Null hypothesis ( $H_0$ ) |        |
|----------|----------|-------------------------|---------------------------|---------------------------|--------|
| Group 1  | Group 2  |                         |                           | 95% CI                    | 90% CI |
| BB 12-4  | BF 12-4  | 0.35                    | -0.68                     | Accept                    | Accept |
| BB 12-8  | BF 12-8  | 0.35                    | 0.38                      | Accept                    | Accept |
| BB 12-12 | BF 12-12 | 0.35                    | 2.07                      | Accept                    | Accept |
| BB 36-4  | BF 36-4  | 0.41                    | -0.49                     | Accept                    | Accept |
| BB 36-8  | BF 36-8  | 0.52                    | -0.88                     | Accept                    | Accept |
| BB 36-12 | BF 36-12 | 0.41                    | -2.61                     | Accept                    | Reject |
| BB 50-4  | BF 50-4  | 0.22                    | -1.80                     | Accept                    | Accept |
| BB 50-8  | BF 50-8  | 0.36                    | -1.13                     | Accept                    | Accept |
| BB 50-12 | BF 50-12 | 0.65                    | -0.69                     | Accept                    | Accept |

Degree of freedom ( $n_A + n_B - 2$ ) = 4,  $t_{crit, \frac{\alpha}{2}} = \pm 2.776$  at 95% confidence level, and  $t_{crit, \frac{\alpha}{2}} = \pm 2.132$  at 90% confidence level (Appendix A) for all the above sample groups.

## 4.5 SUMMARY

- *Basalt bundles vs. control specimens:* The medium length (36 mm) and long (50 mm) bundled fibres at high fibre dosage of  $12 \text{ kg/m}^3$  are statistically similar to SF 38-40 in flexural strength, and compressive strength. The change in split tensile strength of 36 mm bundled fibre at  $12 \text{ kg/m}^3$  is statistically significant when compared with PC, SF 38-40 or PP 40-4.5 specimens.
- *Basalt bundles - Effect of length and dosage:* The change in basalt bundled fibre length from 12 mm to 50 mm for all fibre dosages ( $4 \text{ kg/m}^3$ ,  $8 \text{ kg/m}^3$ , and  $12 \text{ kg/m}^3$ ) has statistically significant influence on the flexural strength. For short bundled fibre (12 mm), the effect of fibre quantity has significant influence on flexural strength and compressive strength only when the fibre dosage increases from  $4 \text{ kg/m}^3$  to  $12 \text{ kg/m}^3$ . The fibre dosages of  $8 \text{ kg/m}^3$  and  $12 \text{ kg/m}^3$  for 36 mm and 50 mm bundled fibres, statistically have significant influence on flexural strength and compressive strength. The change in bundled fibre length from 12 mm to 36 mm at high dosage of  $12 \text{ kg/m}^3$  has significant influence on the split tensile strength.
- *Basalt filaments vs. control specimens:* None of the basalt filament specimens have similar flexural strength as SF 38-40 specimen. The 36 mm filament at  $8 \text{ kg/m}^3$ , and 50 mm filament at  $8 \text{ kg/m}^3$  and  $12 \text{ kg/m}^3$  provide similar flexural strength as PP 40-4.5 specimen. All basalt filament specimens provide compressive strength similar to PP 40-4.5, except 50 mm filament at  $12 \text{ kg/m}^3$  which provides compressive strength similar to SF 38-40 specimen. The change in split tensile strength of 12 mm filament at  $12 \text{ kg/m}^3$  is statistically significant when compared with PC, SF 38-40 or PP 40-4.5 specimens.
- *Basalt filaments - Effect of length and dosage:* The change in filament fibre length from 12 mm to 36 mm or 12 mm to 50 mm at  $8 \text{ kg/m}^3$  has significant influence on the flexural strength. For 12 mm and 50 mm filaments, the change in filament fibre

quantity from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> has significant influence on the flexural strength. The change in filament fibre length from 12 mm to 50 mm or 36 mm to 50 mm at 12 kg/m<sup>3</sup> has significant influence on the compressive strength. The change in fibre length from 12 mm to 50 mm at 4 kg/m<sup>3</sup> has significant influence on the split tensile strength. There is no significant influence of fibre quantity on compressive strength and split tensile strength, for all fibre lengths (12 mm, 36 mm, and 50 mm).

- *Basalt bundles vs. Basalt filaments:* The flexural performance of both bundled fibres and filaments of same length and quantity are statistically similar, except for 36 mm fibres at 8 kg/m<sup>3</sup>. The compressive strength of both bundled fibres and filaments are statistically similar, except for 36 mm fibres at 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup>. The split tensile strength of both bundled fibres and filaments are statistically similar, except for 36 mm fibres at 12 kg/m<sup>3</sup>.

## **5. RESULTS AND DISCUSSIONS**

This chapter provides detailed discussion on how test data were reduced, organized, analyzed, and finally used to make several conclusions. The chapter primarily discusses three mechanical properties of BFRC, and these are: flexural strength, compressive strength, and split tensile strength.

### **5.1 FLEXURAL STRENGTH**

Statistical analysis of flexural specimens were discussed in Chapter 4. These are further referenced in this section to determine the optimum fibre length and dosage.

#### **5.1.1 BASALT BUNDLES**

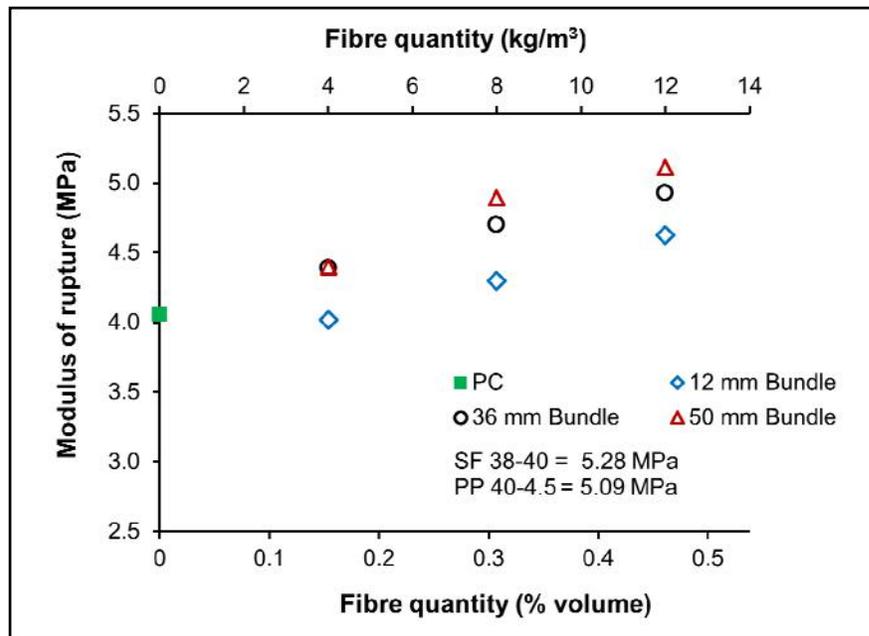
Figure 5.1 shows the mean modulus of rupture (MOR) of basalt bundle specimens and PC. The volume ratio is calculated based on the density of basalt fibre. The density of steel fibre and macro synthetic fibre are different from basalt fibre (Table 2.1). Hence, the mean MOR of steel and macro synthetic fibre specimens are displayed in the legend. The MOR increases with an increase in the fibre volume and fibre length. Initially, BB 50-4 specimens were cast with a water-cement ratio of 0.4, to maintain slump below 200 mm. This resulted in a high MOR. Hence, this set was repeated with water-cement ratio of 0.5, to make this comparable with other specimens.

Independent sample t-test (Table 4.17) on MOR shows that BB 12-4, and BB 12-8 are not statistically different from PC. There is also no significant improvement in MOR for the above specimens from PC as shown in Figure 5.1.

The mean MOR of PC is 30% lower than SF 38-40, and 26% lower than PP 40-4.5. Further, the mean MOR of BB 36-12 (4.93 MPa), and BB 50-12 (5.11 MPa) are similar to SF 38-40 (5.28 MPa). Similarly, the mean MOR of BB 36-12, BB 50-8 (4.89 MPa), and BB 50-

12 are comparable with PP 40-4.5 (5.09 MPa). The increase in MOR from PC for BB 36-12, BB 50-8, and BB 50-12 are 22%, 20.74 %, and 26%, respectively.

The study found that for short fibres (12 mm), there was no significant improvement in flexural strength from PC until a high dosage of 12 kg/m<sup>3</sup> was used. However, for 50 mm bundled fibre, 20.74% increase in MOR was observed from PC at 8 kg/m<sup>3</sup>. The intermediate length (36 mm) bundled fibre at 12 kg/m<sup>3</sup> provides similar improvement in MOR (22%) over PC. Long bundled fibre (50 mm) at high fibre dosage of 12 kg/m<sup>3</sup>, provides 26% increase in flexural strength from PC.



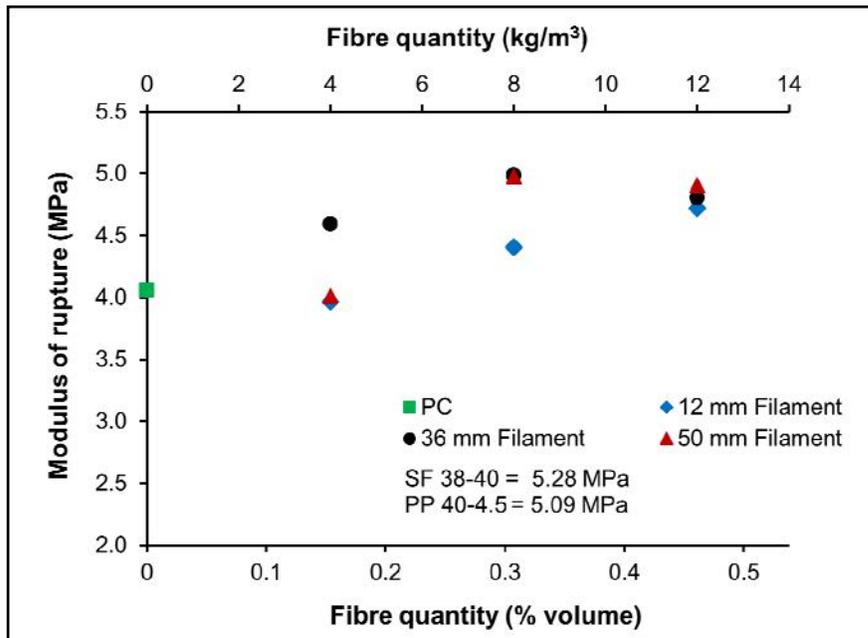
**Figure 5.1: Basalt bundles: Modulus of rupture (MOR)**

### 5.1.2 BASALT FILAMENTS

It can be seen from Figure 5.2, that the MOR of BF 12-4, BF 50-4, and PC are similar, which means that there is no significant increase in mean MOR for these specimens from PC. This is also shown statistically in Table 4.26. The maximum flexural strength is observed for BF 36-8 (4.99 MPa), and BF 50-8 (4.98 MPa).

The increase in mean MOR from PC for BF 36-8, BF 50-8, and BF 50-12 are 23%, 23%, and 21% respectively. Table 4.26 also shows that the above mentioned specimens are similar in flexural strength with PP 40-4.5 (5.09 MPa). None of the basalt filament specimens have flexural strength comparable with SF 38-40 (5.28 MPa).

The study found that short fibres (12 mm) at the high dosage of 12 kg/m<sup>3</sup> provide flexural strength (4.72 MPa) comparable with BF 36-12 (4.8 MPa). The gain in MOR for 36 mm filaments is significant even at 4 kg/m<sup>3</sup>. The optimum fibre dose, for 36 mm, and 50 mm filaments, which provides significant improvement in flexural performance over PC, is 8 kg/m<sup>3</sup>. There is a slight decrease in the flexural strength for 36 mm and 50 mm filaments with the increase in fibre dosage from 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. This might be due to the lumping of long fibres (36 mm and 50 mm) during mixing, at high fibre dosage (12 kg/m<sup>3</sup>).



**Figure 5.2: Basalt filaments: Modulus of rupture (MOR)**

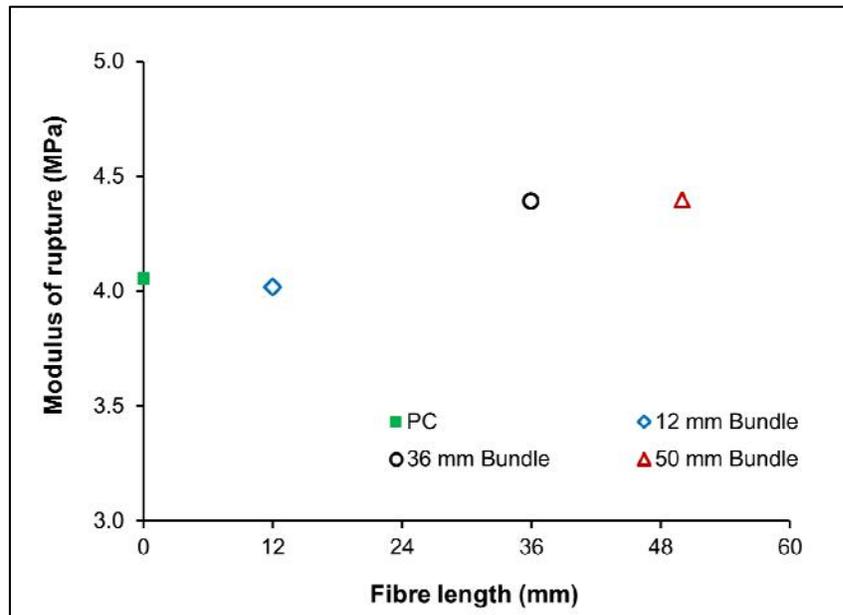
### 5.1.3 EFFECT OF LENGTH

This section provides detailed discussion on the effect of fibre length of basalt bundled fibres and basalt filaments on the flexural strength.

#### 5.1.3.1 FIBRE DOSAGE – 4 kg/m<sup>3</sup>

*Basalt bundles:* Figure 5.3a shows the effect of length of basalt bundled fibres on MOR at 4 kg/m<sup>3</sup>. In general, it was found that the flexural strength increases with the increase in fibre length. It was found that there was no significant improvement in flexural strength for 12 mm basalt bundled specimens over PC. However, 36 mm and 50 mm basalt bundled specimens showed 8.5% improvement in MOR from PC. The gain in MOR for both 36 mm and 50 mm basalt bundles are similar. Hence, the improvement in MOR is obvious when 36 mm long fibre is used. However, no improvement in MOR occurs when the fibre length increases beyond 36 mm.

Independent sample t-test also found that the MOR of 12 mm and PC are statistically similar (Table 4.17). The MOR of 36 mm and 50 mm bundles are also statistically similar (Table 4.18). Hence, both statistical analysis and Figure 5.3a agree well.

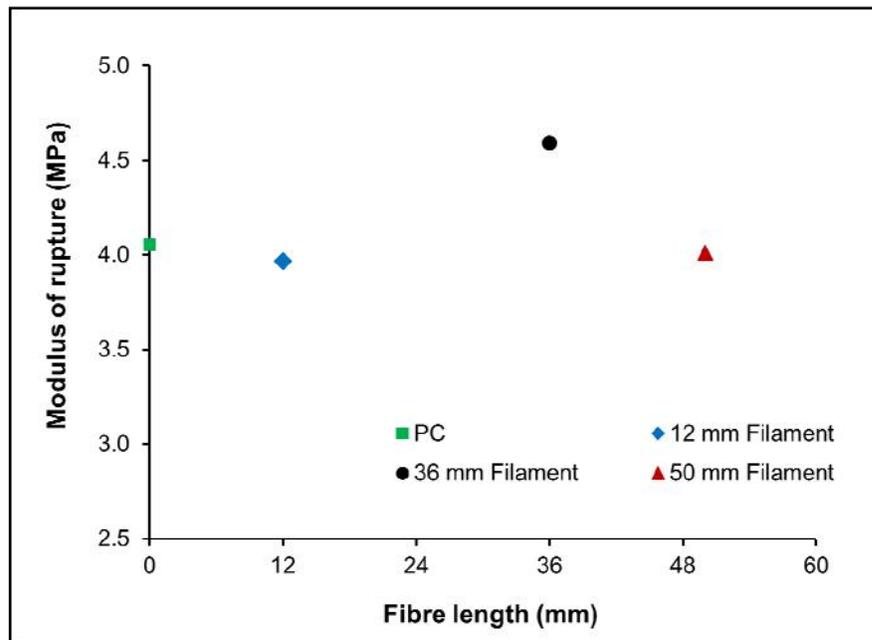


Trend line equation:  $y = 0.0106x + 3.9212$   $R^2 = 0.88$

Figure 5.3a: Basalt bundles: Effect of fibre length at fibre dosage 4 kg/m<sup>3</sup>

*Basalt filaments:* Figure 5.3b shows the effect of length of basalt filaments on MOR at 4 kg/m<sup>3</sup>. It was found that there was no significant improvement in flexural strength for 12 mm and 50 mm basalt filament specimens over PC. Statistical analysis also confirms this (Table 4.26). The improvement in MOR for 50 mm basalt filament over PC is not significant, unlike 50 mm basalt bundled fibre, which requires further research. However, for 36 mm filament specimens, 13% increase in MOR (4.59 MPa) was observed from PC.

Independent sample t-test (Table 4.27) also confirms that the change in MOR with the change in filament length from 12 mm to 36 mm is statistically significant. Further, the change in MOR with the change in filament length from 36 mm to 50 mm is also statistically significant at 90% CI. Hence, both statistical analysis and Figure 5.3b agree well. It can be concluded that the filament length beyond 36 mm reduces the flexural strength.

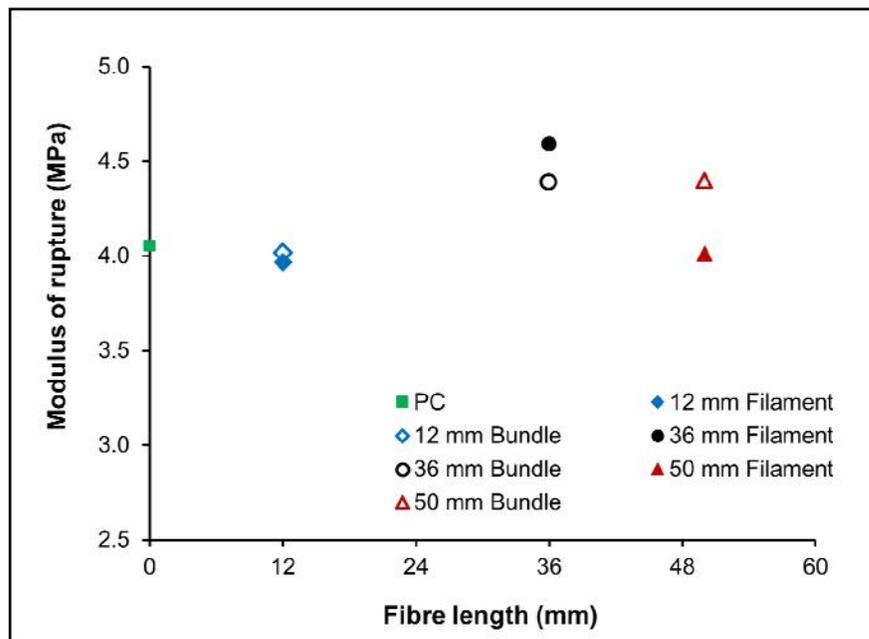


Trend line equation:  $y = -0.0018x^2 + 0.1112x + 2.8867$   $R^2 = 1$

**Figure 5.3b: Basalt filaments: Effect of fibre length at fibre dosage 4 kg/m<sup>3</sup>**

*Basalt bundles vs. filaments:* Figure 5.3c shows the effect of length of basalt bundles and filaments on MOR at fibre dosage of  $4 \text{ kg/m}^3$ . It was found that the flexural performance of basalt bundles and filaments of the same length are similar, except for long fibres (50 mm). The MOR of 50 mm bundled fibre is 9.7% higher than that of 50 mm filaments. The intermediate length (36 mm) fibres, both bundle and filament provide the best flexural performance at  $4 \text{ kg/m}^3$ . Hence, for both 36 mm bundles and filaments, the improvement in MOR from PC is obvious. However, there is no improvement in MOR for 50 mm bundles from 36 mm bundled fibres. Further, for filaments, the MOR decreases with the change in fibre length from 36 mm to 50 mm.

Independent sample t-test (Table 4.35) also confirms that the mean MOR of basalt bundles and filaments of the same length at  $4 \text{ kg/m}^3$  are statistically similar, except for 50 mm long fibres at 90% CI. Hence, both statistical analysis and Figure 5.3c agree well.

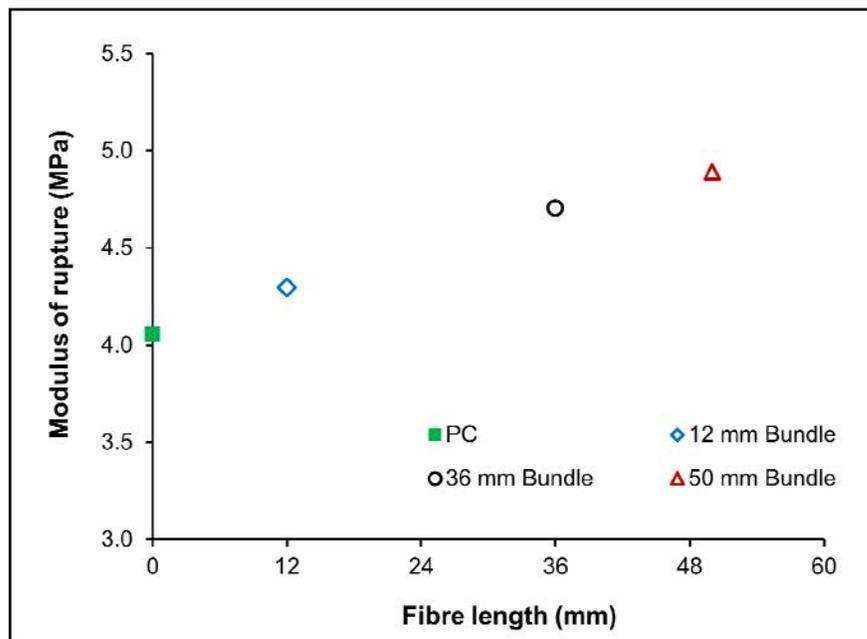


**Figure 5.3c: Effect of fibre length at fibre dosage  $4 \text{ kg/m}^3$**

### 5.1.3.2 FIBRE DOSAGE – 8 kg/m<sup>3</sup>

*Basalt bundles:* Figure 5.4a shows the effect of length of basalt bundled fibres on MOR at 8 kg/m<sup>3</sup>. In general, it can be observed that at 8 kg/m<sup>3</sup>, the flexural strength gradually increases with the increase in bundled fibre length and the trend is almost linear and obvious. For 36 mm and 50 mm bundled fibres, 16% and 20.74% increase in MOR were observed from PC, respectively. The flexural strength of 50 mm bundled fibre (4.89 MPa) is 13.7% higher than that of short bundled fibre (12 mm). Hence, the improvement in MOR is obvious for 36 mm and 50 mm bundled fibres.

Independent sample t-test also found that the MOR of 12 mm and PC are statistically similar (Table 4.17). The MOR of 36 mm and 50 mm bundles are also statistically similar (Table 4.18). Further, the change in MOR with the change in bundled fibre length from 12 mm to 50 mm is statistically significant at 90% CI. However, the change in MOR with the change in bundled fibre length from 12 mm to 36 mm is not statistically significant. Hence, it can be concluded that 50 mm bundled fibres are effective in improving the flexural strength at 8 kg/m<sup>3</sup>.

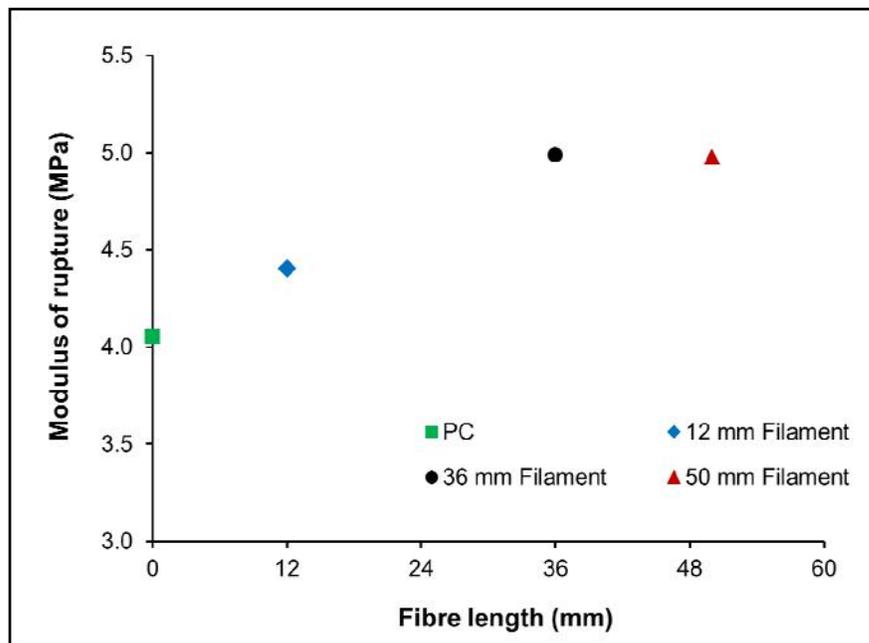


Trend line equation:  $y = 0.0158x + 4.1151$   $R^2 = 1$

**Figure 5.4a: Basalt bundles: Effect of fibre length at fibre dosage 8 kg/m<sup>3</sup>**

*Basalt filaments:* Figure 5.4b shows the effect of length of basalt filaments on MOR at 8 kg/m<sup>3</sup>. It can be observed from Figure 5.4b that the flexural strength increases as the fibre length increases from 12 mm to 36 mm. The MOR is stagnant with the increase in fibre length from 36 mm to 50 mm. This might be due to the lumping of long filaments (50 mm) which was observed during mixing. The peak flexural strength (4.99 MPa) of 36 mm filaments is 23% higher than PC. Hence, the improvement in MOR is obvious when 36 mm long filament is used. However, no improvement in MOR occurs when the fibre length increases beyond 36 mm.

Independent sample t-test (Table 4.27) also confirms that the change in MOR with the change in filament length from 12 mm to 36 mm is statistically significant. However, the change in MOR with the change in filament length from 36 mm to 50 mm is not statistically significant. Hence, both statistical analysis and Figure 5.4b agree well. It can be concluded that the increase in filament length beyond 36 mm does not improve the flexural strength.

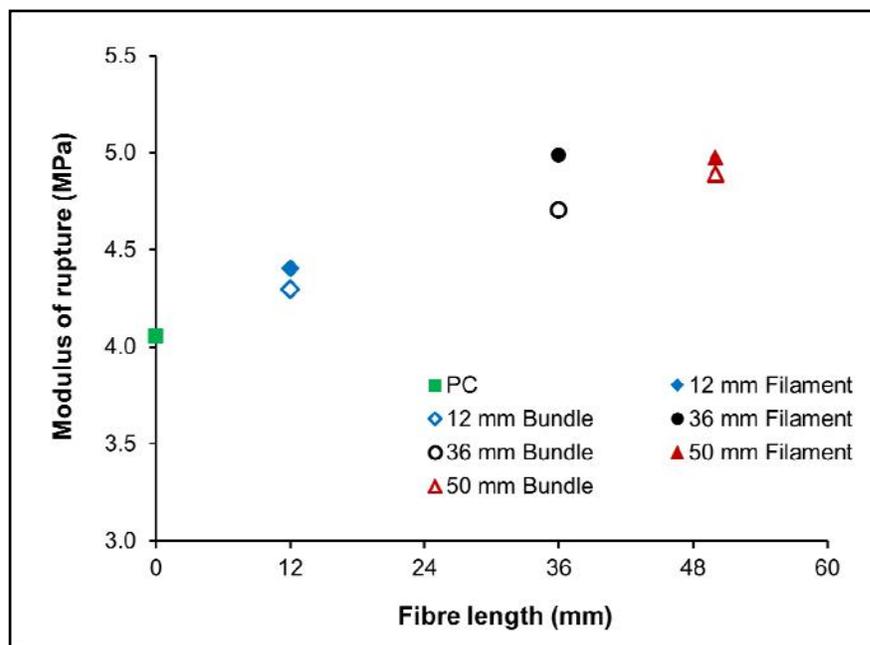


Trend line equation:  $y = 0.0161x + 4.2641$        $R^2 = 0.86$

**Figure 5.4b: Basalt filaments: Effect of fibre length at fibre dosage 8 kg/m<sup>3</sup>**

*Basalt bundles vs. filaments:* Figure 5.4c shows the effect of length of basalt bundles and filaments on MOR at fibre dosage of 8 kg/m<sup>3</sup>. In general, it can be observed that the flexural strength increases with the increase in fibre length for both bundles and filaments. The improvement in MOR is obvious for 50 mm bundled fibre (4.89 MPa). The MOR of 36 mm filament fibre (4.99 MPa) is 6% higher than that of 36 mm bundled fibre (4.70 MPa). Hence, the improvement in MOR is obvious for 36 mm filament and there is no improvement in MOR when the fibre length increases beyond 36 mm.

Independent sample t-test (Table 4.35) also confirms that the mean MOR of basalt bundles and filaments of the same length at 8 kg/m<sup>3</sup> are statistically similar, except for 36 mm fibres. Hence, both statistical analysis and Figure 5.4c agree well.



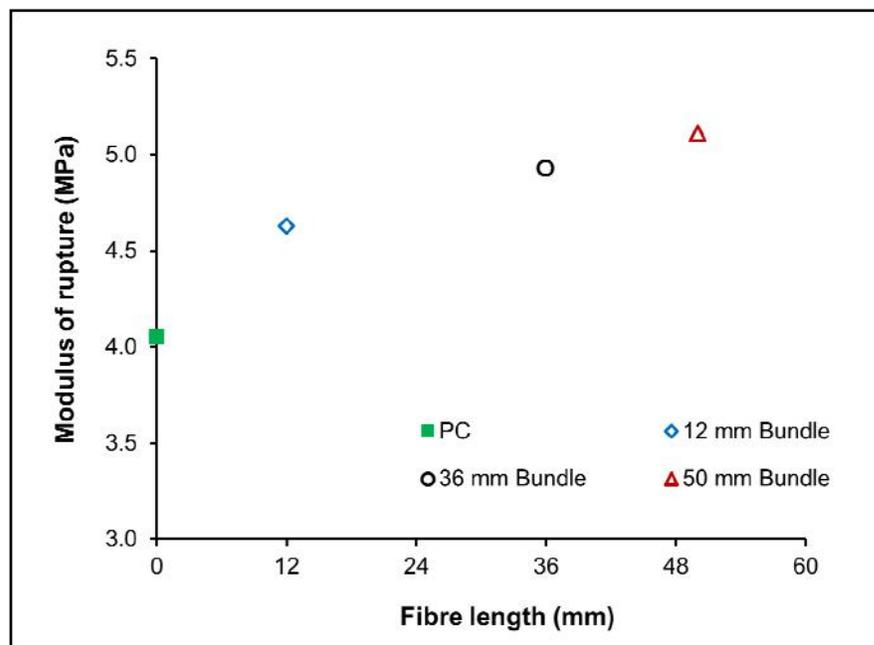
**Figure 5.4c: Effect of fibre length at fibre dosage 8 kg/m<sup>3</sup>**

### 5.1.3.3 FIBRE DOSAGE – 12 kg/m<sup>3</sup>

*Basalt bundles:* Figure 5.5a shows the effect of length of basalt bundled fibres on MOR at 12 kg/m<sup>3</sup>. In general, it can be observed that at 12 kg/m<sup>3</sup>, the flexural strength increases with the increase in fibre length of bundled fibres. If Figure 5.5a is compared with Figure

5.3a, the increasing trend in MOR with the increasing fibre length is more obvious at 12 kg/m<sup>3</sup> than at 4 kg/m<sup>3</sup>. For short (12 mm) bundled fibre, there is a sharp increase in MOR of 14% from PC, after which the increase in flexural strength is gradual with the increasing fibre length. The MOR of long (50 mm) bundled fibre (5.11 MPa) is 26% higher than that of PC. The increase in MOR for 36 mm bundled fibre (4.93 MPa) from PC is 21.7%. Hence, the improvement in MOR from PC is obvious for all three bundled fibres (12 mm, 36 mm, and 50 mm).

Independent sample t-test also found that the MOR of all three bundled fibres (12 mm, 36 mm, and 50 mm) are statistically different from PC (Table 4.17). The MOR of 36 mm and 50 mm bundles are statistically similar (Table 4.18). Further, the change in MOR with the change in bundled fibre length from 12 mm to 50 mm is statistically significant. However, the change in MOR with the change in bundled fibre length from 12 mm to 36 mm is not statistically significant. It can be concluded that all three bundled fibres, especially 50 mm, are effective in improving the flexural strength at 12 kg/m<sup>3</sup>.

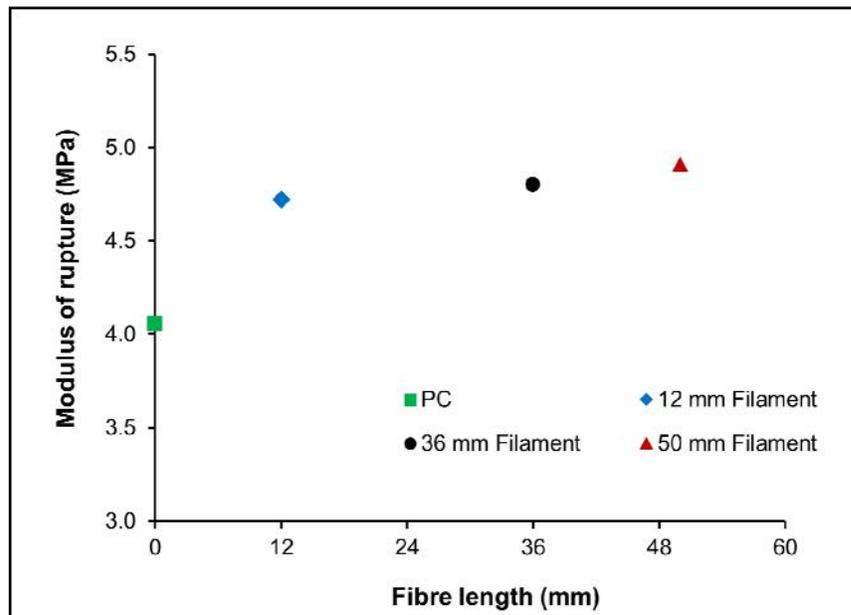


Trend line equation:  $y = 0.0127x + 4.4743$        $R^2 = 0.99$

**Figure 5.5a: Basalt bundles: Effect of fibre length at fibre dosage 12 kg/m<sup>3</sup>**

*Basalt filaments:* Figure 5.5b shows the effect of length of basalt filaments on MOR at 12 kg/m<sup>3</sup>. It can be seen from Figure 5.5b that there is a sharp increase of 16.5% in the flexural strength of short (12 mm) filament (4.72 MPa) from PC. There is no significant increase in MOR from 12 mm to 36 mm or 12 mm to 50 mm.

Independent sample t-test also found that the MOR of all three filaments (12 mm, 36 mm, and 50 mm) are statistically different from PC (Table 4.26). However, the increase in filament fibre length from 12 mm to 36 mm or 12 mm to 50 mm has no significant effect on the flexural strength (Table 4.27). Hence, both statistical analysis and Figure 5.5b agree well.



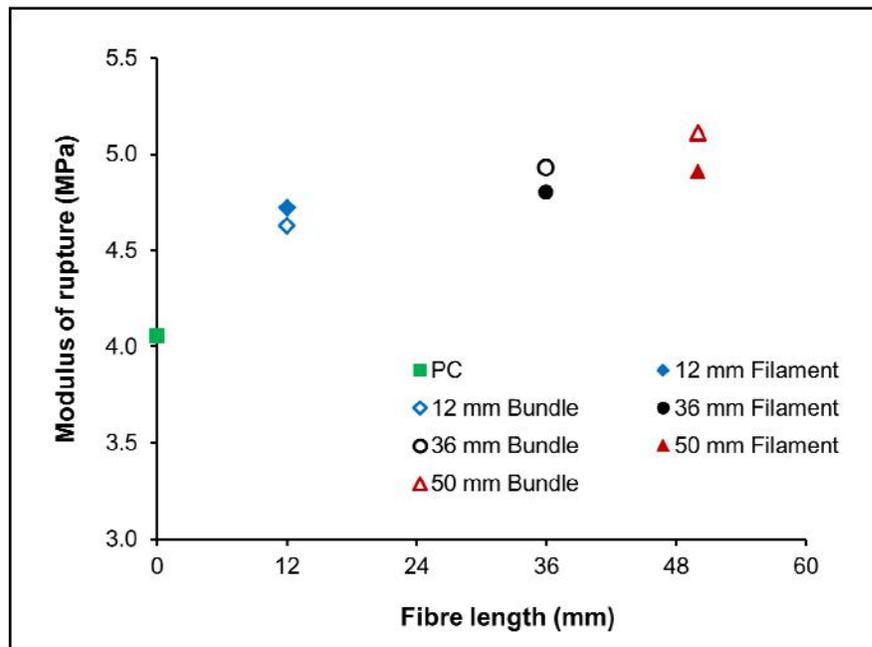
Trend line equation:  $y = 0.0047x + 4.6573$       $R^2 = 0.94$

**Figure 5.5b: Basalt filaments: Effect of fibre length at fibre dosage 12 kg/m<sup>3</sup>**

*Basalt bundles vs. filaments:* Figure 5.5c shows the effect of length of basalt bundles and filaments on MOR at fibre dosage of 12 kg/m<sup>3</sup>. It can be found from Figure 5.5c that the flexural strength of basalt bundles and filaments of the same fibre length are similar. A sharp increase in MOR is observed for both 12 mm bundles and filaments from PC. A nice and clear increasing trend in MOR is observed for both bundles and filaments with

increasing fibre length at  $12 \text{ kg/m}^3$ . The peak MOR of long (50 mm) bundled fibre (5.11 MPa) is 26% higher than that of PC.

Independent sample t-test (Table 4.35) also confirms that the mean MOR of basalt bundles and filaments of the same length at  $12 \text{ kg/m}^3$  are statistically similar. Hence, both statistical analysis and Figure 5.5c agree well.



**Figure 5.5c: Effect of fibre length at fibre dosage  $12 \text{ kg/m}^3$**

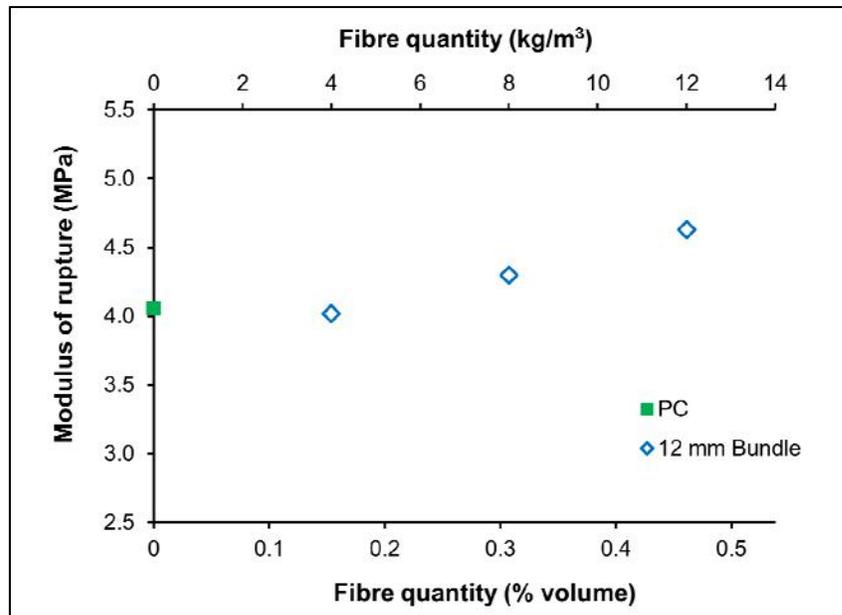
### 5.1.4 EFFECT OF FIBRE QUANTITY

This section provides detailed discussion on the effect of fibre quantity of basalt bundled fibres and filaments on the flexural strength.

#### 5.1.4.1 FIBRE LENGTH – 12 mm

*Basalt bundles:* Figure 5.6a shows the effect of quantity of 12 mm basalt bundled fibre on MOR. In general, it can be observed that the flexural strength of 12 mm basalt bundled fibre increases with an increase in fibre dosage from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. However, the MOR reduces only by 0.03 MPa from PC at 4 kg/m<sup>3</sup> and this reduction is insignificant. The independent sample t-test indicates that this difference is not statistically significant (Table 4.17). The MOR of 12 mm bundled fibre (4.63 MPa) at high fibre dosage of 12 kg/m<sup>3</sup> is 14% higher than PC.

Independent sample t-test (Table 4.19) shows that the change in MOR with the change in fibre quantity from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is not statistically significant. However, the change in MOR with the change in fibre quantity from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is statistically significant. Hence, both statistical analysis and Figure 5.6a agree well.

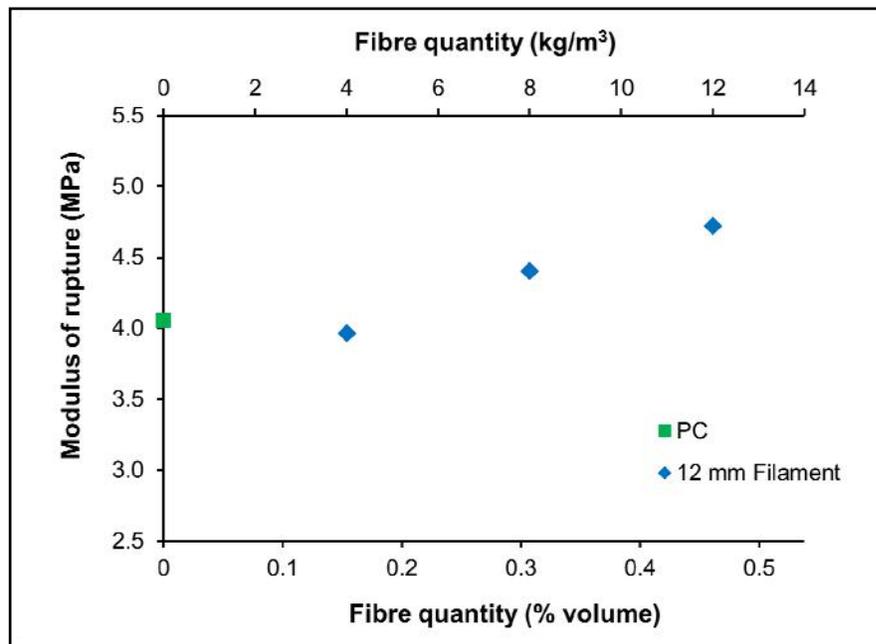


Trend line equation:  $y = 0.0764x + 3.7032$   $R^2 = 1$

**Figure 5.6a: Basalt bundles: Effect of fibre quantity of 12 mm fibres**

*Basalt filaments:* Figure 5.6b shows the effect of quantity of 12 mm basalt filament on MOR. In general, it can be observed that the flexural strength of 12 mm basalt filament increases with the increase in fibre dosage from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> or 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. However, the MOR reduces only by 0.08 MPa from PC at 4 kg/m<sup>3</sup> and this reduction is insignificant. The independent sample t-test also indicates that this difference is not statistically significant (Table 4.26). The MOR of 12 mm filament (4.72 MPa) at high fibre dosage of 12 kg/m<sup>3</sup> is 16.5% higher than PC.

Independent sample t-test (Table 4.28) also confirms that the change in MOR with the change in fibre quantity from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> or 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is statistically significant. Hence, both statistical analysis and Figure 5.6b agree well.



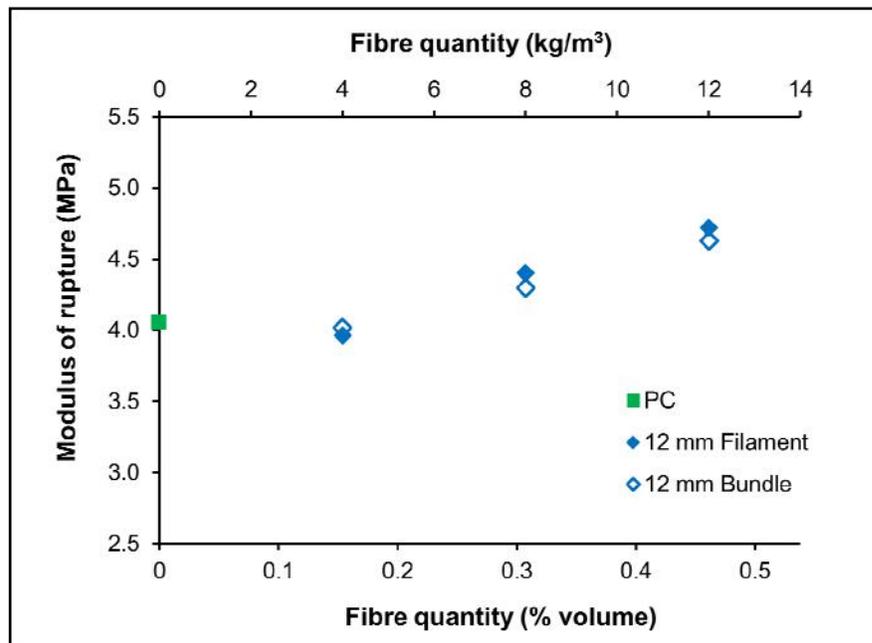
Trend line equation:  $y = 0.0947x + 3.6065$   $R^2 = 1$

**Figure 5.6b: Basalt filaments: Effect of fibre quantity of 12 mm fibres**

*Basalt bundles vs. filaments:* Figure 5.6c shows the effect of quantity of 12 mm basalt bundles and 12 mm filaments on MOR. It can be observed that in general, the MOR increases for both bundles and filaments with the increase in fibre dosage from 4 kg/m<sup>3</sup> to

12 kg/m<sup>3</sup>. However, the change in MOR at 4 kg/m<sup>3</sup> from PC is negligible and this is also confirmed by independent sample t-test (Table 4.17 and Table 4.26).

Independent sample t-test (Table 4.35) also confirms that the flexural performance of 12 mm bundles and filaments of same fibre dosage are statistically similar. Hence, both statistical analysis and Figure 5.6c agree well.

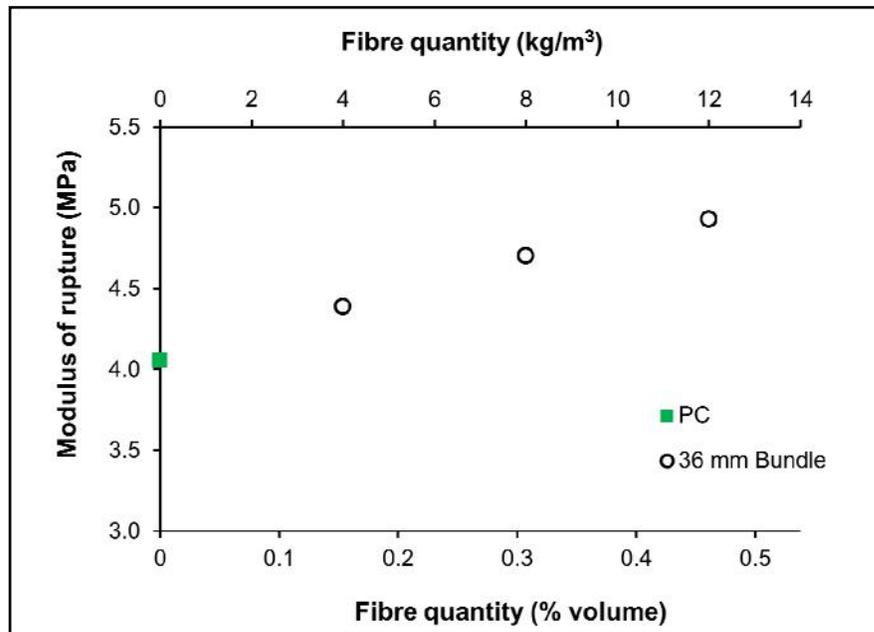


**Figure 5.6c: Effect of fibre quantity of 12 mm basalt fibres**

#### 5.1.4.2 FIBRE LENGTH – 36 mm

*Basalt bundles:* Figure 5.7a shows the effect of quantity of 36 mm basalt bundled fibre on MOR. It was observed that the MOR of 36 mm bundled fibre increases with the increase in fibre quantity and the increasing trend for 36 mm bundled fibre is more obvious than 12 mm bundled fibre (see Figure 5.6a and Figure 5.7a). The peak flexural strength for 36 mm bundled fibre was observed at high fibre dosage of 12 kg/m<sup>3</sup> (4.93 MPa) which is 21.7% higher than that of PC.

Independent sample t-test (Table 4.19) shows that the change in MOR with the change in fibre quantity from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is statistically significant at 90% confidence interval. However, the change in MOR with the change in fibre quantity from 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is not statistically significant at both 90% and 95% confidence intervals.

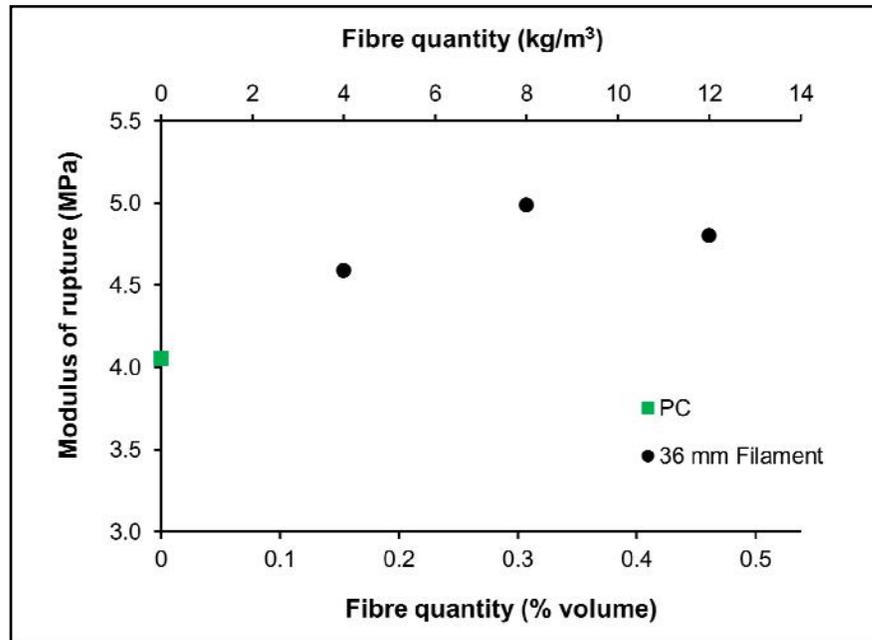


Trend line equation:  $y = 0.0673x + 4.1342$   $R^2 = 1$

**Figure 5.7a: Basalt bundles: Effect of fibre quantity of 36 mm fibres**

*Basalt filaments:* Figure 5.7b shows the effect of quantity of 36 mm basalt filament on MOR. It was observed that for 36 mm filament, the flexural strength increases with the change in fibre quantity from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup>. The flexural strength decreases (4.80 MPa) by 4% with the increase in fibre quantity from 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. This could be due to the lumping of fibres during mixing of 36 mm filaments at high fibre dosage of 12 kg/m<sup>3</sup>. The decrease in flexural strength at 12 kg/m<sup>3</sup> for 36 mm filament was not observed for 12 mm filaments at 12 kg/m<sup>3</sup> (Figure 5.6b). The maximum flexural strength for 36 mm filament was observed at 8 kg/m<sup>3</sup>, and its mean MOR (4.99 MPa) is 23% higher than PC.

Independent sample t-test (Table 4.28) also confirms that the change in MOR with the change in fibre quantity from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> is statistically significant at 90% confidence interval. However, the change in MOR with the change in fibre quantity from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> or 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is not statistically significant. Hence, both statistical analysis and Figure 5.7b agree well.

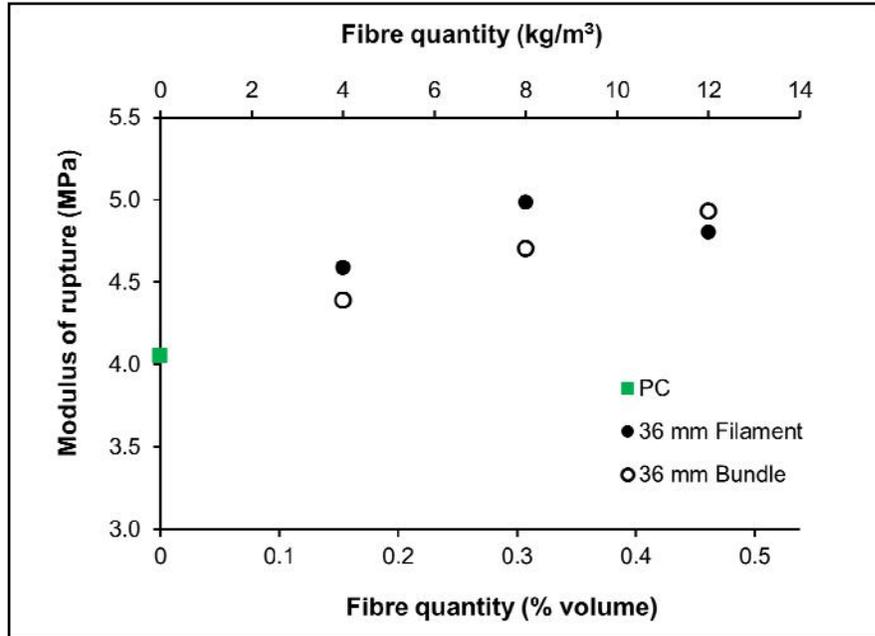


Trend line equation:  $y = -0.0181x^2 + 0.3167x + 3.6148$   $R^2 = 1$

**Figure 5.7b: Basalt filaments: Effect of fibre quantity of 36 mm fibres**

*Basalt bundles vs. filaments:* Figure 5.7c shows the effect of quantity of 36 mm basalt bundles and filaments on MOR. In general, it was found that for 36 mm basalt bundle, the MOR increases with the increase in fibre dosage (up to 8 kg/m<sup>3</sup> or 12 kg/m<sup>3</sup>). For 36 mm filament, the MOR increases with increase in fibre dosage upto 8 kg/m<sup>3</sup> and then there is a slight reduction in MOR (4%) at 12 kg/m<sup>3</sup>. This could be due to lumping of filaments at high fibre dosage (12 kg/m<sup>3</sup>). The basalt bundles even at high fibre dosage of 12 kg/m<sup>3</sup>, dispersed evenly during mixing. At 8 kg/m<sup>3</sup>, the MOR of 36 mm filament (4.99 MPa) is 6% higher than that of 36 mm bundles (4.70 MPa).

Independent sample t-test (Table 4.35) also confirms that the MOR of 36 mm bundles and filaments at the same fibre dosage are statistically similar, except at 8 kg/m<sup>3</sup>. Hence, both statistical analysis and Figure 5.7c agree well.

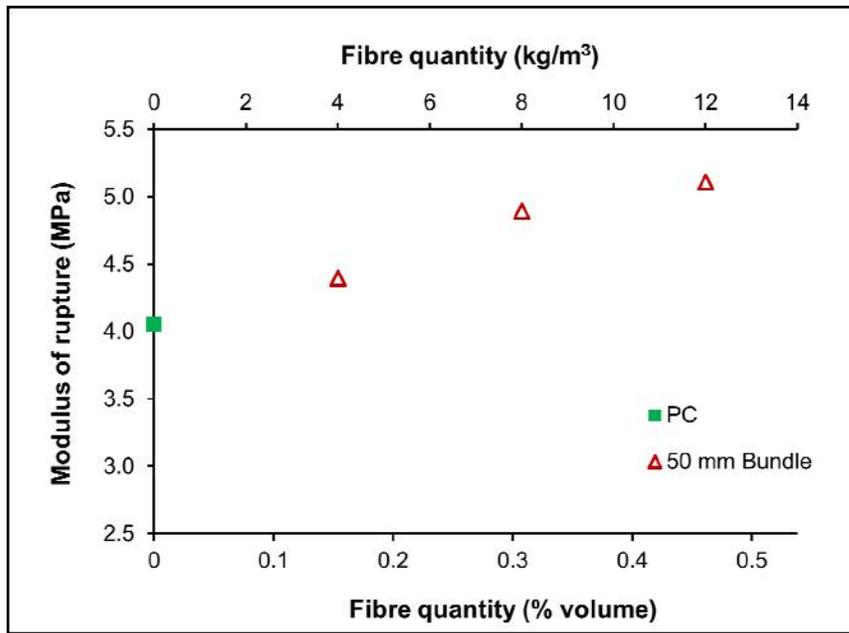


**Figure 5.7c: Effect of fibre quantity of 36 mm basalt fibres**

#### 5.1.4.3 FIBRE LENGTH – 50 mm

*Basalt bundles:* Figure 5.8a shows the effect of quantity of 50 mm basalt bundled fibre on MOR. It was observed that the MOR of 50 mm bundled fibre increases with the increase in fibre quantity and the increasing trend for 50 mm bundled fibre is more obvious than 12 mm bundled fibre (see Figure 5.6a and Figure 5.8a). The peak flexural strength for 50 mm bundled fibre was observed at high fibre dosage of 12 kg/m<sup>3</sup> (5.11 MPa), which is 26% higher than that of PC.

Independent sample t-test (Table 4.19) shows that the change in MOR with the change in fibre quantity from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is statistically significant. However, the change in MOR with the change in fibre quantity from 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is not statistically significant. Hence, both statistical analysis and Figure 5.8a agree well.



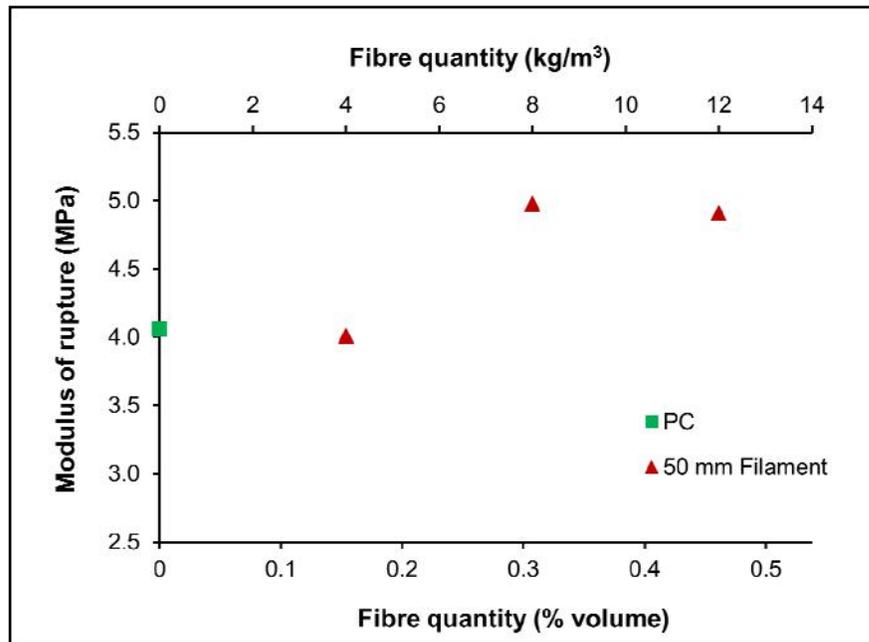
Trend line equation:  $y = 0.0891x + 4.0868$   $R^2 = 0.95$

**Figure 5.8a: Basalt bundles: Effect of fibre quantity of 50 mm fibres**

*Basalt filaments:* Figure 5.8b shows the effect of quantity of 50 mm basalt filament on MOR. It was observed that for 50 mm filament, the flexural strength increases with the change in fibre quantity from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. However, the MOR reduces by 0.04 MPa from PC at 4 kg/m<sup>3</sup>. The independent sample t-test indicates that this difference is not statistically significant (Table 4.26). A slight reduction in flexural strength (1.4%) was observed with the increase in fibre quantity from 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. This could be due to the lumping of fibres during mixing of 50 mm filaments at high fibre dosage of 12 kg/m<sup>3</sup>. The decrease in flexural strength at 12 kg/m<sup>3</sup> for 50 mm filament was not observed for 12 mm filament at 12 kg/m<sup>3</sup> (Figure 5.6b). The maximum flexural strength for 50 mm filament was observed at 8 kg/m<sup>3</sup>, and its mean MOR (4.98 MPa) is 23% higher than PC.

Independent sample t-test (Table 4.28) shows that the change in MOR with the change in fibre quantity from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is statistically significant.

However, the change in MOR with the change in fibre quantity from 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is not statistically significant. Hence, both statistical analysis and Figure 5.8b agree well.



Trend line equation:  $y = -0.0322x^2 + 0.6281x + 2.0165$   $R^2 = 1$

**Figure 5.8b: Basalt filaments: Effect of fibre quantity of 50 mm fibres**

*Basalt bundles vs. filaments:* Figure 5.8c shows the effect of quantity of 50 mm basalt bundles and filaments on MOR. In general, it was found that for 50 mm basalt bundled fibre, the MOR increases with the increase in fibre dosage (up to 8 kg/m<sup>3</sup> or 12 kg/m<sup>3</sup>). For 50 mm filament, the MOR increases with increase in fibre dosage upto 8 kg/m<sup>3</sup> and then there is a slight reduction in MOR (1.4%) at 12 kg/m<sup>3</sup>. This could be due to lumping of filaments at high fibre dosage (12 kg/m<sup>3</sup>). The basalt bundles even at high fibre dosage of 12 kg/m<sup>3</sup> dispersed evenly during mixing. The change in MOR for 50 mm filament at 4 kg/m<sup>3</sup> from PC is negligible and this is also confirmed by independent sample t-test (Table 4.26).

Independent sample t-test (Table 4.35) also confirms that the MOR of 50 mm bundles and filaments at the same fibre dosage are statistically similar, except at 4 kg/m<sup>3</sup>. Hence, both statistical analysis and Figure 5.8c agree well.

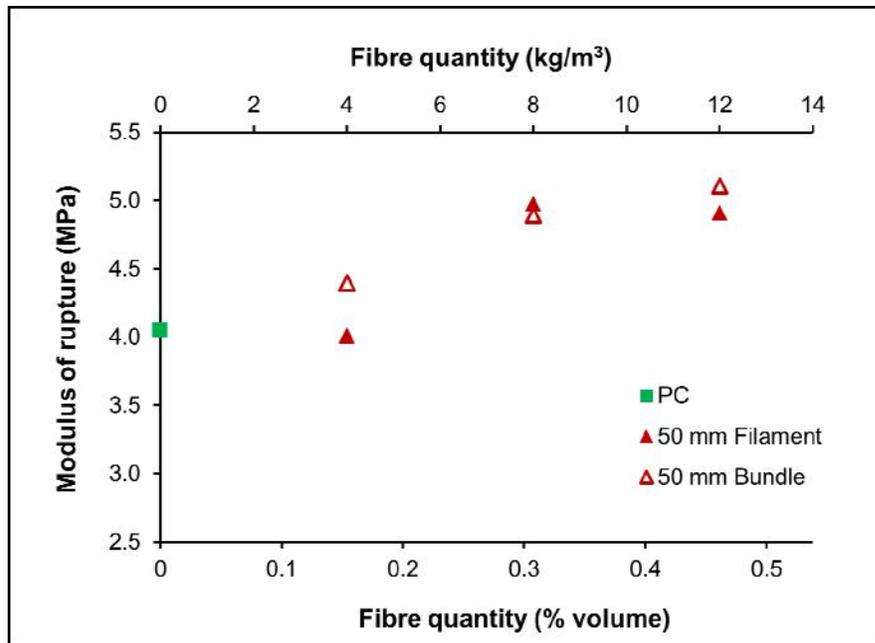


Figure 5.8c: Effect of fibre quantity of 50 mm basalt fibres

### 5.1.5 SUMMARY – FLEXURAL STRENGTH

*Basalt bundles vs. control specimens:* There was no significant improvement in MOR of short (12 mm) bundled fibres at 4 kg/m<sup>3</sup> and 8 kg/m<sup>3</sup> from PC. The medium (36 mm) and long (50 mm) bundled fibres at high fibre dosage of 12 kg/m<sup>3</sup> provide flexural strength similar to SF 38-40 and PP 40-4.5 specimens. The long (50 mm) bundled fibre at 8 kg/m<sup>3</sup> provide flexural strength similar to PP 40-4.5 specimen.

*Basalt bundles: Effect of fibre length and dosage:* The short bundled fibre (12 mm) shows significant improvement (14%) in flexural strength from PC only at high fibre dosage of 12 kg/m<sup>3</sup>. However, the medium length (36 mm) bundled fibre provides 16% and 22% increase in MOR from PC at 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup>, respectively. Similarly, the long (50 mm) bundled fibre shows 21% and 26% increase in the flexural strength from PC at 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup>, respectively. The gain in MOR for 36 mm and 50 mm bundled fibres with the change in fibre quantity from 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is not statistically significant. Hence, the optimum fibre dose for 36 mm and 50 mm bundled fibres which provides significant improvement in flexural performance over PC is 8 kg/m<sup>3</sup>. The results also show that the medium (36 mm) and long (50 mm) bundled fibres are effective in bridging macro-cracks leading to better flexural performance.

*Basalt filaments vs. control specimens:* There was no significant improvement in MOR from PC for short (12 mm) and long (50 mm) filament fibres at 4 kg/m<sup>3</sup>. None of the basalt filament specimens have flexural strength comparable with SF 38-40 specimen. The medium length (36 mm) filament at 8 kg/m<sup>3</sup> and long (50 mm) filament at 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup> are similar in flexural strength with PP 40-4.5 specimen.

*Basalt filaments: Effect of fibre length and dosage:* The short filament fibre (12 mm) shows significant improvement (16.5%) in flexural strength from PC only at high fibre dosage of 12 kg/m<sup>3</sup>. However, the intermediate length (36 mm) filament shows 13% increase in MOR even at low fibre dosage of 4 kg/m<sup>3</sup>. The optimum fibre dose for 36 mm filament which

provides best flexural performance is  $8 \text{ kg/m}^3$  which is 23% higher than that of PC. Long (50 mm) filament at  $8 \text{ kg/m}^3$  provides similar flexural strength as 36 mm filament at  $8 \text{ kg/m}^3$ . Lumping occurs for 36 mm and 50 mm filaments at high fibre dosage of  $12 \text{ kg/m}^3$  which causes slight reduction (2% to 4%) in flexural strength.

*Basalt bundles vs. filaments:* The flexural performance of 12 mm bundle and 12 mm filament are similar at all fibre dosages. The flexural performance of 36 mm bundle and 36 mm filament are similar at  $4 \text{ kg/m}^3$  and  $12 \text{ kg/m}^3$ . At  $8 \text{ kg/m}^3$ , the MOR of 36 mm filament is 6% higher than that of 36 mm bundles. The flexural performance of the 50 mm bundle and 50 mm filament are similar at all fibre dosages, except at  $4 \text{ kg/m}^3$ .

## **5.2 COMPRESSIVE STRENGTH – 28 DAY**

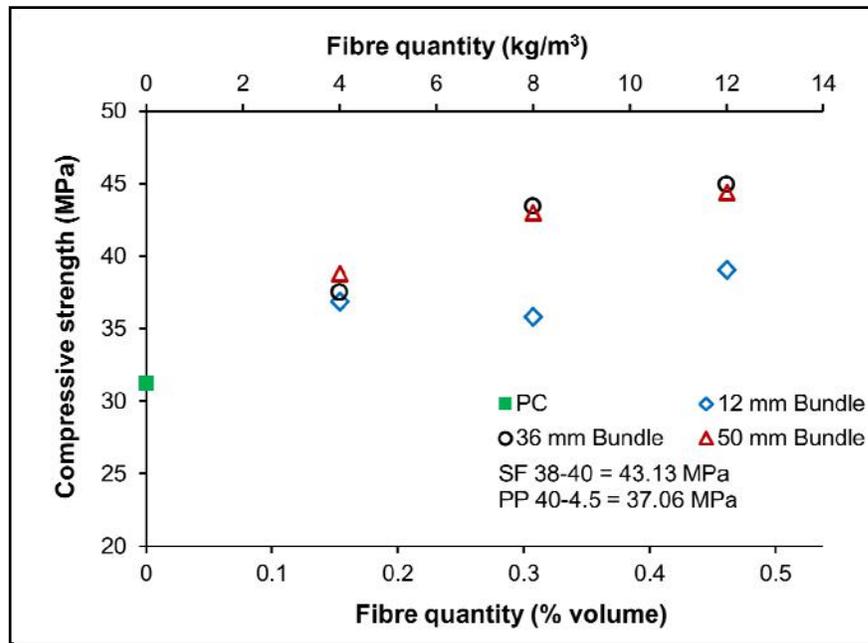
Statistical analysis of 28 day compressive strength results were discussed in Chapter 4. These are further analyzed in this section to determine the optimum fibre length and dosage which will provide the best compressive strength. The 7 day compressive strength test results of basalt bundles and filaments are shown in Appendix C. However, these were not further analyzed as the trend was not clear.

### **5.2.1 BASALT BUNDLES**

Figure 5.9 shows the mean compressive strength of basalt bundle specimens and PC. It was observed that the mean compressive strength of PC was 38% lower than SF 38-40 and 18.7% lower than PP 40-4.5.

There was significant improvement in compressive strength between PC and all the basalt bundle specimens. The average compressive strength of 36 mm and 50 mm bundled fibres at high fibre dosages ( $8 \text{ kg/m}^3$  and  $12 \text{ kg/m}^3$ ) are comparable with SF 38-40 and the remaining basalt bundle specimens are similar in compressive strength with PP 40-4.5. The increase in compressive strength from PC to BB 36-8, BB 36-12, BB 50-8, and BB 50-12 are 39%, 44%, 37.8%, and 42%, respectively. Similar results were obtained through statistical analysis (Table 4.20).

In general, 36 mm and 50 mm bundled fibres provide significant improvement in compressive strength with an increase in fibre dosage from  $4 \text{ kg/m}^3$  to  $8 \text{ kg/m}^3$  or  $4 \text{ kg/m}^3$  to  $12 \text{ kg/m}^3$ . The study found that the short bundled fibres (12 mm) at all dosages ( $4 \text{ kg/m}^3$ ,  $8 \text{ kg/m}^3$ , and  $12 \text{ kg/m}^3$ ), and 36 mm and 50 mm bundled fibres at low fibre dosage ( $4 \text{ kg/m}^3$ ) provide similar compressive strength as PP 40-4.5 (37.06 MPa). The medium length (36 mm) and long (50 mm) bundled fibres at  $8 \text{ kg/m}^3$  and  $12 \text{ kg/m}^3$  provide compressive strength similar to SF 38-40 (43.13 MPa).



**Figure 5.9: Basalt bundles - 28 day Compressive strength**

### 5.2.2 BASALT FILAMENTS

Figure 5.10 shows the mean compressive strength of basalt filament specimens and PC. The 28 day compressive strength of all filament specimens (12 mm, 36 mm, and 50mm) are higher than that of PC. Long filament fibre (50 mm) at high dosage of 12 kg/m<sup>3</sup> provided a compressive strength (41.05 MPa) similar to SF 38-40 (43.13 MPa) and it is 31.5% higher than PC. All remaining basalt filament specimens provided compressive strengths similar to PP 40-4.5 (37.06 MPa). Table 4.29 shows that the long filaments (50 mm) at high dosage of 12 kg/m<sup>3</sup> provide compressive strength similar to SF 38-40, while all other filament specimens are statistically similar to PP 40-4.5.

The study found that for 36 mm filaments, there was slight reduction (4%) in compressive strength with the change in fibre dosage from 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. This might be because of lumping of 36 mm filament fibres at high fibre dosage of 12 kg/m<sup>3</sup> during mixing. This trend was not observed for 50 mm filament fibres. In order to maintain the workability of the mix for long filaments (50 mm) at high fibre dosage (12 kg/m<sup>3</sup>), Rheobuild 1000

superplasticizer (55 ml) was added. The superplasticizer could have helped in the uniform distribution of filaments in the matrix. This might be the reason for higher compressive strength for 50 mm filament when compared to 12 mm and 36 mm filaments at 12 kg/m<sup>3</sup>.

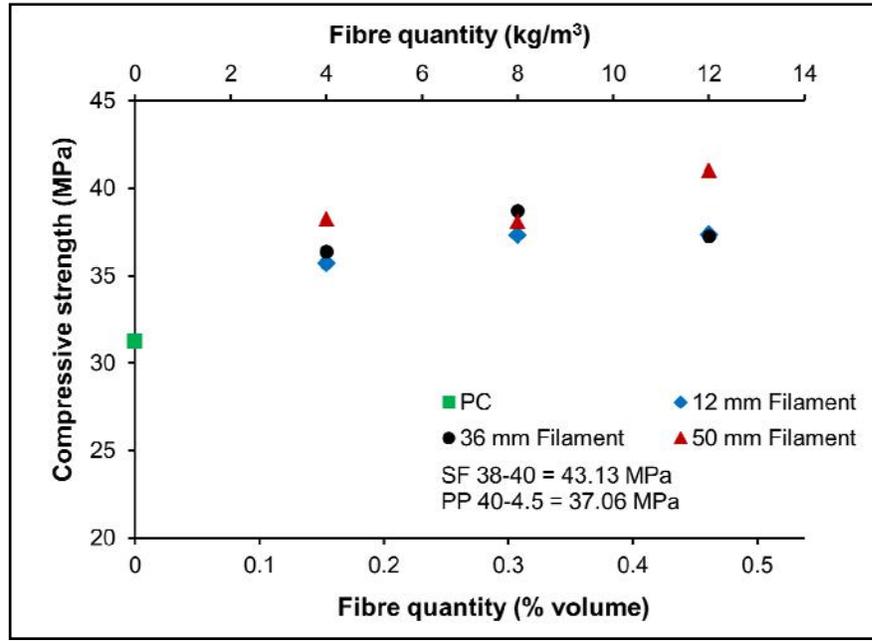


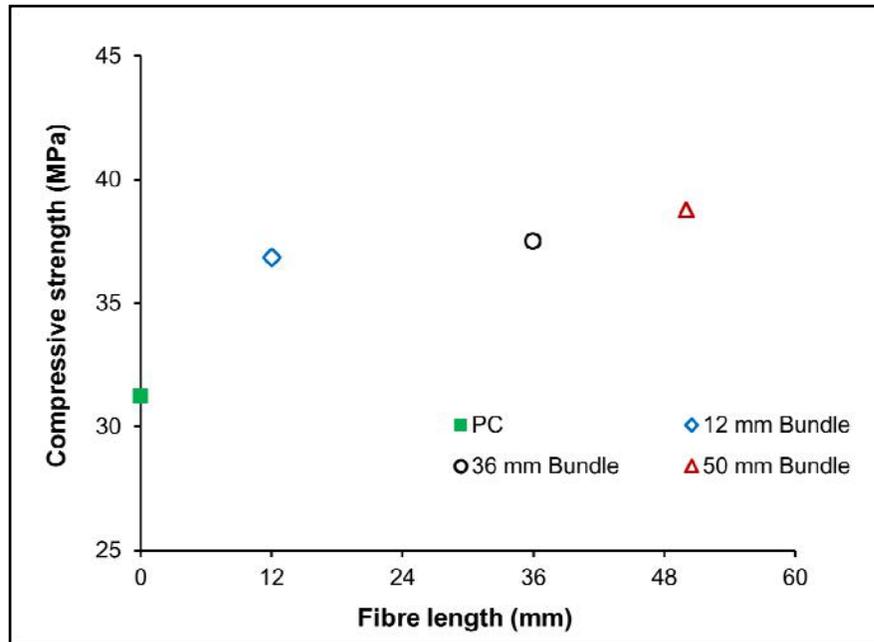
Figure 5.10: Basalt filaments - 28 day Compressive strength

## 5.2.3 EFFECT OF LENGTH

### 5.2.3.1 FIBRE DOSAGE – 4 kg/m<sup>3</sup>

*Basalt bundles:* Figure 5.11a shows the effect of length of basalt bundled fibres on 28 day compressive strength at 4 kg/m<sup>3</sup>. In general, it was found that the 28 day compressive strength of all basalt bundled fibres (12 mm, 36 mm and 50 mm) at 4 kg/m<sup>3</sup> are higher than that of PC. A sharp increase (18%) in the mean compressive strength (36.85 MPa) was observed for short bundled fibre (12 mm) from PC. This is similar to the mean compressive strength of PP 40-4.5 (37.06 MPa). For 36 mm bundled fibre, no significant increase in the compressive strength from that of 12 mm bundled fibre was observed. However, the compressive strength of 50 mm bundled fibre (38.78 MPa) is 24% higher than that of PC and 5% higher than that of 12 mm bundled fibre.

Independent sample t-test also confirms that the 28 day compressive strength of all three bundled fibres (12 mm, 36 mm, and 50 mm) are statistically different from PC (Table 4.20). The increase in fibre length from 12 mm to 36 mm or 36 mm to 50 mm is not statistically significant. However, the increase in fibre length from 12 mm to 50 mm is statistically significant at 90% CI (Table 4.21). Hence, both statistical analysis and Figure 5.11a agree well.

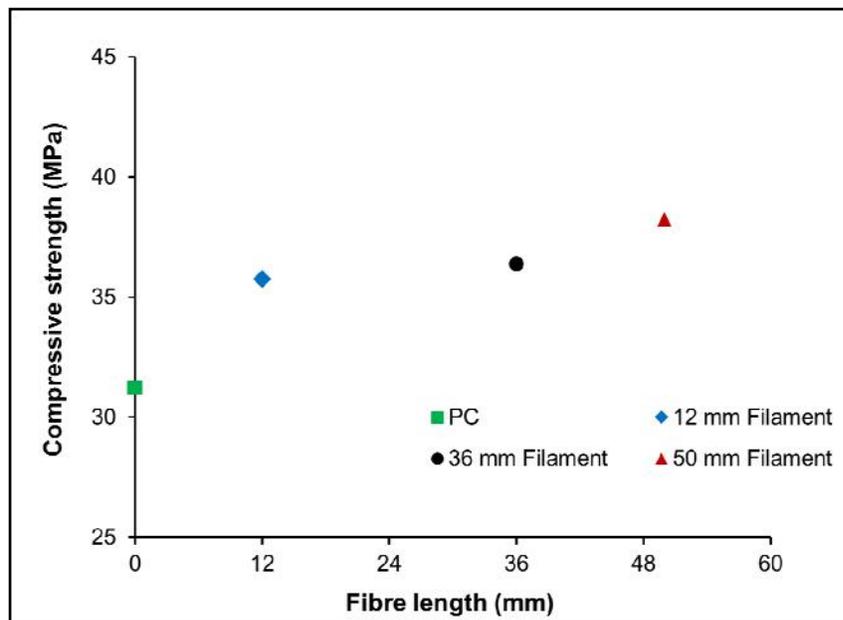


Trend line equation:  $y = 0.0482x + 36.131$   $R^2 = 0.89$

**Figure 5.11a: Basalt bundles: Effect of fibre length at fibre dosage 4 kg/m<sup>3</sup>**

*Basalt filaments:* Figure 5.11b shows the effect of length of basalt filaments on 28 day compressive strength at 4 kg/m<sup>3</sup>. In general, it can be found that the 28 day compressive strength of all basalt filaments (12 mm, 36 mm and 50 mm) at 4 kg/m<sup>3</sup> are higher than that of PC. A sharp increase (14.5%) in the mean compressive strength (35.74 MPa) was observed for short filaments (12 mm) from PC. However, for 36 mm and 50 mm filaments, no significant increase in the compressive strength from that of 12 mm filament was observed.

Independent sample t-test (Table 4.29) shows that the compressive strength of 12 mm and 50 mm filaments are statistically different from PC. However, the compressive strength of 36 mm filament (36.38 MPa) is statistically similar to PC (31.21 MPa). This could be because of high standard deviation (4.01) observed for BF 36-4 (see one-sample t-test Table 4.9). However, Figure 5.11b shows that there is improvement in compressive strength from PC to 36 mm filament. The independent sample t-tests from Table 4.30 also indicate that the compressive strength of 36 mm filament (36.38 MPa) is statistically similar to that of 12 mm (35.74 MPa) and 50 mm (38.23 MPa) filaments. The change in fibre length from 12 mm to 36 mm or 12 mm to 50 mm or 36 mm to 50 mm at 4 kg/m<sup>3</sup> has no statistical influence on the compressive strength. Hence, it can be concluded that the effect of 36 mm filament on compressive strength is similar to that of 12 mm and 50 mm filaments.



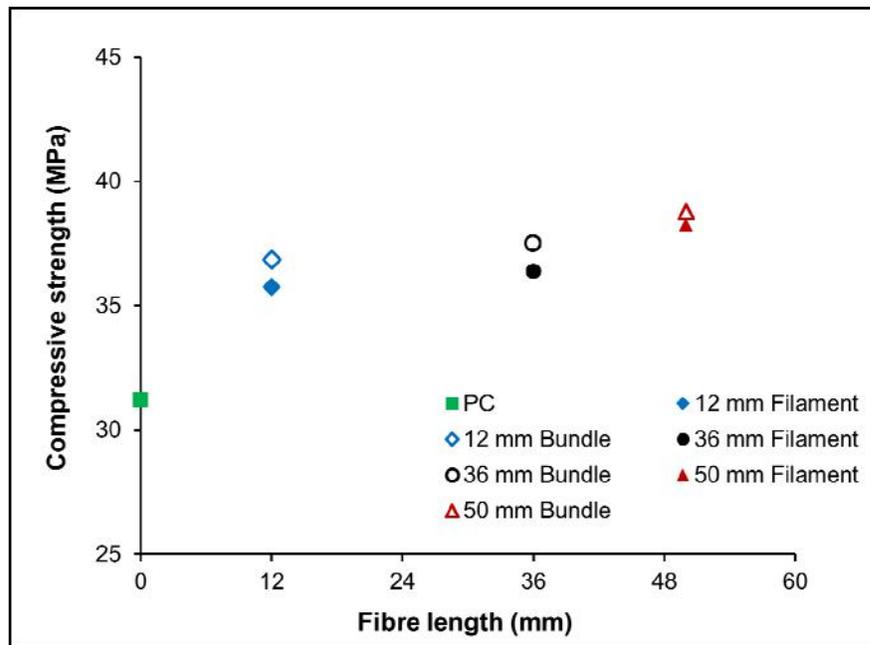
Trend line equation:  $y = 0.0613x + 34.783$   $R^2 = 0.82$

**Figure 5.11b: Basalt filaments: Effect of fibre length at fibre dosage 4 kg/m<sup>3</sup>**

*Basalt bundles vs. filaments:* Figure 5.11c shows the effect of length of basalt bundles and filaments on 28 day compressive strength at 4 kg/m<sup>3</sup>. A sharp increase in the compressive strength is observed for both 12 mm bundles and filaments from PC. It can be seen from

Figure 5.11c that the compressive strength of basalt bundles and filaments of the same fibre length are similar.

Independent sample t-test (Table 4.36) also confirms that the mean compressive strength of basalt bundles and filaments of the same length at  $4 \text{ kg/m}^3$  are statistically similar. Hence, both statistical analysis and Figure 5.11c agree well.



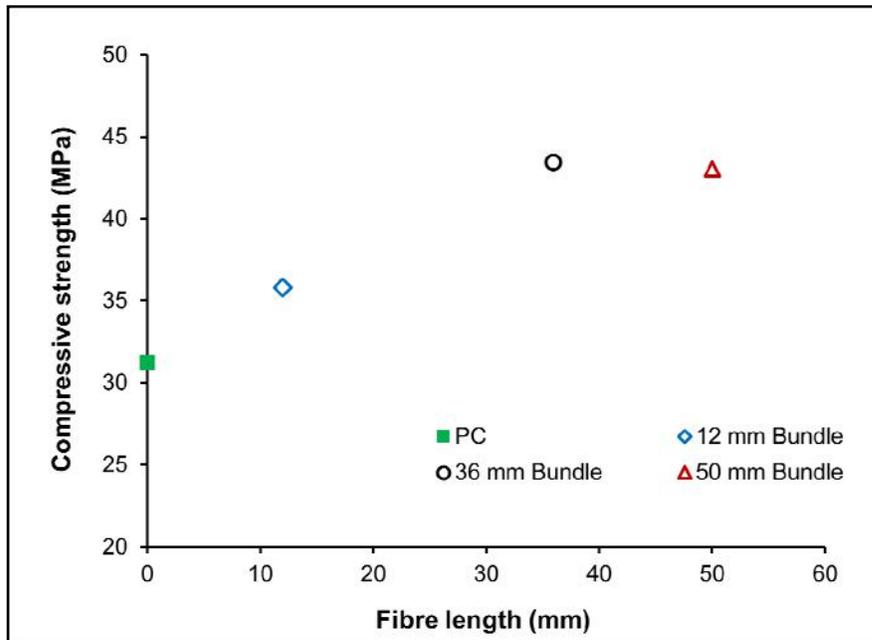
**Figure 5.11c: Effect of fibre length at fibre dosage  $4 \text{ kg/m}^3$**

### 5.2.3.2 FIBRE DOSAGE – $8 \text{ kg/m}^3$

*Basalt bundles:* Figure 5.12a shows the effect of length of basalt bundled fibres on 28 day compressive strength at  $8 \text{ kg/m}^3$ . In general, it was found that all basalt bundled fibres (12 mm, 36 mm, and 50 mm) at  $8 \text{ kg/m}^3$  fibre dosage, provide significantly higher compressive strength than PC. It was observed that the compressive strength of short bundled fibre (12 mm) at this fibre dosage (35.81 MPa) is 14.7% higher than PC. There was 21% increase in the compressive strength with the change in fibre length from 12 mm to 36 mm or 12 mm to 50 mm. If Figure 5.12a is compared with Figure 5.11a, the increasing trend in compressive strength with the increasing fibre length is more obvious at  $8 \text{ kg/m}^3$

than at 4 kg/m<sup>3</sup>. The peak compressive strength at 8 kg/m<sup>3</sup> was observed for 36 mm bundled fibre (43.42 MPa) which is similar to that of long (50 mm) bundled fibre (43.01 MPa). The compressive strength of PC is 39% lower than that of 36 mm and 50 mm bundled fibre specimens at 8 kg/m<sup>3</sup>.

Independent sample t-test also confirms that the 28 day compressive strength of all three bundled fibres (12 mm, 36 mm, and 50 mm) are statistically different from PC (Table 4.20). The increase in fibre length from 12 mm to 36 mm or 12 mm to 50 mm is statistically significant. However, the increase in fibre length from 36 mm to 50 mm is not statistically significant (Table 4.21). Hence, both statistical analysis and Figure 5.12a agree well.



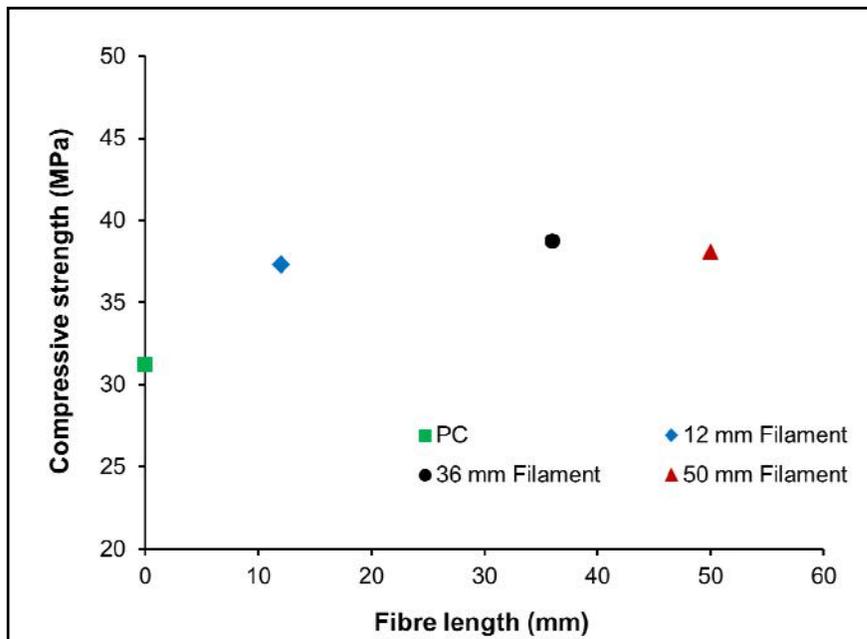
Trend line equation:  $y = 0.2034x + 34.104$       $R^2 = 0.83$

**Figure 5.12a: Basalt bundles: Effect of fibre length at fibre dosage 8 kg/m<sup>3</sup>**

*Basalt filaments:* Figure 5.12b shows the effect of length of basalt filaments on 28 day compressive strength at 8 kg/m<sup>3</sup>. A sharp increase (19.6%) in the mean compressive strength (37.33 MPa) was observed for short filaments (12 mm) from PC. However, for

36 mm and 50 mm filaments, no significant increase in the compressive strength from that of 12 mm filament was observed. This could be because of lumping of filaments during mixing at 8 kg/m<sup>3</sup>.

Independent sample t-test also found that the 28 day compressive strength of all three filaments (12 mm, 36 mm, and 50 mm) are statistically different from PC (Table 4.29). However, the increase in filament fibre length from 12 mm to 36 mm or 12 mm to 50 mm or 36 mm to 50 mm has no significant effect on the compressive strength (Table 4.30). Hence, both statistical analysis and Figure 5.12b agree well.



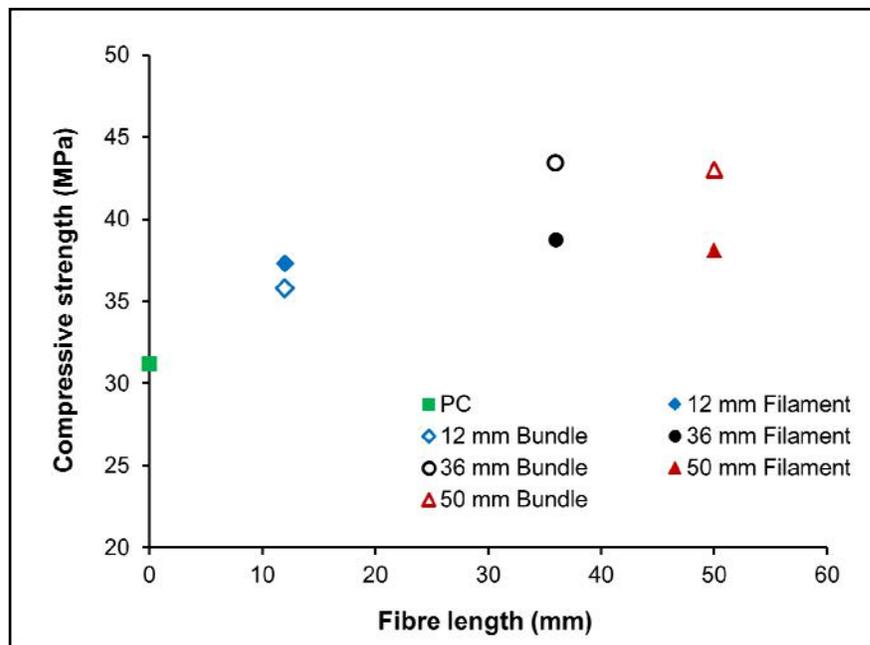
Trend line equation:  $y = -0.0027x^2 + 0.1876x + 35.467$       $R^2 = 1$

**Figure 5.12b: Basalt filaments: Effect of fibre length at fibre dosage 8 kg/m<sup>3</sup>**

*Basalt bundles vs. filaments:* Figure 5.12c shows the effect of length of basalt bundles and filaments on 28 day compressive strength at 8 kg/m<sup>3</sup>. In general, it was found that for basalt bundles, the compressive strength increases with the change in fibre length from 12 mm to 36 mm or 12 mm to 50 mm. However, for basalt filaments, the change in fibre length from

12 mm to 36 mm or 12 mm to 50 mm has no significant influence on the compressive strength. This could be due to the lumping of filaments (36 mm or 50 mm) at 8 kg/m<sup>3</sup>. The 36 mm and 50 mm bundles dispersed uniformly at 8 kg/m<sup>3</sup> which has resulted in higher compressive strength than filaments. The compressive strength of 36 mm and 50 mm filaments are 12% to 13% lower than that of the corresponding bundle specimens.

Independent sample t-test (Table 4.36) also confirms that the 28 day compressive strength of bundles and filaments are statistically different for 36 mm (90% and 95% CIs) and 50 mm (90% CI) fibres. However, the compressive strength of bundles and filaments are statistically similar for 12 mm fibres. Hence, both statistical analysis and Figure 5.12c agree well.



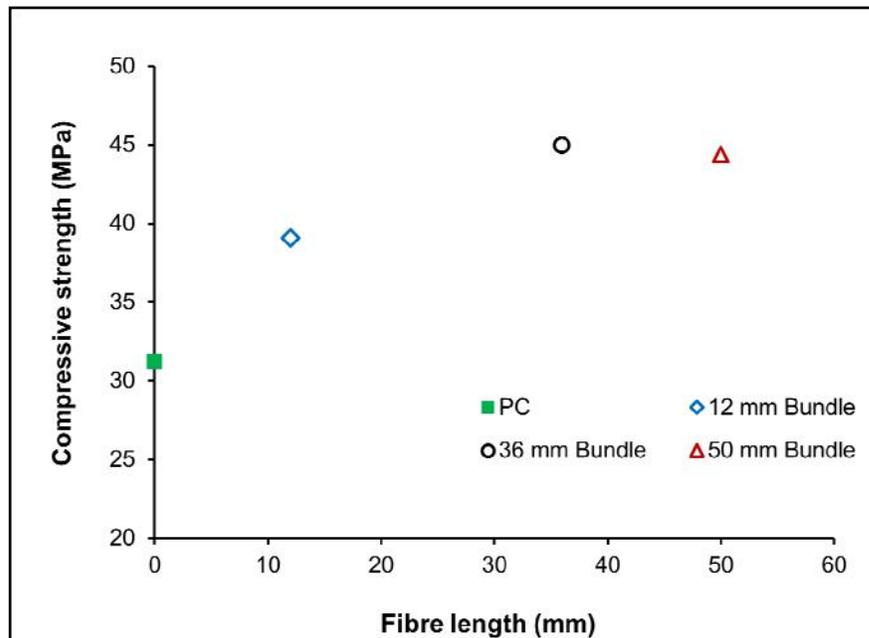
**Figure 5.12c: Effect of fibre length at fibre dosage 8 kg/m<sup>3</sup>**

### 5.2.3.3 FIBRE DOSAGE – 12 kg/m<sup>3</sup>

*Basalt bundles:* Figure 5.13a shows the effect of length of basalt bundled fibres on 28 day compressive strength at 12 kg/m<sup>3</sup>. In general, it was found that all basalt bundled fibres (12 mm, 36 mm, and 50 mm) at 12 kg/m<sup>3</sup> fibre dosage, provide significantly higher

compressive strength than PC. It was observed that the compressive strength of short bundled fibre (12 mm) at this fibre dosage (39.06 MPa) is 25% higher than PC. There was 15% increase in the compressive strength with the change in fibre length from 12 mm to 36 mm or 12 mm to 50 mm. If Figure 5.13a is compared with Figure 5.11a, the increasing trend in compressive strength with the increasing fibre length is more obvious at 12 kg/m<sup>3</sup> than at 4 kg/m<sup>3</sup>. The peak compressive strength at 12 kg/m<sup>3</sup> was observed for 36 mm bundled fibre (44.95 MPa) which is similar to that of 50 mm fibre (44.40 MPa). The compressive strength of PC is 43% lower than that of 36 mm and 50 mm bundled fibre specimens at 12 kg/m<sup>3</sup>.

Independent sample t-test also confirms that the 28 day compressive strength of all three bundled fibres (12 mm, 36 mm, and 50 mm) are statistically different from PC (Table 4.20). The increase in fibre length from 12 mm to 36 mm or 12 mm to 50 mm is statistically significant. However, the increase in fibre length from 36 mm to 50 mm is not statistically significant (Table 4.21). Hence, both statistical analysis and Figure 5.13a agree well.

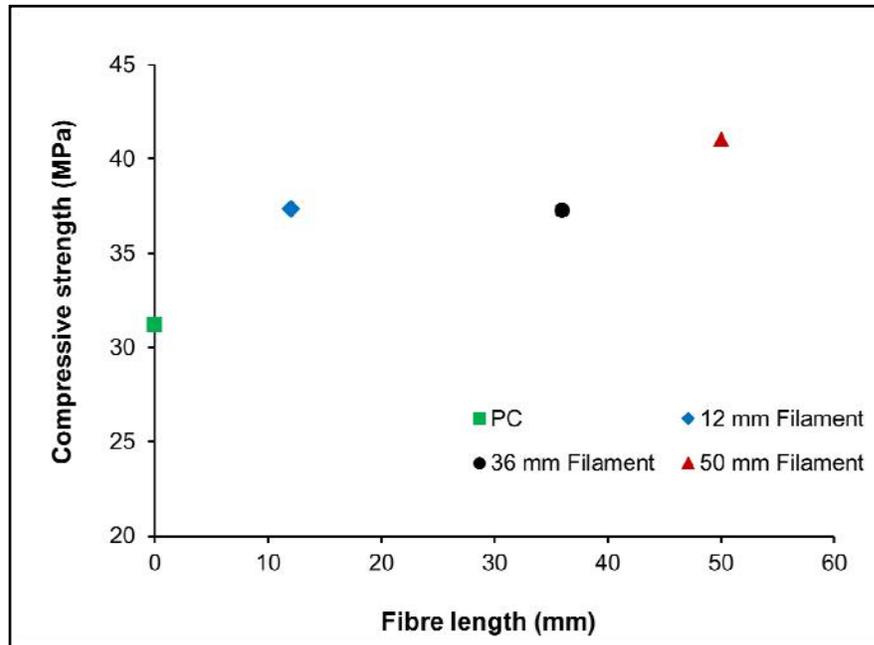


Trend line equation:  $y = 0.1518x + 37.843$       $R^2 = 0.80$

**Figure 5.13a: Basalt bundles: Effect of fibre length at fibre dosage 12 kg/m<sup>3</sup>**

*Basalt filaments:* Figure 5.13b shows the effect of length of basalt filaments on 28 day compressive strength at  $12 \text{ kg/m}^3$ . A sharp increase in compressive strength (20%) was observed for 12 mm filament from PC. It was found that there was no gain in the compressive strength with the change in filament fibre length from 12 mm to 36 mm. This might be due to lumping of 36 mm filaments during mixing. Hence, the 36 mm filament mix was repeated. However, repeated test data also indicated similar results. Further, there was 10% increase in compressive strength for 50 mm filament (41.05 MPa) from that of 12 mm filament (37.36 MPa). In order to maintain the workability of the mix for long filaments (50 mm) at high fibre dosage ( $12 \text{ kg/m}^3$ ), Rheobuild 1000 superplasticizer (55 ml) was added. The superplasticizer could have helped in the uniform distribution of filaments in the matrix. This might be the reason for higher compressive strength for 50 mm filament when compared to 12 mm and 36 mm filaments at  $12 \text{ kg/m}^3$ .

Independent sample t-test also found that the 28 day compressive strength of all three filaments (12 mm, 36 mm, and 50 mm) are statistically different from PC (Table 4.29). However, the increase in filament fibre length from 12 mm to 36 mm has no significant effect on the compressive strength. The increase in filament fibre length from 12 mm to 50 mm or 36 mm to 50 mm has significant effect on the compressive strength (Table 4.30). Hence, both statistical analysis and Figure 5.13b agree well.



Trend line equation:  $y = 0.0073x^2 - 0.3532x + 40.553$   $R^2 = 1$

**Figure 5.13b: Basalt filaments: Effect of fibre length at fibre dosage 12 kg/m<sup>3</sup>**

*Basalt bundles vs. filaments:* Figure 5.13c shows the effect of length of basalt bundles and filaments on 28 day compressive strength at 12 kg/m<sup>3</sup>. In general, for bundled fibres, the compressive strength increases with the change in fibre length from 12 mm to 36 mm or 12 mm to 50 mm. However, the same trend was not observed for basalt filaments. It was found that the compressive strength of 36 mm filament was 20.7% lower than that of 36 mm bundled fibre. This could be due to the lumping of filaments at high fibre dosage (12 kg/m<sup>3</sup>). However, 50 mm filament exhibited higher compressive strength than that of 12 mm (or 36 mm) filaments. This could be due to the addition of superplasticizer which might have helped in improving the dispersion of filaments in the concrete mix. It was observed that the basalt bundles (36 mm or 50 mm) even at high fibre dosage of 12 kg/m<sup>3</sup>, dispersed evenly without the addition of superplasticizer during mixing.

Independent sample t-test (Table 4.36) shows that the 28 day compressive strength of bundles and filaments are statistically different for 12 mm (90% CI) and 36 mm (90% and

95% CIs) fibres. However, the compressive strength of bundles and filaments are statistically similar for 50 mm fibres.

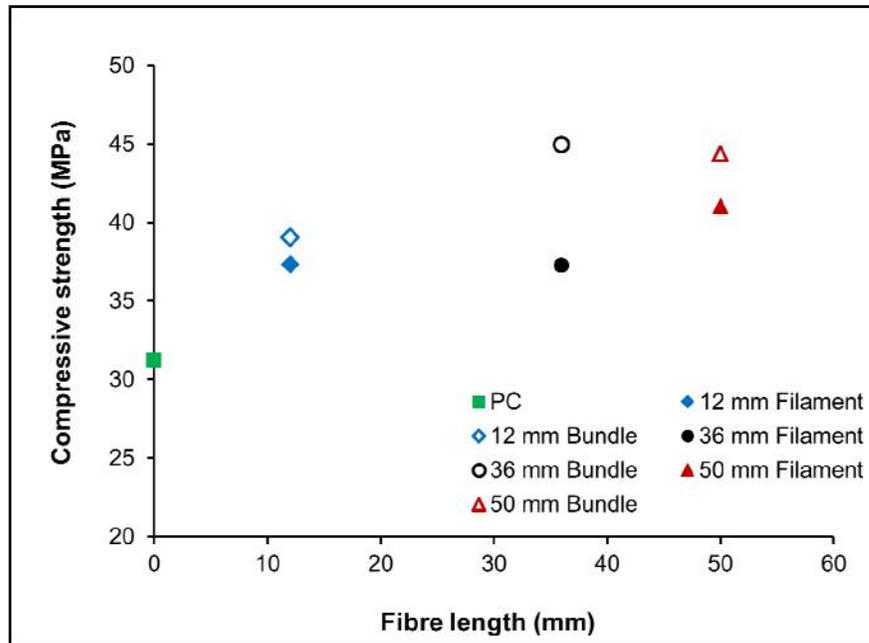


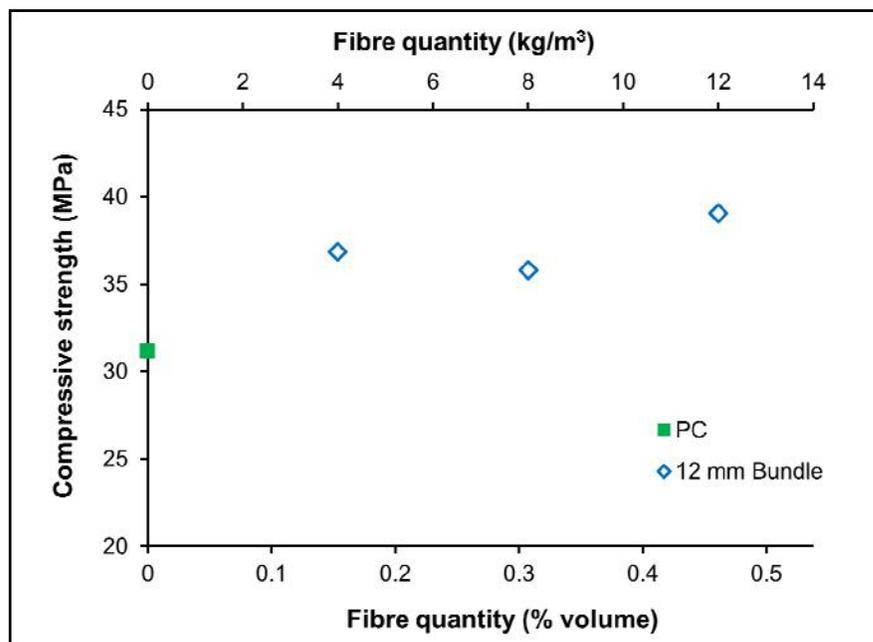
Figure 5.13c: Effect of fibre length at fibre dosage 12 kg/m<sup>3</sup>

## 5.2.4 EFFECT OF FIBRE QUANTITY

### 5.2.4.1 FIBRE LENGTH – 12 mm

*Basalt bundles:* Figure 5.14a shows the effect of quantity of 12 mm basalt bundled fibre on 28 day compressive strength. It was found that the compressive strength of 12 mm bundled fibre at all dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>) are higher than PC. A sharp increase (18%) in compressive strength was observed for 12 mm bundled fibre even at low fibre dosage of 4 kg/m<sup>3</sup> from PC. It was found that there was slight reduction (1.04 MPa) in compressive strength with the change in fibre dosage from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup>. The independent sample t-test (Table 4.22) indicates that this reduction is not statistically significant. There was 6% increase in compressive strength with the increase in fibre dosage from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>.

Independent sample t-test also confirms that the 28 day compressive strength of all three fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>) are statistically different from PC (Table 4.20). Independent sample t-test (Table 4.22) also shows that the change in 28 day compressive strength with the change in fibre quantity from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is statistically significant at 90% confidence interval. The change in fibre quantity from 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is also statistically significant at 90% and 95% confidence intervals. However, the change in fibre quantity from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> is not statistically significant. Hence, both statistical analysis and Figure 5.14a agree well.

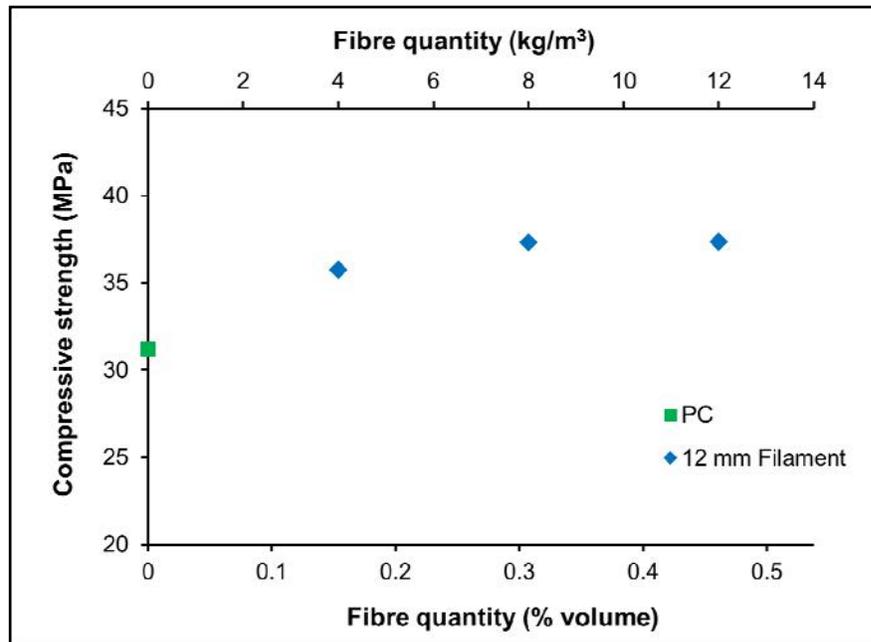


Trend line equation:  $y = 0.1341x^2 - 1.8687x + 42.18$       $R^2 = 1$

**Figure 5.14a: Basalt bundles: Effect of fibre quantity of 12 mm fibres**

*Basalt filaments:* Figure 5.14b shows the effect of quantity of 12 mm basalt filament on 28 day compressive strength. In general, it was found that the compressive strength of 12 mm filament increases with the increase in fibre dosage from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. There was a sharp increase in compressive strength (35.74 MPa) of 14.5% even at low fibre dosage of 4 kg/m<sup>3</sup> from PC.

Independent sample t-test also found that the 28 day compressive strength of all three fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>) are statistically different from PC (Table 4.29). Independent sample t-test (Table 4.31) shows that the change in fibre quantity from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is statistically significant at 90% confidence interval. However, the change in fibre quantity from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is not statistically significant.

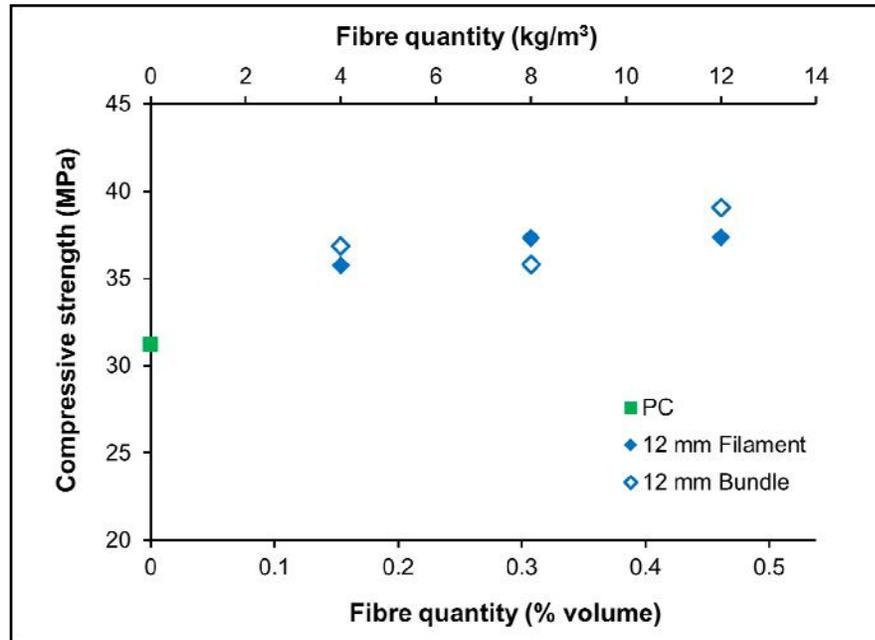


Trend line equation:  $y = -0.0486x^2 + 0.9804x + 32.6$   $R^2 = 1$

**Figure 5.14b: Basalt filaments: Effect of fibre quantity of 12 mm fibres**

*Basalt bundles vs. filaments:* Figure 5.14c shows the effect of quantity of 12 mm basalt bundles and filaments on 28 day compressive strength. In general, it was observed that the compressive strength of 12 mm bundles and 12 mm filaments increase with the increase in fibre dosage from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. It can be seen from Figure 5.14c that there was no major difference in compressive strength between bundles and filaments of the same fibre quantity, except at 12 kg/m<sup>3</sup>. There is a slight improvement in compressive strength for 12 mm bundled fibres (39.06 MPa) compared to 12 mm filaments (37.36 MPa) at 12 kg/m<sup>3</sup>. This could be due the uniform dispersion of bundled fibres in the concrete mix even at high dosage of 12 kg/m<sup>3</sup>.

Independent sample t-test (Table 4.36) shows that the mean compressive strength of basalt bundles and filaments are statistically similar for 4 kg/m<sup>3</sup> and 8 kg/m<sup>3</sup> at both 90% and 95% CIs. The mean compressive strength of basalt bundles and filaments are not statistically similar for 12 kg/m<sup>3</sup> at 90% CI. However, this is not obvious in Figure 5.14c.



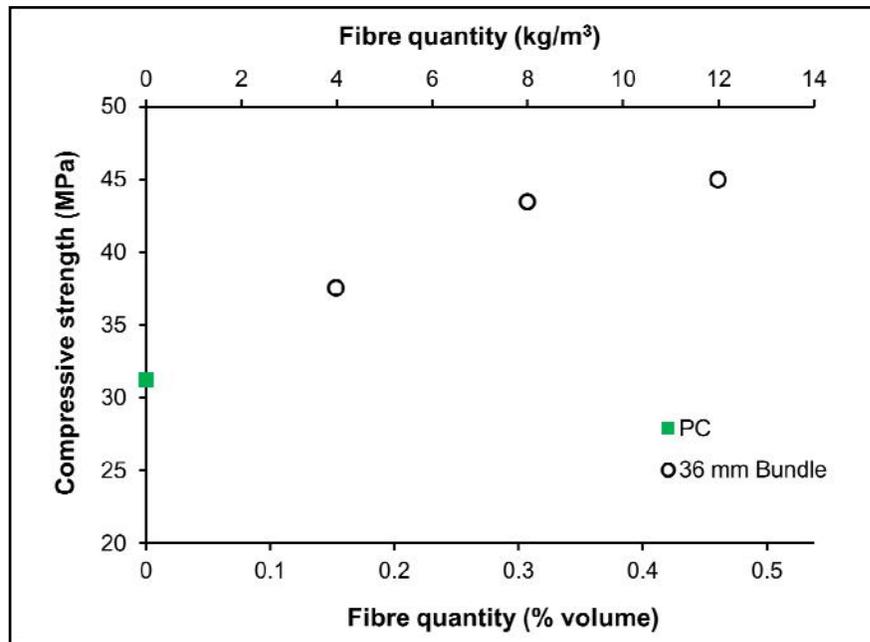
**Figure 5.14c: Effect of fibre quantity of 12 mm basalt fibres**

#### 5.2.4.2 FIBRE LENGTH – 36 mm

*Basalt bundles:* Figure 5.15a shows the effect of quantity of 36 mm basalt bundled fibre on 28 day compressive strength. It was observed for 36 mm bundled fibre that the compressive strength increases with the increasing fibre quantity and the increasing trend for 36 mm bundled fibre is more obvious than 12 mm bundled fibre (see Figure 5.14a and Figure 5.15a). The peak compressive strength (44.95 MPa) for 36 mm bundled fibre was observed at 12 kg/m<sup>3</sup> which is 44% higher than that of PC. A sharp increase in compressive strength (37.49 MPa) of 20% was observed even at low fibre dosage of 4 kg/m<sup>3</sup> from PC.

Independent sample t-test (Table 4.22) shows that the change in compressive strength with the change in fibre quantity from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> or 8 kg/m<sup>3</sup> to

12 kg/m<sup>3</sup> is statistically significant. Hence, both statistical analysis and Figure 5.15a agree well.

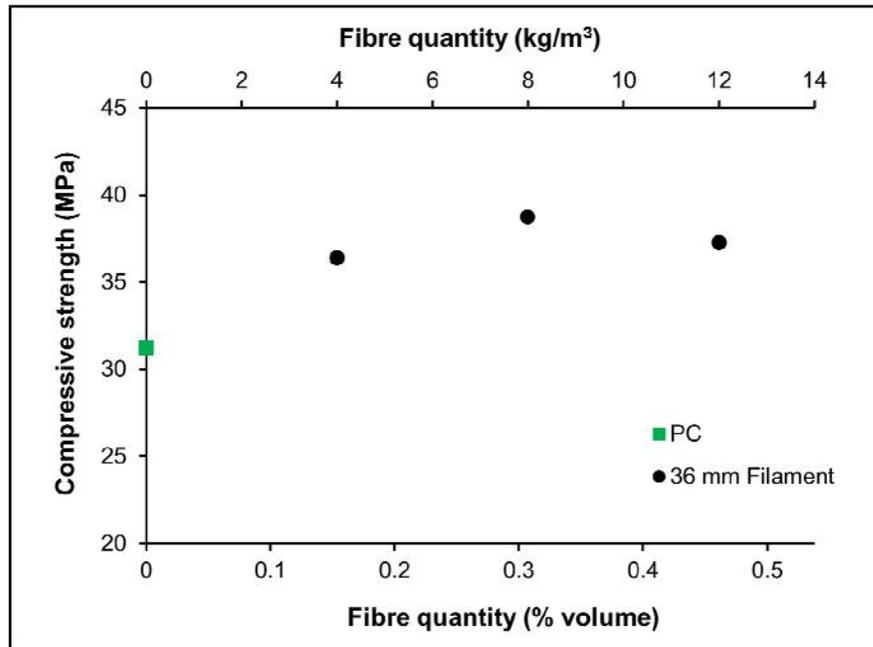


Trend line equation:  $y = 0.9325x + 34.49$   $R^2 = 0.90$

**Figure 5.15a: Basalt bundles: Effect of fibre quantity of 36 mm fibres**

*Basalt filaments:* Figure 5.15b shows the effect of quantity of 36 mm basalt filaments on 28 day compressive strength. It was observed that there was no significant improvement in the compressive strength of 36 mm filament as the fibre quantity increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup>. However, there was a slight reduction (4%) in compressive strength as the fibre dosage increases from 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> which might be due to the lumping of filaments at high fibre dosage. Independent sample t-test (Table 4.31) indicates that this reduction is not statistically significant. A sharp increase (16.5%) in compressive strength (36.38 MPa) from PC was observed even at low fibre dosage of 4 kg/m<sup>3</sup>. The peak compressive strength for 36 mm filaments was observed at 8 kg/m<sup>3</sup> (38.73 MPa) which is 24% higher than PC.

Independent sample t-test (Table 4.31) also confirms that the change in compressive strength with the change in fibre quantity from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> or 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is not statistically significant. Hence, both statistical analysis and Figure 5.15b agree well.

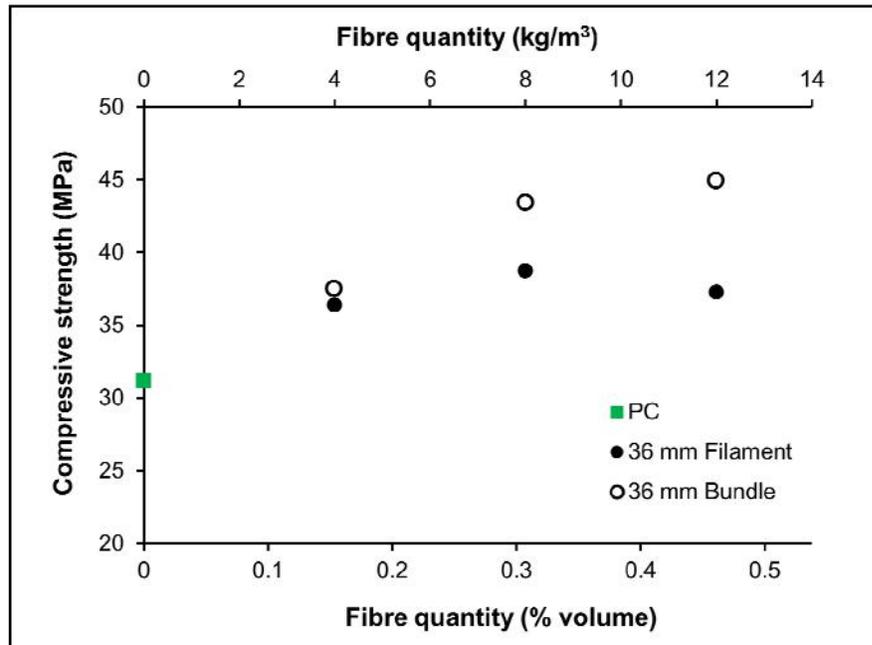


Trend line equation:  $y = -0.1195x^2 + 2.0204x + 30.21$   $R^2 = 1$

**Figure 5.15b: Basalt filaments: Effect of fibre quantity of 36 mm fibres**

*Basalt bundles vs. filaments:* Figure 5.15c shows the effect of quantity of 36 mm basalt bundles and filaments on 28 day compressive strength. In general, it was found that for 36 mm bundled fibre, the compressive strength increases with the increase in fibre quantity. However, for 36 mm filament, there is no significant increase in the compressive strength as the fibre quantity increases from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. A sharp increase in compressive strength was observed for both 36 mm bundles and filaments from PC. The compressive strength at 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup> of 36 mm bundles are 12% and 20% higher than that of the corresponding 36 mm filament specimens.

Independent sample t-test (Table 4.36) also confirms that the mean compressive strength of basalt bundles and filaments are statistically similar at 4 kg/m<sup>3</sup>. However, the mean compressive strength of basalt bundles and filaments are not statistically similar at 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup>. Hence, both statistical analysis and Figure 5.15c agree well.

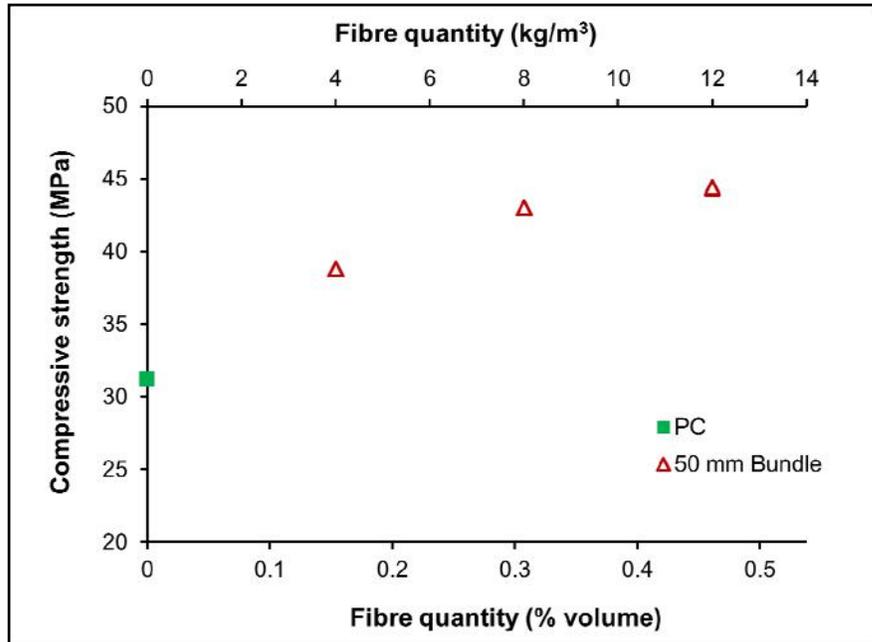


**Figure 5.15c: Effect of fibre quantity of 36 mm basalt fibres**

#### 5.2.4.3 FIBRE LENGTH – 50 mm

*Basalt bundles:* Figure 5.16a shows the effect of quantity of 50 mm basalt bundled fibre on 28 day compressive strength. It was observed for 50 mm bundled fibre that the compressive strength increases with the increasing fibre quantity and the increasing trend for 50 mm bundled fibre is more obvious than 12 mm bundled fibre (see Figure 5.14a and Figure 5.16a). The peak compressive strength for 50 mm bundled fibre was observed at 12 kg/m<sup>3</sup> (44.40 MPa) which is similar to the compressive strength at 8 kg/m<sup>3</sup> (43.01 MPa). A sharp increase in compressive strength (38.78 MPa) of 24% was observed from PC even at low fibre dosage of 4 kg/m<sup>3</sup>.

Independent sample t-test (Table 4.22) also confirms that the change in compressive strength with the change in fibre quantity from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> is statistically significant at 90% CI. The increase in fibre quantity from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is statistically significant at both 90% and 95% CIs. However, the increase in fibre quantity from 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is not statistically significant. Hence, both statistical analysis and Figure 5.16a agree well.



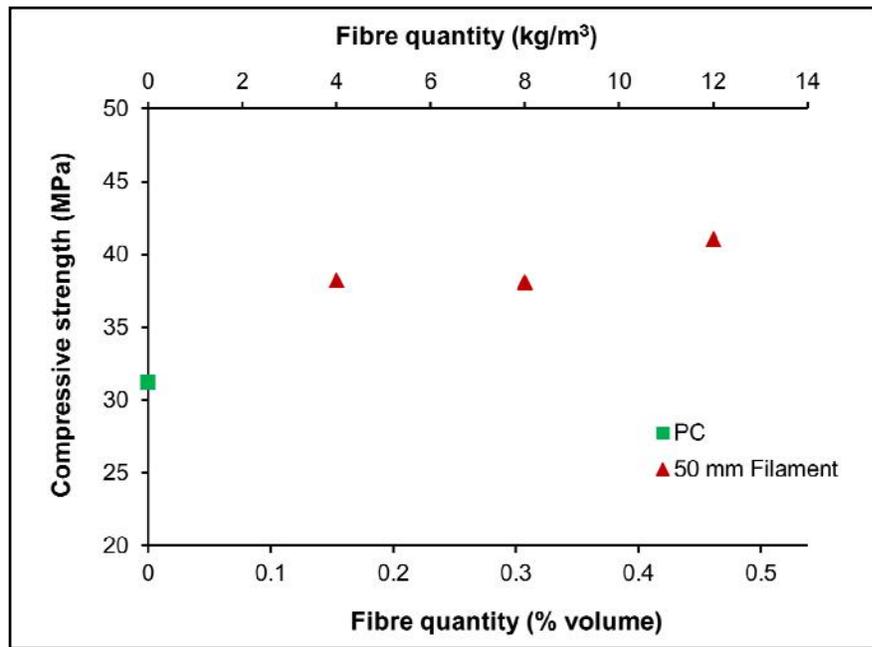
Trend line equation:  $y = 0.7017x + 36.451$       $R^2 = 0.92$

**Figure 5.16a: Basalt bundles: Effect of fibre quantity of 50 mm fibres**

*Basalt filaments:* Figure 5.16b shows the effect of quantity of 50 mm basalt filament on 28 day compressive strength. It was observed that there was a sharp increase (22%) in the compressive strength (38.23 MPa) of 50 mm filament from PC even at low fibre dosage of 4 kg/m<sup>3</sup>. There was no significant improvement in the compressive strength with the change in fibre dosage from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup>. This might be because of lumping of long filaments (50 mm) at 8 kg/m<sup>3</sup>. It can be seen that the compressive strength at 12 kg/m<sup>3</sup> (41.05 MPa) is slightly higher (7%) than that at 4 kg/m<sup>3</sup> which could be due to the addition

of superplasticiser (provides uniform dispersion of filaments). However, the independent sample t-test (Table 4.31) indicates that this increase is not statistically significant.

Independent sample t-test (Table 4.31) shows that the change in compressive strength with the change in fibre quantity from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> or 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is not statistically significant.



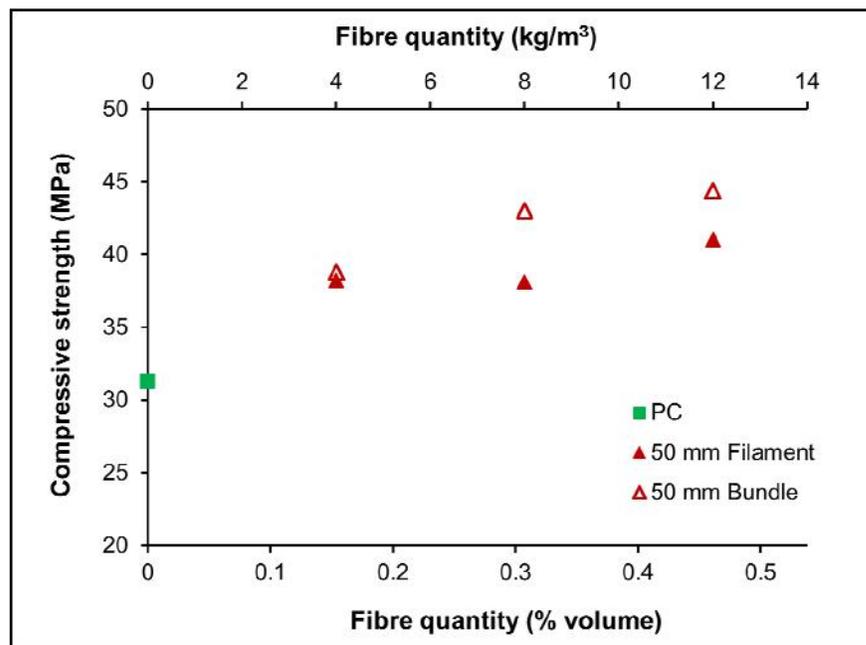
Trend line equation:  $y = 0.0959x^2 - 1.1829x + 41.43$   $R^2 = 1$

**Figure 5.16b: Basalt filaments: Effect of fibre quantity of 50 mm fibres**

*Basalt bundles vs. filaments:* Figure 5.16c shows the effect of quantity of 50 mm basalt bundles and 50 mm filaments on 28 day compressive strength. It was observed that for 50 mm bundled fibre, the compressive strength increases with the increase in fibre dosage. This could be due to the uniform dispersion of bundled fibres in the matrix. However, for 50 mm filaments, there was no significant improvement in the compressive strength with the increase in fibre dosage from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> which might be due to the lumping of filaments at 8 kg/m<sup>3</sup>. The compressive strength of 50 mm filament at 12 kg/m<sup>3</sup> is slightly

higher (7%) than that at 4 kg/m<sup>3</sup> which could be due to the addition of superplasticiser (provides uniform dispersion). A sharp increase in compressive strength was observed for both 50 mm bundles and filaments from PC. The compressive strength of 50 mm bundled fibre was observed to be 13% and 8% higher than the corresponding 50 mm filament at 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup>.

Independent sample t-test (Table 4.36) shows that the mean compressive strength of basalt bundles and filaments are statistically similar at 4 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup>. However, they are not statistically similar for 8 kg/m<sup>3</sup> at 90% CI. Hence, both statistical analysis and Figure 5.16c are comparable.



**Figure 5.16c: Effect of fibre quantity of 50 mm basalt fibres**

### 5.2.5 SUMMARY – COMPRESSIVE STRENGTH

*Basalt bundles vs. control specimens:* The 28 day compressive strength of all three bundled fibres (12 mm, 36 mm, and 50 mm) at all three fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>) are higher than that of PC. The medium length (36 mm) and long (50 mm) bundled fibres at 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup> provide compressive strength similar to SF 38-40. Short bundled fibres (12 mm) at all dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>), and 36 mm and 50 mm bundled fibres at low fibre dosage (4 kg/m<sup>3</sup>) provide similar compressive strength as PP 40-4.5 specimen.

*Basalt bundles: Effect of fibre length and dosage:* All three bundled fibres (12 mm, 36 mm, and 50 mm) provide significant improvement in the compressive strength of 18%, 20%, and 24%, respectively from PC even at low fibre dosage of 4 kg/m<sup>3</sup>. The short bundled fibre (12 mm) shows significant improvement (25%) in compressive strength from PC at high fibre dosage of 12 kg/m<sup>3</sup>. However, the medium length (36 mm) bundled fibre provides 39% and 44% increase in compressive strength from PC at 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup>, respectively. Similarly, the long (50 mm) bundled fibre shows 38% and 42% increase in compressive strength from PC at 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup>, respectively. The gain in compressive strength for 50 mm bundled fibre with the change in fibre quantity from 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is not statistically significant. Hence, the optimum fibre dose for 50 mm bundled fibre which provides significant improvement in compressive strength over PC is 8 kg/m<sup>3</sup>.

*Basalt filaments vs. control specimens:* The 28 day compressive strength of all filament specimens (12 mm, 36 mm, and 50mm) at all three fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>) are higher than that of PC. The compressive strength of long filament fibre (50 mm) at high fibre dosage of 12 kg/m<sup>3</sup> is similar to that of SF 38-40. All basalt filament specimens, except 50 mm filament at 12 kg/m<sup>3</sup>, provide compressive strength similar to PP 40-4.5.

*Basalt filaments: Effect of fibre length and dosage:* All three filaments (12 mm, 36 mm, and 50 mm) provide significant improvement in the compressive strength of 14.5%, 16.5%, and 22%, respectively from PC even at low fibre dosage of 4 kg/m<sup>3</sup>. The short filament (12 mm) shows significant improvement (20%) in compressive strength from PC at high fibre dosage of 12 kg/m<sup>3</sup>. For 36 mm and 50 mm filaments, the change in fibre quantity from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> has no significant effect on the 28 day compressive strength. Lumping occurs for 36 mm and 50 mm filaments at high fibre dosage ( $\geq 8$  kg/m<sup>3</sup>).

*Basalt bundles vs. filaments:* The compressive strength of 12 mm bundle and 12 mm filament are similar at 4 kg/m<sup>3</sup> and 8 kg/m<sup>3</sup>. However, at 12 kg/m<sup>3</sup>, the compressive strength of 12 mm bundle is 4.5% higher than that of 12 mm filament. The compressive strength of 36 mm bundle and 36 mm filament are similar at 4 kg/m<sup>3</sup>. However, the compressive strength of 36 mm bundle at 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup> are 12% and 20% higher than that of 36 mm filament. The compressive strength of 50 mm bundle and 50 mm filament are similar at 4 kg/m<sup>3</sup>. However, the compressive strength of 50 mm bundle at 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup> are 13% and 8% higher than that of 50 mm filament. In all the above mentioned cases, bundles have consistently performed better than filaments which is due to uniform dispersion of bundles in the concrete mix.

### 5.3 SPLIT TENSILE STRENGTH

Statistical analysis of split tensile strength were discussed in Chapter 4. These are further analyzed in this section.

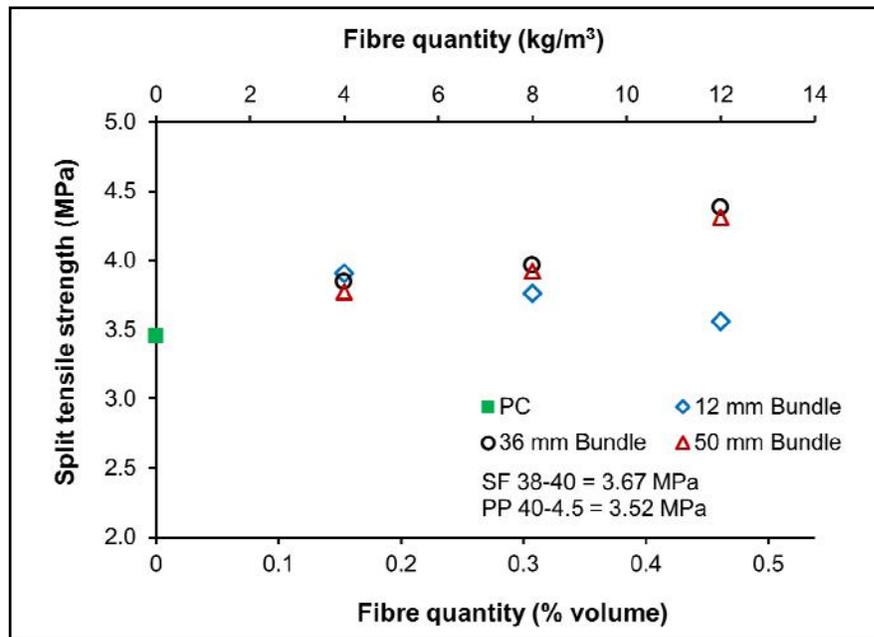
#### 5.3.1 BASALT BUNDLES

Figure 5.17 shows the mean split tensile strength of all basalt bundle specimens and PC. The mean split tensile strength of PC is 6% lower than that of SF 38-40 and 2% lower than that of PP 40-4.5. The improvement in split tensile strength is minimal for both SF 38-40 and PP 40-4.5. However, the mode of failure changed from brittle to ductile for specimens SF 38-40 and PP 40-4.5 specimens.

The maximum split tensile strength (4.38 MPa) was observed for 36 mm bundled fibre at high fibre dosage of  $12 \text{ kg/m}^3$  which is 27% higher than that of PC and 19% higher than that of SF 38-40 specimen. It was found that 50 mm bundled fibre at  $12 \text{ kg/m}^3$  also provides similar split tensile strength (4.31 MPa). Table 4.23 shows that the 36 mm bundled fibre at high dosage of  $12 \text{ kg/m}^3$  has significant influence on the split tensile strength when compared with PC, SF 38-40, or PP 40-4.5 specimens. It was observed that all the basalt bundled fibre specimens failed in a brittle manner, though there was improvement in the split tensile strength.

The study found that the split tensile strength of 36 mm and 50 mm bundled fibres increased with the change in fibre dosage from  $4 \text{ kg/m}^3$  to  $8 \text{ kg/m}^3$  or  $4 \text{ kg/m}^3$  to  $12 \text{ kg/m}^3$ . However, for short bundled fibre (12 mm), there was no significant improvement in the split tensile strength with the increase in fibre quantity. It was also found that there was a slight reduction in the split tensile strength for 12 mm bundled fibre with the change in fibre dosage from  $4 \text{ kg/m}^3$  to  $8 \text{ kg/m}^3$  or  $4 \text{ kg/m}^3$  to  $12 \text{ kg/m}^3$ . However, Table 4.25 shows that this reduction in strength was not statistically significant. It was observed that the medium

(36 mm) and long (50 mm) bundled fibres at high fibre dosage of 12 kg/m<sup>3</sup> help in bridging macro-cracks effectively.



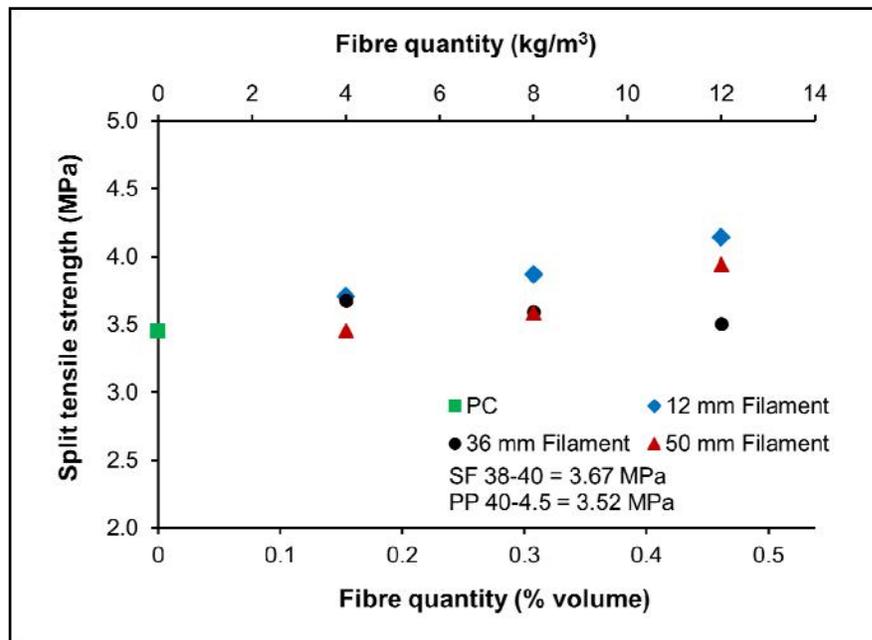
**Figure 5.17: Basalt bundles - 28 day Split tensile strength**

### 5.3.2 BASALT FILAMENTS

Figure 5.18 shows the mean split tensile strength of basalt filament specimens and PC. The peak split tensile strength of 4.14 MPa was observed for 12 mm filament at high fibre dosage of 12 kg/m<sup>3</sup> which is 20% higher than that of PC, 12.8% higher than that of SF 38-40 specimen. Table 4.32 shows that the 12 mm filament fibre at high dosage of 12 kg/m<sup>3</sup> has significant influence on the split tensile strength when compared with PC, SF 38-40, or PP 40-4.5 specimens. All the basalt filament fibre specimens failed in a brittle manner, though there was improvement in the split tensile strength.

The study found that the split tensile strength of short filament (12 mm) increases with the increase in fibre dosage from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. It was observed that for 36 mm filament, there was no significant improvement in the split tensile strength with the increase in fibre quantity from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. There

was 2.5% reduction in the split tensile strength of 36 mm filament with the change in fibre dosage from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. This might be due to the lumping of filaments at high fibre dosages (8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup>). However, the long filament (50 mm) exhibit an increasing trend in the split tensile strength with the increase in fibre dosage from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. In order to maintain the workability of the mix for long filaments (50 mm) at high fibre dosage (12 kg/m<sup>3</sup>), Rheobuild 1000 superplasticizer (55 ml) was added. The superplasticizer could have helped in the uniform distribution of filaments in the matrix. This might be the reason for higher split tensile strength for 50 mm filament when compared to 36 mm filaments at 12 kg/m<sup>3</sup>.



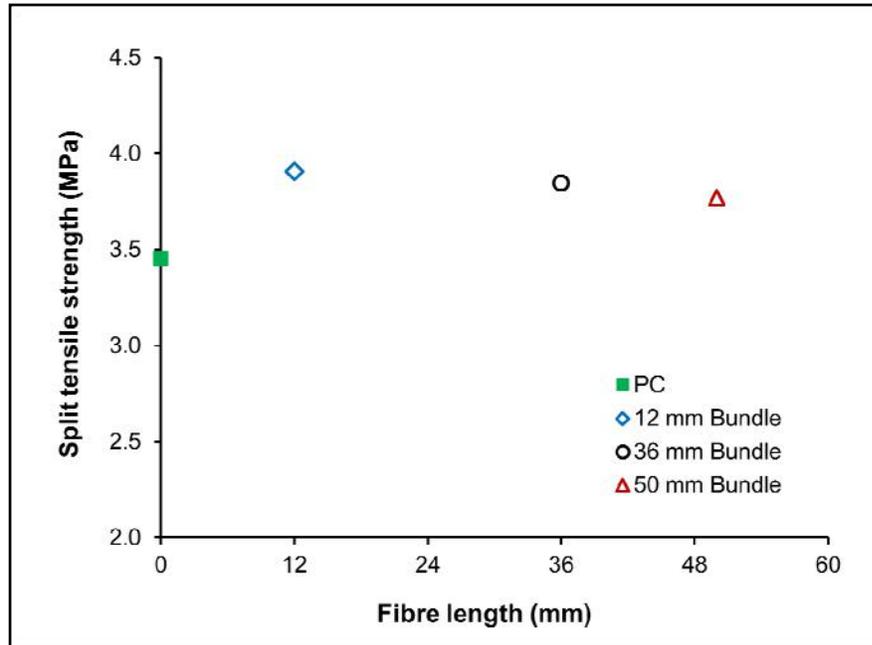
**Figure 5.18: Basalt filaments - 28 day Split tensile strength**

### 5.3.3 EFFECT OF LENGTH

#### 5.3.3.1 FIBRE DOSAGE – 4 kg/m<sup>3</sup>

*Basalt bundles:* Figure 5.19a shows the effect of length of basalt bundled fibres on split tensile strength at 4 kg/m<sup>3</sup>. The peak split tensile strength at 4 kg/m<sup>3</sup> was observed for 12 mm bundled fibre (3.91 MPa) which is 13% higher than that of PC. It was observed that there was no significant improvement in the split tensile strength at 4 kg/m<sup>3</sup> with the increase in fibre length from 12 mm to 36 mm or 12 mm to 50 mm. It could be seen from Figure 5.19a that there was a slight reduction (4%) in the split tensile strength with the change in fibre length from 12 mm (3.91 MPa) to 50 mm (3.77 MPa). However, the independent sample t-test (Table 4.24) shows that the change in fibre length from 12 mm to 50 mm has no statistical influence on the split tensile strength.

Independent sample t-test (Table 4.23) shows that the split tensile strength of 12 mm and 50 mm bundled fibres are statistically similar to PC. Further, the split tensile strength of 36 mm bundled fibre is not statistically similar to PC. This is not obvious from Figure 5.19a. However, the independent sample t-test (Table 4.24) and Figure 5.19a show that the change in split tensile strength with the change in fibre length from 12 mm to 36 mm or 12 mm to 50 mm or 36 mm to 50 mm is not statistically significant.



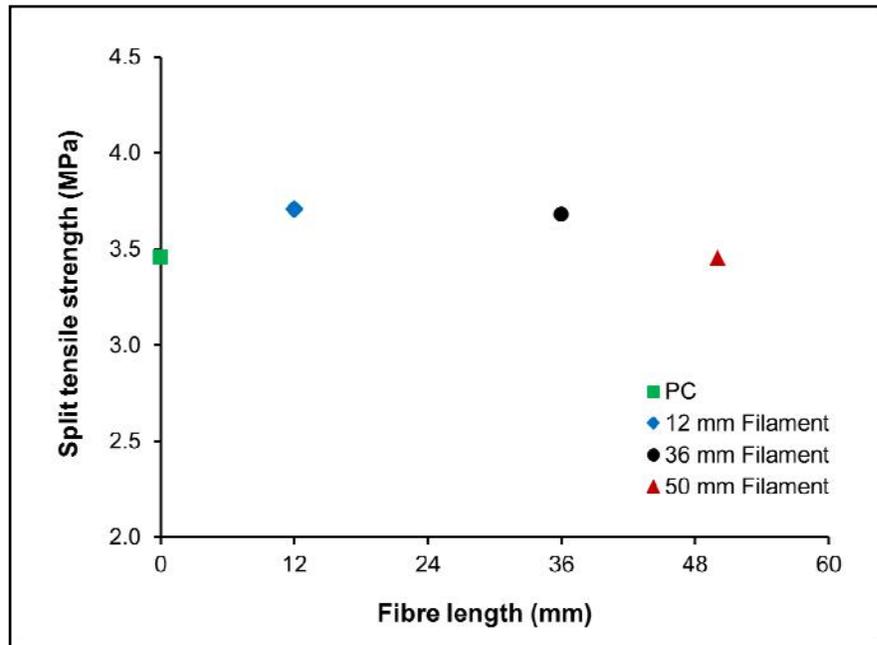
Trend line equation:  $y = -0.0035x + 3.9541$   $R^2 = 0.96$

**Figure 5.19a: Basalt bundles: Effect of fibre length at fibre dosage 4 kg/m<sup>3</sup>**

*Basalt filaments:* Figure 5.19b shows the effect of length of basalt filaments on the split tensile strength at 4 kg/m<sup>3</sup>. The peak split tensile strength at 4 kg/m<sup>3</sup> was observed for 12 mm filament fibre (3.71 MPa) which is 7.5% higher than that of PC. It was observed that there was no significant improvement in the split tensile strength at 4 kg/m<sup>3</sup> with the increase in fibre length from 12 mm to 36 mm or 12 mm to 50 mm. It could be seen from Figure 5.19b that there was reduction (7.5%) in the split tensile strength with the change in fibre length from 12 mm (3.71 MPa) to 50 mm (3.45 MPa). The split tensile strength of 50 mm filament at 4 kg/m<sup>3</sup> is similar to PC. The reason for this reduction in split tensile strength is not obvious and requires further research.

Independent sample t-test (Table 4.32) also confirms that the split tensile strength of 12 mm filament is not statistically similar to PC. Further, the split tensile strength of 36 mm and 50 mm filaments are statistically similar to PC. Independent sample t-test (Table 4.33) shows that the change in split tensile strength with the change in fibre length from 12 mm

to 50 mm is statistically significant. This is also obvious from Figure 5.19b which shows reduction in split tensile strength for 50 mm filament from 12 mm filament. However, the change in split tensile strength with the change in fibre length from 12 mm to 36 mm or 36 mm to 50 mm is not statistically significant.

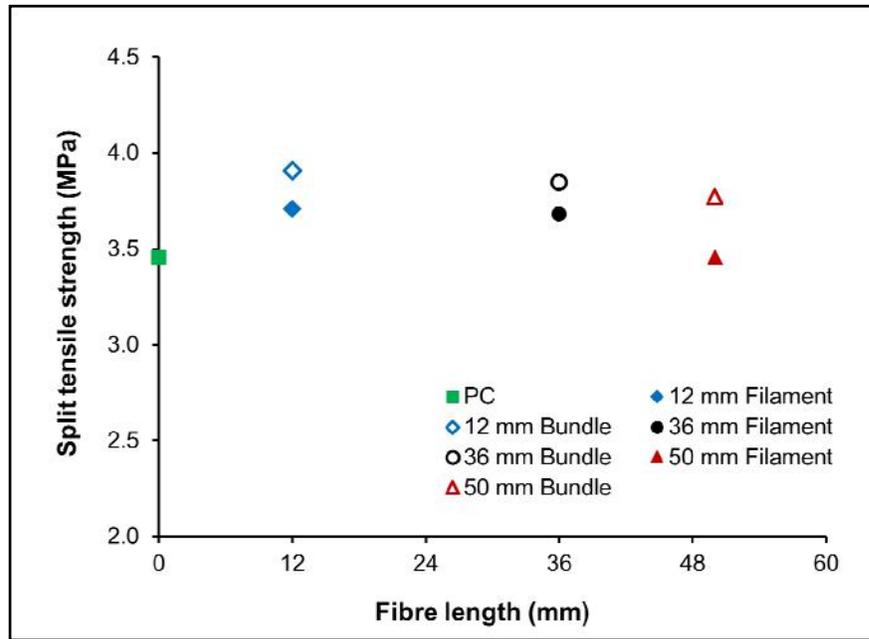


Trend line equation:  $y = -0.0004x^2 + 0.0176x + 3.5552$   $R^2 = 1$

**Figure 5.19b: Basalt filaments: Effect of fibre length at fibre dosage 4 kg/m<sup>3</sup>**

*Basalt bundles vs. filaments:* Figure 5.19c shows the effect of length of basalt bundles and filaments on split tensile strength at 4 kg/m<sup>3</sup>. It was observed that both bundles and filaments at 4 kg/m<sup>3</sup> exhibit a decreasing trend in the split tensile strength with the increase in fibre length from 12 mm to 50 mm.

Independent sample t-test (Table 4.37) also confirms that the split tensile strength of bundles and filaments of same same fibre length are statically similar at 4 kg/m<sup>3</sup>. Hence, both statistical analysis and Figure 5.19c agree well.



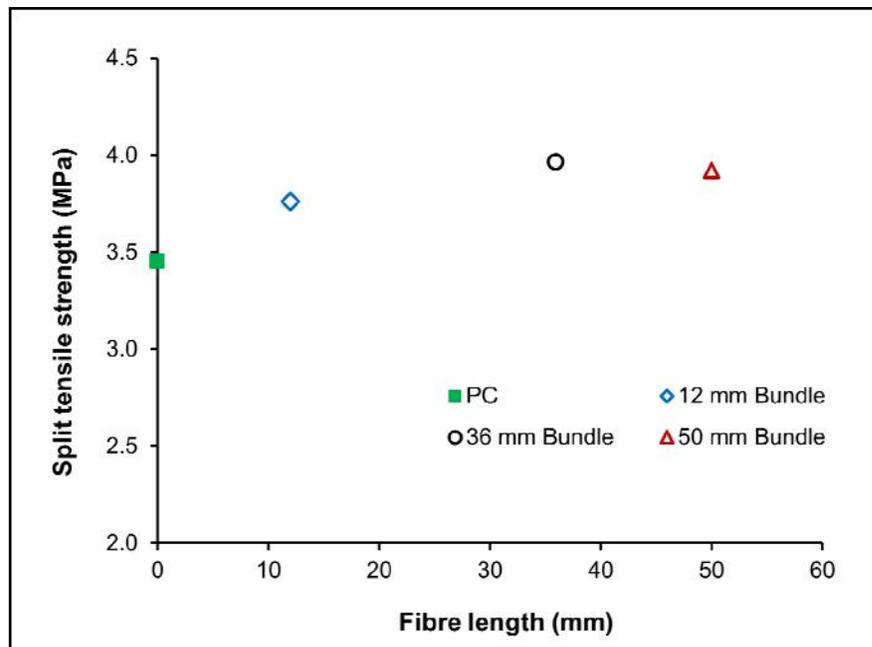
**Figure 5.19c: Effect of fibre length at fibre dosage 4 kg/m<sup>3</sup>**

### 5.3.3.2 FIBRE DOSAGE – 8 kg/m<sup>3</sup>

*Basalt bundles:* Figure 5.20a shows the effect of length of basalt bundled fibres on split tensile strength at 8 kg/m<sup>3</sup>. It was observed that at 8 kg/m<sup>3</sup>, the split tensile strength of bundled fibres increases with the change in fibre length. An increasing trend is observed at 8 kg/m<sup>3</sup> (Figure 5.20a) unlike the decreasing trend at 4 kg/m<sup>3</sup> (Figure 5.19a). The peak split tensile strength (3.96 MPa) was observed for 36 mm bundled fibre which is 14.8% higher than that of PC. Long bundled fibres (50 mm) at this fibre dosage also provide similar split tensile strength (3.92 MPa). Hence, the improvement in split tensile strength is obvious when 36 mm fibres are used. However, no improvement in split tensile strength occurs when the fibre length increases beyond 36 mm.

Independent sample t-test (Table 4.23) shows that the split tensile strength of all three bundled fibres (12 mm, 36 mm, and 50 mm) are statistically similar to PC. Further, the independent sample t-test (Table 4.24) shows that the change in split tensile strength with

the change in fibre length from 12 mm to 36 mm or 12 mm to 50 mm or 36 mm to 50 mm is not statistically significant. This is not obvious from Figure 5.20a.



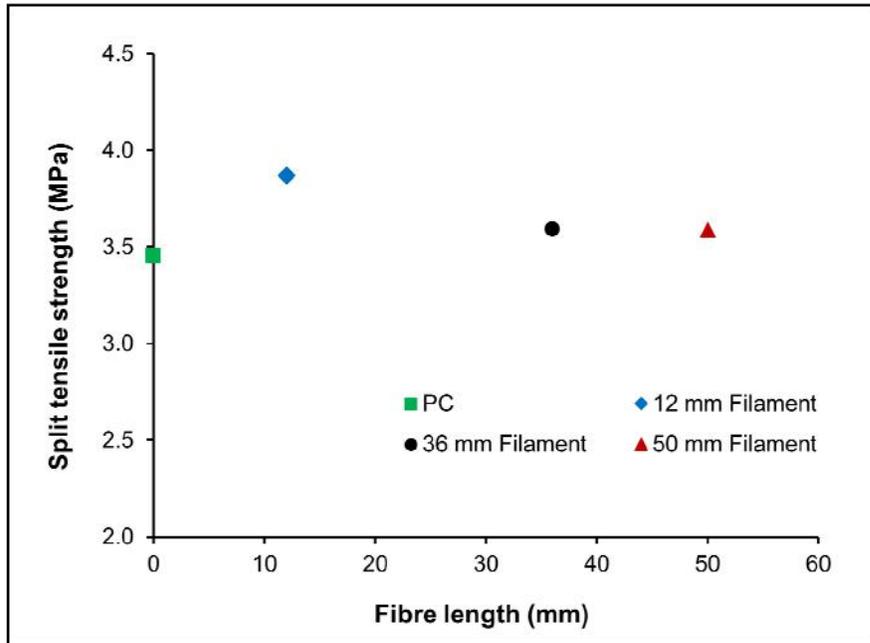
Trend line equation:  $y = -0.0003x^2 + 0.0228x + 3.5295$   $R^2 = 1$

**Figure 5.20a: Basalt bundles: Effect of fibre length at fibre dosage 8 kg/m<sup>3</sup>**

*Basalt filaments:* Figure 5.20b shows the effect of length of basalt filaments on split tensile strength at 8 kg/m<sup>3</sup>. It was observed that at 8 kg/m<sup>3</sup>, the split tensile strength of basalt filaments decreases with the increase in fibre length. This might be due to the lumping of 36 mm and 50 mm filaments during mixing at 8 kg/m<sup>3</sup>. The decreasing trend in split tensile strength is more obvious at 8 kg/m<sup>3</sup> (Figure 5.20b) than at 4 kg/m<sup>3</sup> (Figure 5.19b). The tests were repeated for 36 mm filament. However, the repeat test data also provided similar results. Hence, it can be concluded that there is no improvement in the split tensile strength with the increase in filament length.

Independent sample t-test (Table 4.32) shows that the split tensile strength of 12 mm and 36 mm filaments are not statistically similar to PC at 90% CI. However, the split tensile

strength of 50 mm filament is statistically similar to PC at both CIs. Independent sample t-test (Table 4.33) shows that the change in split tensile strength with change in filament fibre length from 12 mm to 36 mm or 12 mm to 50 mm or 36 mm to 50 mm is not statistically significant. However, this not obvious from Figure 5.20b.

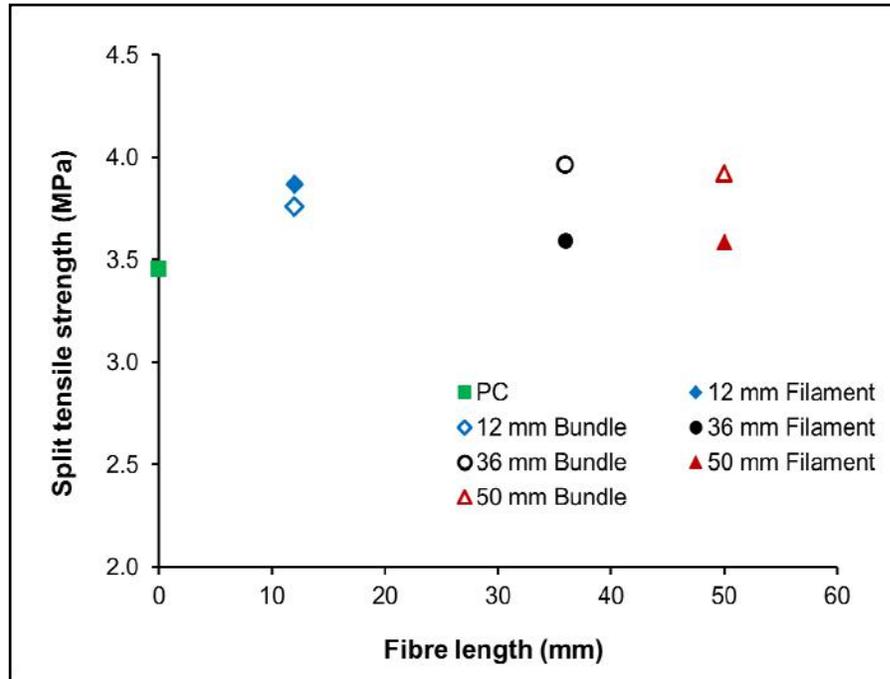


Trend line equation:  $y = -0.0078x + 3.9399$   $R^2 = 0.87$

**Figure 5.20b: Basalt filaments: Effect of fibre length at fibre dosage 8 kg/m<sup>3</sup>**

*Basalt bundles vs. filaments:* Figure 5.20c shows the effect of length of basalt bundles and filaments on split tensile strength at 8 kg/m<sup>3</sup>. It was observed that the split tensile strength of basalt bundles increases with the increase in fibre length. However, for basalt filaments, it was observed that the split tensile strength decreases with the increase in fibre length from 12 mm to 36 mm or 12 mm to 50 mm which could be due to lumping of filaments at 8 kg/m<sup>3</sup>. It was observed that the split tensile strength of 36 mm bundle was 10% higher than that of 36 mm filament at 8 kg/m<sup>3</sup>. The split tensile strength of 50 mm bundle was 9% higher than that of 50 mm filament at 8 kg/m<sup>3</sup>.

Independent sample t-test (Table 4.37) shows that the split tensile strength of bundles and filaments of the same fibre length are statistically similar though bundles and filaments follow a different trend.



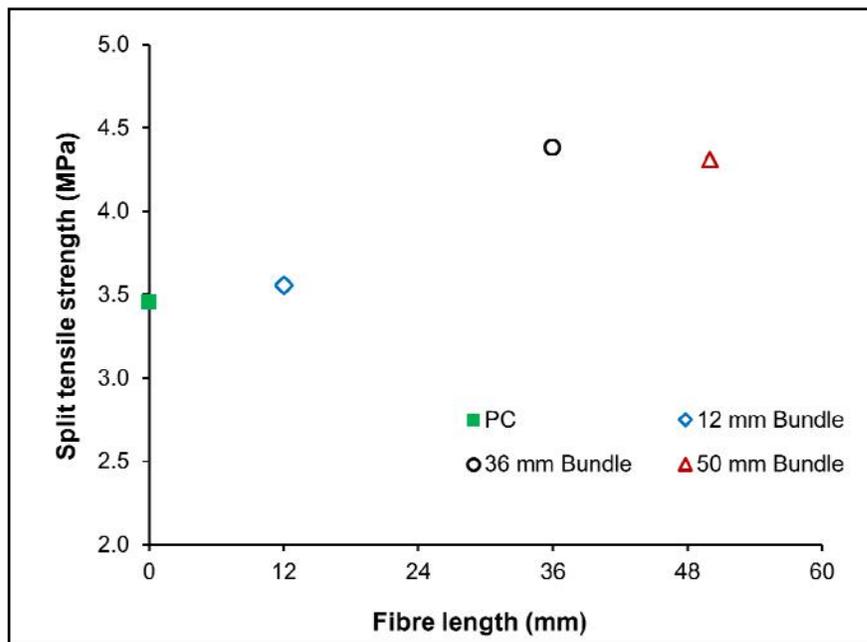
**Figure 5.20c: Effect of fibre length at fibre dosage 8 kg/m<sup>3</sup>**

### 5.3.3.3 FIBRE DOSAGE – 12 kg/m<sup>3</sup>

*Basalt bundles:* Figure 5.21a shows the effect of length of basalt bundled fibres on split tensile strength at 12 kg/m<sup>3</sup>. A sharp increase in the split tensile strength was observed for 36 mm bundled fibre from 12 mm bundled fibre. This trend is similar to the trend observed for 8 kg/m<sup>3</sup> (Figure 5.20a). The peak split tensile strength (4.38 MPa) was observed for 36 mm bundled fibre which is 27% higher than that of PC. Long bundled fibre (50 mm) at this fibre dosage also provide similar split tensile strength (4.31 MPa) which is 25% higher than that of PC. However, there is a slight reduction of 0.07 MPa in split tensile strength from that of 36 mm bundled fibre.

Independent sample t-test (Table 4.23) shows that the split tensile strength of 12 mm and 50 mm bundled fibres are statistically similar to PC. It is also obvious from Figure 5.21a

that there is no significant improvement in split tensile strength for 12 mm bundles. However, Figure 5.21a also shows 25% improvement in split tensile strength for 50 mm bundles. Hence, for this case the statistical analysis results differ from the actual trend. Further, the split tensile strength of 36 mm bundled fibre are statistically different from PC. Independent sample t-test (Table 4.24) shows that the change in split tensile strength with the change in fibre length from 12 mm to 50 mm or 36 mm to 50 mm is not statistically significant. However, the change in split tensile strength with the change in fibre length from 12 mm to 36 mm is statistically significant. This is obvious from Figure 5.21a.



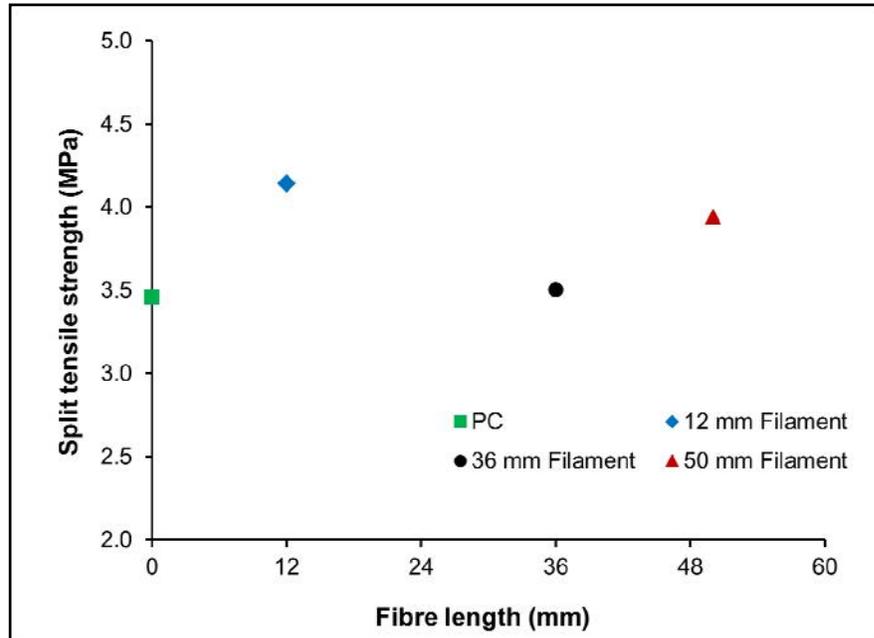
Trend line equation:  $y = 0.0214x + 3.3834$   $R^2 = 0.81$

**Figure 5.21a: Basalt bundles: Effect of fibre length at fibre dosage 12 kg/m<sup>3</sup>**

*Basalt filaments:* Figure 5.21b shows the effect of length of basalt filaments on split tensile strength at 12 kg/m<sup>3</sup>. A sharp increase in split tensile strength was observed for 12 mm filaments (4.14 MPa) which is 20% higher than that of PC. This trend is similar to the trend observed for 8 kg/m<sup>3</sup> (Figure 5.20b). In general, the split tensile strength decreases with an increase in fibre length. This might be due to the lumping of 36 mm and 50 mm filament fibres at high fibre dosage of 12 kg/m<sup>3</sup>. However, the split tensile of 50 mm filament

(3.94 MPa) is higher (12.5%) than that of 36 mm filament (3.5 MPa). In order to maintain the workability of the mix for long filaments (50 mm) at high fibre dosage (12 kg/m<sup>3</sup>), Rheobuild 1000 superplasticizer (55 ml) was added. The superplasticizer could have helped in the uniform distribution of filaments in the matrix. This might be the reason for higher split tensile strength for 50 mm filament (12.5%) when compared to 36 mm filaments at 12 kg/m<sup>3</sup>.

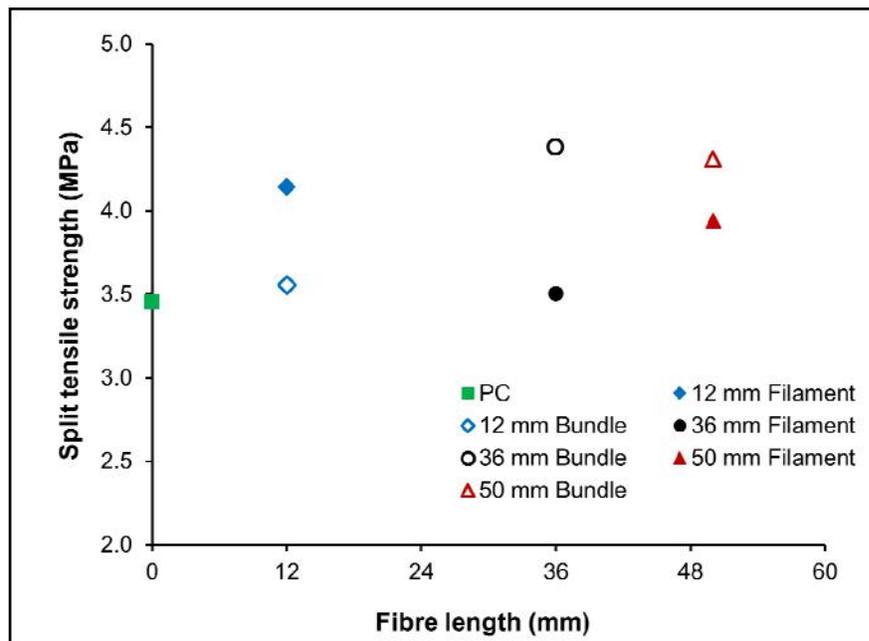
Independent sample t-test (Table 4.32) also confirms that the split tensile strength of 12 mm filament is statistically different from PC. This is also obvious from Figure 5.21b. However, the split tensile strength of 36 mm and 50 mm filaments are statistically similar to PC. Independent sample t-test (Table 4.33) shows that the change in split tensile strength with change in filament length from 12 mm to 36 mm is statistically significant at 90% CI. However, the increase in filament length from 12 mm to 50 mm or 36 mm to 50 mm is not statistically significant. Hence, both statistical analysis and Figure 5.21b agree well.



**Figure 5.21b: Basalt filaments: Effect of fibre length at fibre dosage 12 kg/m<sup>3</sup>**

*Basalt bundles vs. filaments:* Figure 5.21c shows the effect of length of basalt bundles and filaments on split tensile strength at 12 kg/m<sup>3</sup>. It was observed that at 12 kg/m<sup>3</sup>, the split tensile strength of basalt bundles increases with the increase in fibre length. However, for basalt filaments, the split tensile strength decreases with the increase in fibre length from 12 mm to 36 mm or 12 mm to 50 mm which could due to lumping of filaments at high fibre dosage (12 kg/m<sup>3</sup>). It was observed that the split tensile strength of 36 mm bundle was 25% higher than that of 36 mm filament at 12 kg/m<sup>3</sup>. The split tensile strength of 50 mm bundle was 9% higher than that of 50 mm filament at 12 kg/m<sup>3</sup>.

Independent sample t-test (Table 4.37) shows that the split tensile strength of bundles and filaments are statistically similar for 12 mm and 50 mm at both 90% and 95% confidence intervals. However, they statistically different for 36 mm fibres at 90% CI.



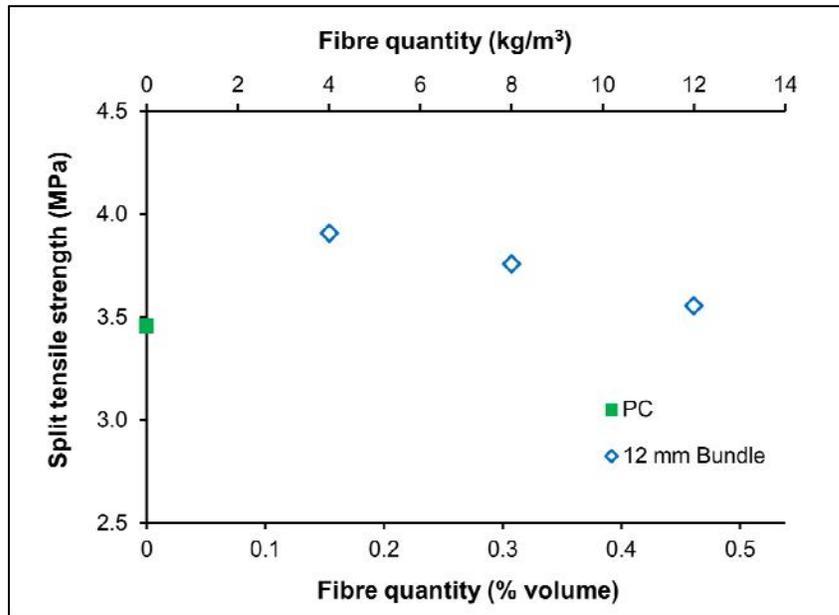
**Figure 5.21c: Effect of fibre length at fibre dosage 12 kg/m<sup>3</sup>**

### 5.3.4 EFFECT OF FIBRE QUANTITY

#### 5.3.4.1 FIBRE LENGTH – 12 mm

*Basalt bundles:* Figure 5.22a shows the effect of quantity of 12 mm basalt bundled fibre on the split tensile strength. It was observed that the split tensile strength of 12 mm bundled fibre decreases with an increase in fibre dosage. The peak split tensile strength for 12 mm bundled fibre (3.91 MPa) was observed at low fibre dosage of 4 kg/m<sup>3</sup> which is 13% higher than that of PC. The split tensile strength of 12 mm bundled fibre at 12 kg/m<sup>3</sup> is 10% lower than that at 4 kg/m<sup>3</sup>. However, the independent sample t-test (Table 4.25) indicates that this decrease is not statistically significant. The reason for reduction is not obvious and requires further research.

Independent sample t-test (Table 4.23) confirms that the split tensile strength of 12 mm bundled fibres at all three fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>) are statistically similar to PC. Table 4.25 also shows that the change in fibre dosage from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> or 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is not statistically significant. Hence, it can be concluded that there is no improvement in the split tensile strength with the increase in fibre quantity for 12 mm bundled fibres.

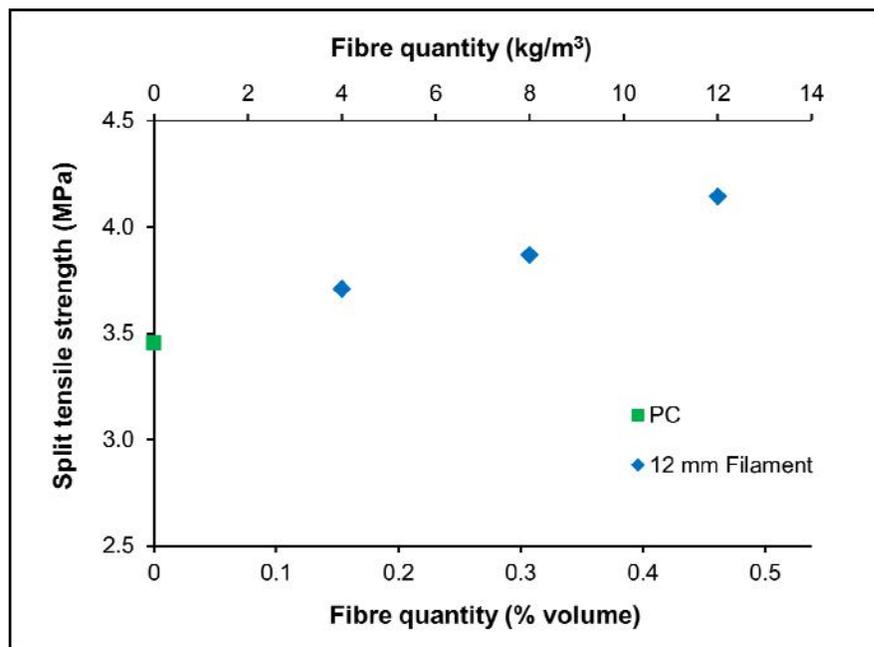


Trend line equation:  $y = -0.0438x + 4.0911$   $R^2 = 1$

**Figure 5.22a: Basalt bundles: Effect of fibre quantity of 12 mm fibres**

*Basalt filaments:* Figure 5.22b shows the effect of quantity of 12 mm basalt filament on the split tensile strength. An increasing trend was observed in the split tensile strength of 12 mm filaments with the increase in fibre dosage. The peak split tensile strength for 12 mm filament was observed at 12 kg/m<sup>3</sup> (4.14 MPa) which is 20% higher than that of PC. Hence, it can be concluded that the split tensile strength increases with the increase in fibre quantity for 12 mm filaments.

Independent sample t-test (Table 4.32) confirms that the split tensile strength of 12 mm filaments at all three fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>) are not statistically similar to PC at 90% CI. Table 4.34 shows that the change in fibre dosage from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is not statistically significant. However, the change in fibre dosage from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is statistically significant at 90% CI. Hence, both statistical analysis and Figure 5.22b agree well.

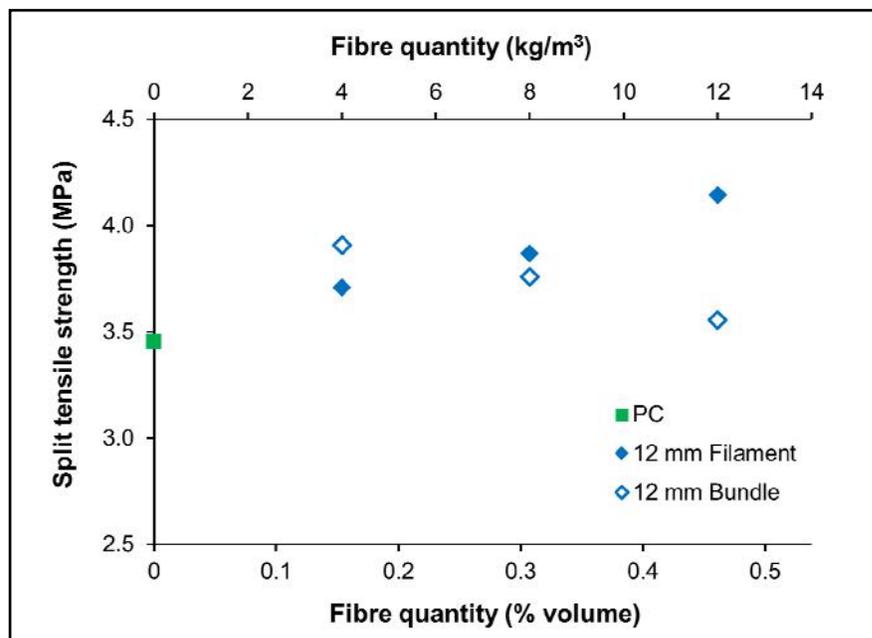


Trend line equation:  $y = 0.0542x + 3.4744$   $R^2 = 0.98$

**Figure 5.22b: Basalt filaments: Effect of fibre quantity of 12 mm fibres**

*Basalt bundles vs. filaments:* Figure 5.22c shows the effect of quantity of 12 mm basalt bundles and filaments on the split tensile strength. It was observed for 12 mm basalt bundles that the split tensile strength decreases with the increase in fibre dosage. However, for 12 mm filaments, the split tensile strength increases with the increase in fibre dosage from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. The split tensile strength of 12 mm filament is 16% higher than that of 12 mm bundle at 12 kg/m<sup>3</sup>. However, the reason for this difference in split tensile strength is not obvious and requires further research.

Independent sample t-test (Table 4.37) shows that the split tensile strength of 12 mm bundles and filaments are statistically similar at all three fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>). However, this is not obvious from Figure 5.22c.



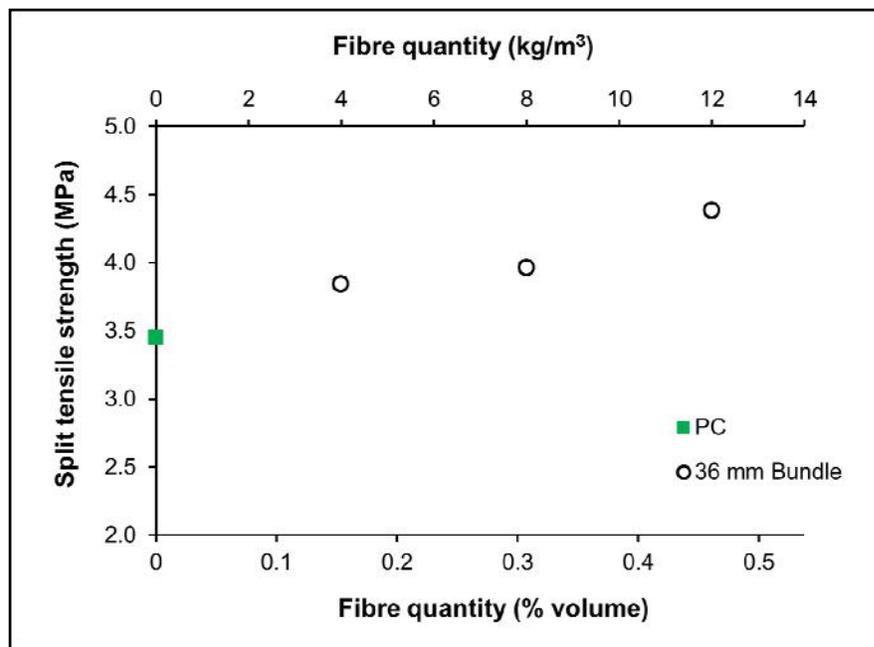
**Figure 5.22c: Effect of fibre quantity of 12 mm basalt fibres**

#### 5.3.4.2 FIBRE LENGTH – 36 mm

*Basalt bundles:* Figure 5.23a shows the effect of quantity of 36 mm basalt bundled fibre on the split tensile strength. An increasing trend was observed in the split tensile strength of 36 mm bundled fibre with the increase in fibre dosage. It was observed that the split

tensile strength of 36 mm bundled fibre at 4 kg/m<sup>3</sup> is 11% higher than that of PC. The peak split tensile strength for 36 mm bundled fibre was observed at 12 kg/m<sup>3</sup> (4.38 MPa) which is 27% higher than that of PC. There is 14% increase in split tensile strength with the increase in fibre dosage from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. However, the independent sample t-test (Table 4.25) shows that this increase is not statistically significant.

Independent sample t-test (Table 4.23) shows that the split tensile strength of 36 mm bundled fibre at 4 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup> are not statistically similar to PC. However, it is statistically similar to PC at 8 kg/m<sup>3</sup>. This is not obvious from Figure 5.23a. Independent sample t-test (Table 4.25) shows that the change in fibre dosage from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> or 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is not statistically significant. This is also not obvious from Figure 5.23a.

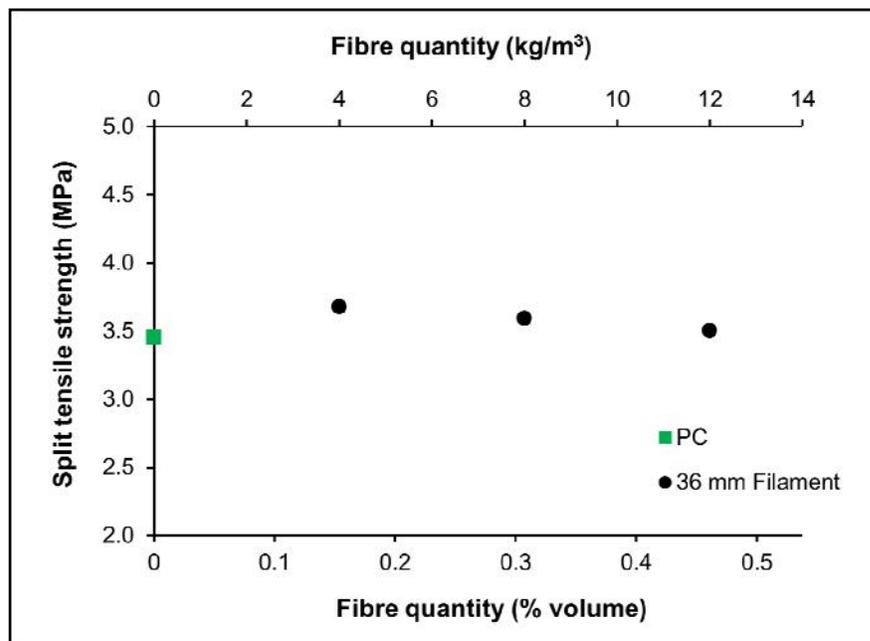


Trend line equation:  $y = 0.0671x + 3.5256$   $R^2 = 0.91$

**Figure 5.23a: Basalt bundles: Effect of fibre quantity of 36 mm fibres**

*Basalt filaments:* Figure 5.23b shows the effect of quantity of 36 mm basalt filament on the split tensile strength. It was observed that the split tensile strength of 36 mm filament decreases with the increase in fibre dosage. This might be because of lumping of 36 mm filament fibres at high fibre dosages (8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup>). The peak split tensile strength for 36 mm filament (3.68 MPa) was observed at 4 kg/m<sup>3</sup> which is 6% higher than that of PC. There is 5% reduction in the split tensile strength with the increase in fibre dosage from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. However, the independent sample t-test (Table 4.34) shows that this decrease is not statistically significant.

Independent sample t-test (Table 4.32) shows that the split tensile strength of 36 mm filament at 4 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup> are statistically similar to PC. However, it is not statistically similar to PC for 8 kg/m<sup>3</sup> at 90% CI. Independent sample t-test (Table 4.34) shows that the change in fibre dosage from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> or 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is not statistically significant. Hence, both statistical analysis and Figure 5.23b agree well. It can be concluded that there is no improvement in the split tensile strength of 36 mm filaments with the increase in fibre dosage.

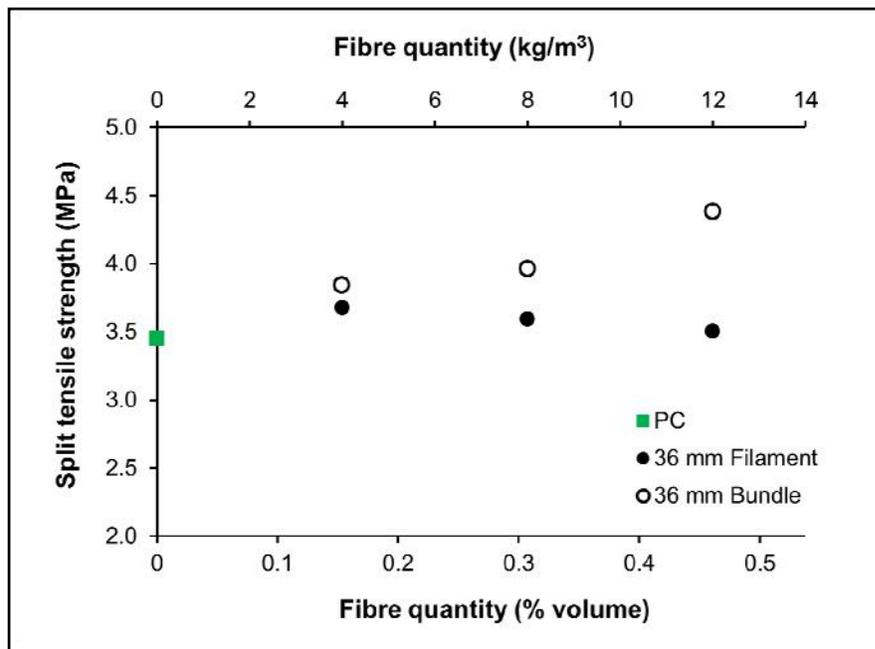


Trend line equation:  $y = -0.0221x + 3.7689$       $R^2 = 1$

**Figure 5.23b: Basalt filaments: Effect of fibre quantity of 36 mm fibres**

*Basalt bundles vs. filaments:* Figure 5.23c shows the effect of quantity of 36 mm basalt bundles and 36 mm filaments on the split tensile strength. It was observed for 36 mm bundles that the split tensile strength increases with the increase in fibre dosage. However, for 36 mm filaments, the split tensile strength decreases with the increase in fibre dosage. This might be due to lumping of 36 mm filament fibres at high fibre dosage (8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup>) during mixing. The split tensile strength of 36 mm bundled fibre is 25% higher than that of 36 mm filament at 12 kg/m<sup>3</sup>.

Independent sample t-test (Table 4.37) also confirms that the split tensile strength of 36 mm bundles and filaments are statistically similar at 4 kg/m<sup>3</sup> and 8 kg/m<sup>3</sup>. However, they are statistically different for 12 kg/m<sup>3</sup> at 90% CI. Hence, both statistical analysis and Figure 5.23c agree well.

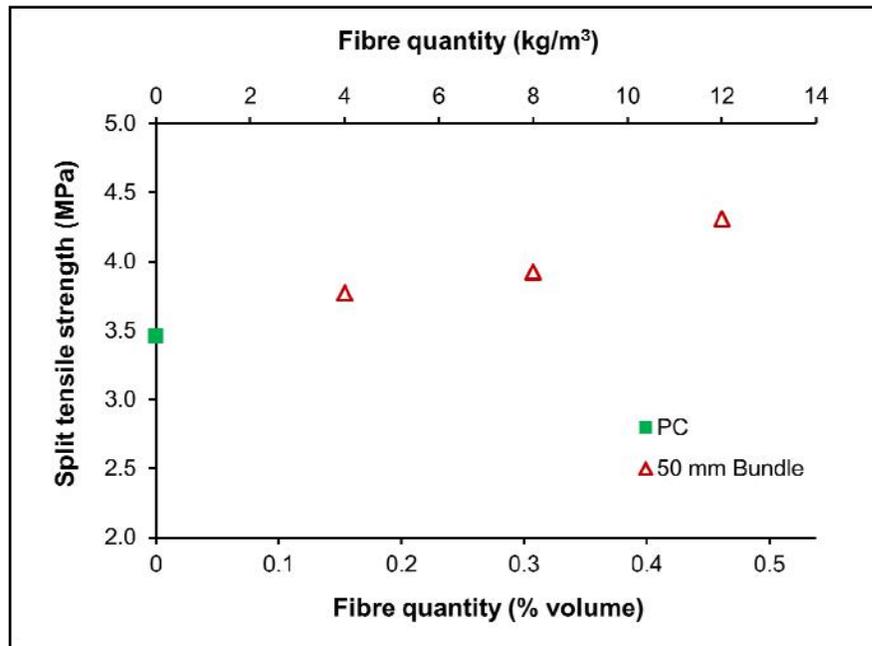


**Figure 5.23c: Effect of fibre quantity of 36 mm basalt fibres**

### 5.3.4.3 FIBRE LENGTH – 50 mm

*Basalt bundles:* Figure 5.24a shows the effect of quantity of 50 mm basalt bundled fibre on the split tensile strength. An increasing trend was observed in the split tensile strength of 50 mm bundled fibre with the increase in fibre dosage. It was observed that the split tensile strength of 50 mm bundled fibre at 4 kg/m<sup>3</sup> is 9% higher than that of PC. The peak split tensile strength was observed at 12 kg/m<sup>3</sup> (4.31 MPa) which is 25% higher than that of PC. There is 14% increase in split tensile strength with the increase in fibre dosage from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. However, the independent sample t-test (Table 4.25) shows that this increase is not statistically significant.

Independent sample t-test (Table 4.23) shows that the split tensile strength of 50 mm bundled fibre at all three fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>) are statistically similar to PC. This is not obvious from Figure 5.24a. Independent sample t-test (Table 4.25) shows that the change in fibre dosage from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> or 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is not statistically significant. This is also not obvious from Figure 5.24a.

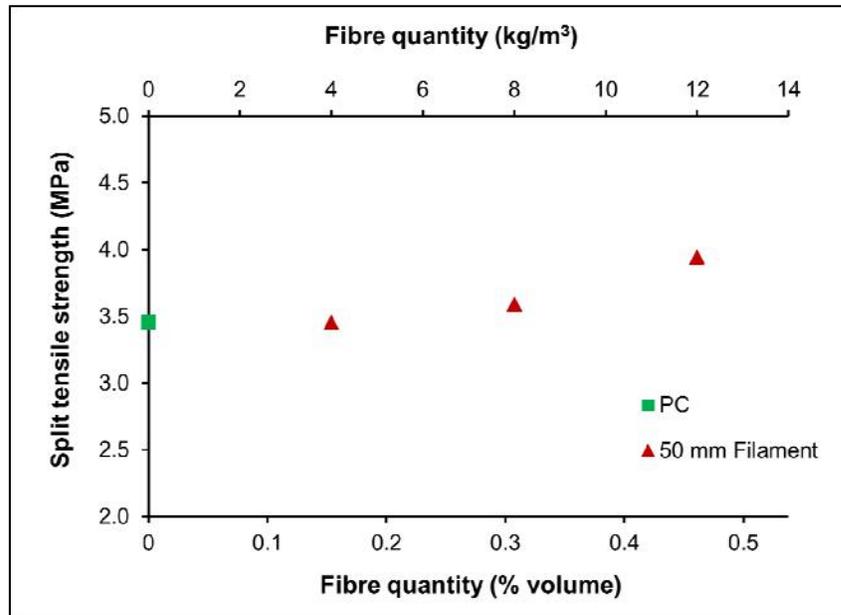


Trend line equation:  $y = 0.0675x + 3.4611$   $R^2 = 0.94$

**Figure 5.24a: Basalt bundles: Effect of fibre quantity of 50 mm fibres**

*Basalt filaments:* Figure 5.24b shows the effect of quantity of 50 mm basalt filament on the split tensile strength. It was observed that the split tensile strength of 50 mm filament increases with the increase in fibre dosage. In order to maintain the workability of the mix for long filaments (50 mm) at high fibre dosage (12 kg/m<sup>3</sup>), Rheobuild 1000 superplasticizer (55 ml) was added. The superplasticizer could have helped in the uniform distribution of filaments in the matrix which could have led to high split tensile strength for 50 mm filament at 12 kg/m<sup>3</sup>. The peak split tensile strength for 50 mm filament was observed at 12 kg/m<sup>3</sup> (3.94 MPa) which is 14% higher than that of PC. There is 14% increase in split tensile strength with the increase in fibre dosage from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. However, the independent sample t-test (Table 4.34) shows that this increase is not statistically significant.

Independent sample t-test (Table 4.32) shows that the split tensile strength of 50 mm filament at all three fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>) are statistically similar to PC. This is not obvious from Figure 5.24b. Independent sample t-test (Table 4.34) shows that the change in fibre dosage from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> or 8 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> is not statistically significant. This is also not obvious from Figure 5.24b.

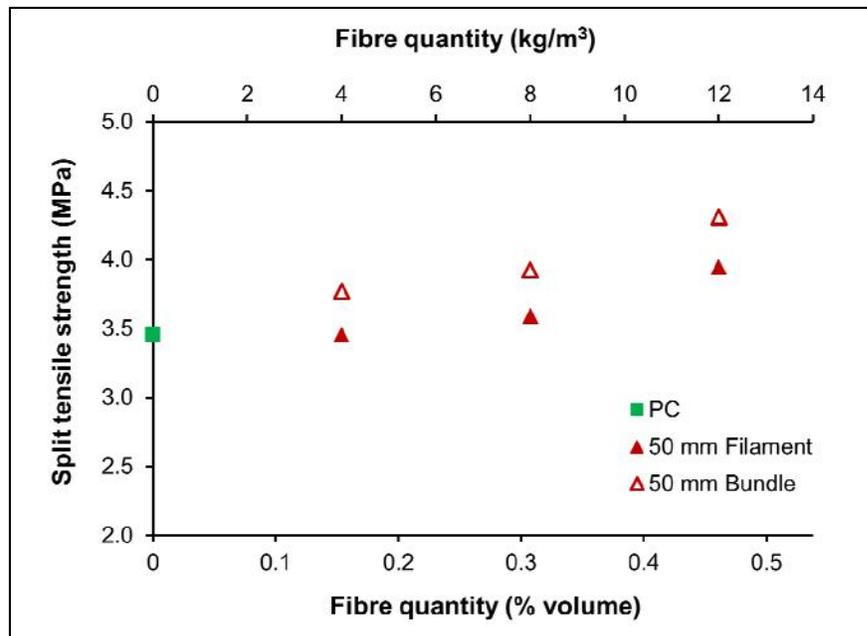


Trend line equation:  $y = 0.0612x + 3.1722$   $R^2 = 0.94$

**Figure 5.24b: Basalt filaments: Effect of fibre quantity of 50 mm fibres**

*Basalt bundles vs. filaments:* Figure 5.24c shows the effect of quantity of 50 mm basalt bundles and 50 mm filaments on the split tensile strength. It was observed that the split tensile strength increases for both 50 mm bundles and 50 mm filaments with the increase in fibre dosage.

Independent sample t-test (Table 4.37) also confirms that the split tensile strength of 50 mm bundles and filaments are statistically similar at all three fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>). Hence, both statistical analysis and Figure 5.24c agree well.



**Figure 5.24c: Effect of fibre quantity of 50 mm basalt fibres**

### 5.3.5 SUMMARY - SPLIT TENSILE STRENGTH

*Basalt bundles vs. control specimens:* The short bundled fibre (12 mm) at all three fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>) shows no improvement in the split tensile strength compared to PC. The medium length (36 mm) bundled fibre at high fibre dosage of 12 kg/m<sup>3</sup> shows significant improvement in split tensile strength over PC. It is 27% higher than that of PC, 19% higher than that of SF 38-40, and 24% higher than that of PP 40-4.5. Long (50 mm) bundled fibre at 12 kg/m<sup>3</sup> also provides similar split tensile strength which is 25% higher than that of PC.

*Basalt bundles: Effect of fibre length and dosage:* The short bundled fibre (12 mm) shows no significant improvement in the split tensile strength with the increase in fibre quantity from 4 kg/m<sup>3</sup> to 8 kg/m<sup>3</sup> or 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup>. However, the medium length (36 mm) and long (50 mm) bundled fibres at low fibre dosage of 4 kg/m<sup>3</sup> provide higher split tensile strength than PC of 11% and 9%, respectively. For medium length (36 mm) and long (50 mm) bundled fibres, the change in fibre dosage from 4 kg/m<sup>3</sup> to 12 kg/m<sup>3</sup> provides 14% increase in split tensile strength. It was observed that the medium (36 mm) and long (50 mm) bundled fibres at high fibre dosage of 12 kg/m<sup>3</sup> help in bridging macro-cracks effectively.

*Basalt filaments vs. control specimens:* The short filament (12 mm) at high fibre dosage of 12 kg/m<sup>3</sup> shows significant improvement in split tensile strength over PC. It is 20% higher than that of PC, 12.8% higher than that of SF 38-40, and 17.6% higher than that of PP 40-4.5. The medium length (36 mm) and long (50 mm) filaments at all three fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>) show no significant improvement in the split tensile strength compared to PC.

*Basalt filaments: Effect of fibre length and dosage:* The short filament fibre (12 mm) shows significant improvement (20%) in split tensile strength from PC at high fibre dosage of 12 kg/m<sup>3</sup>. The medium length (36 mm) filament at low fibre dosage of 4 kg/m<sup>3</sup> provides

6% higher split tensile strength than PC. The split tensile strength of 36 mm filament decreases for fibre dosages beyond 4 kg/m<sup>3</sup> which might be due to lumping of 36 mm filaments at 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup>. There is no significant improvement in the split tensile strength of 50 mm filament from PC at all three fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>).

*Basalt bundles vs. filaments:* The split tensile strength of 12 mm bundle and 12 mm filament are similar at all fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>). The split tensile strength of 36 mm bundle and 36 mm filament are similar at 4 kg/m<sup>3</sup> and 8 kg/m<sup>3</sup>. However, the split tensile strength of 36 mm bundled fibre is 25% higher than that of 36 mm filament at 12 kg/m<sup>3</sup>. This is due to lumping of filaments at high fibre dosage of 12 kg/m<sup>3</sup>. The split tensile strength of the 50 mm bundle and 50 mm filament are similar at all fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>).

## 5.4 BEAM LOAD DEFLECTION PLOTS

The load-deflection curves for plain concrete, basalt bundles, basalt filaments, steel fibre, and macro synthetic fibre beam specimens are shown in Figure 5.25 to Figure 5.46. There is little improvement in ductility in basalt specimens from the PC specimen, although, there is improvement in the peak load carrying capacity of basalt specimens with the increasing fibre quantity and length. This was also observed during the flexural test, where all the basalt fibre specimens failed in a brittle and sudden manner after the first crack (after reaching the peak load). The steel fibre and macro-synthetic specimens failed in a ductile manner after reaching the maximum load. The fibres were able to take the load in tension after the first crack. Figure 5.45 and Figure 5.46 shows considerable improvement in flexural toughness for both steel and macro synthetic specimens over PC.

Toughness indices ( $I_5$ ,  $I_{10}$ ,  $I_{20}$ ) are dimensionless parameters which are defined on the basis of three service levels identified as the multiples of the first crack deflection. The index  $I_5$  is computed by dividing the area under the load-deflection curve up to three times the first crack deflection divided by the area up to first crack deflection. Likewise,  $I_{10}$  and  $I_{20}$  are the indices up to 5.5 and 10.5 times the first crack deflection, respectively. Flexural toughness for basalt fibre specimens (bundles and filaments) were not calculated in this research as the maximum deflection obtained for basalt fibre specimens were below three times the first-crack deflection (specimens failed in a brittle and sudden manner after the first crack).

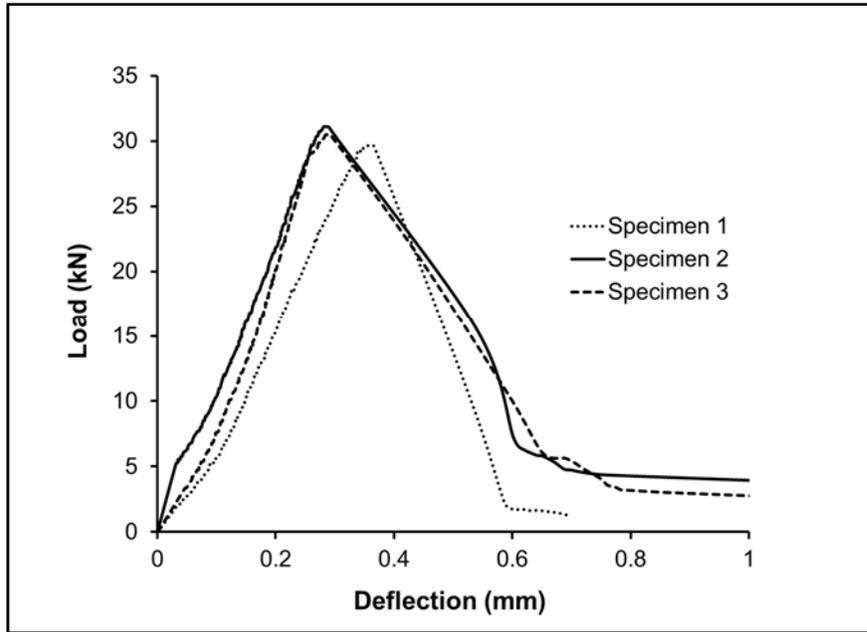


Figure 5.25: PC

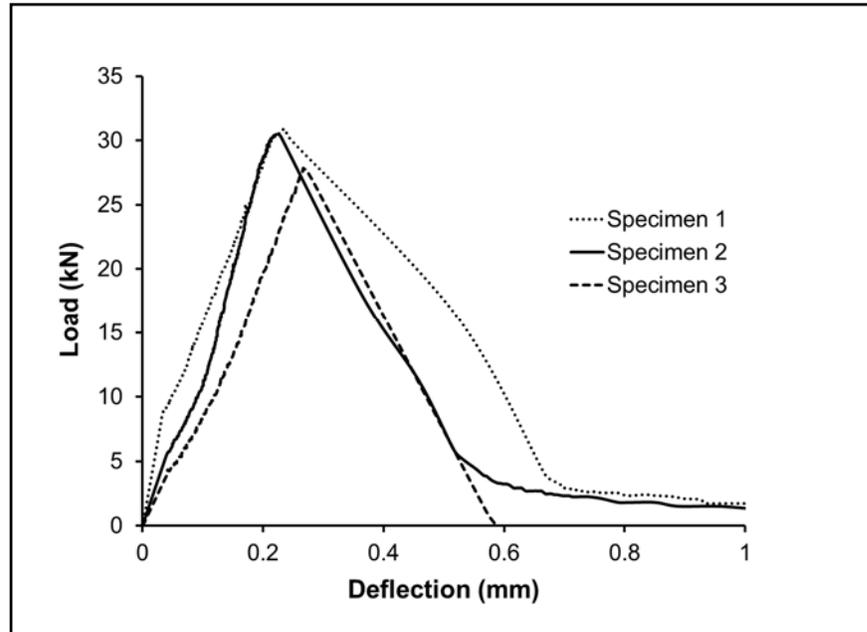


Figure 5.26: BF 12-4

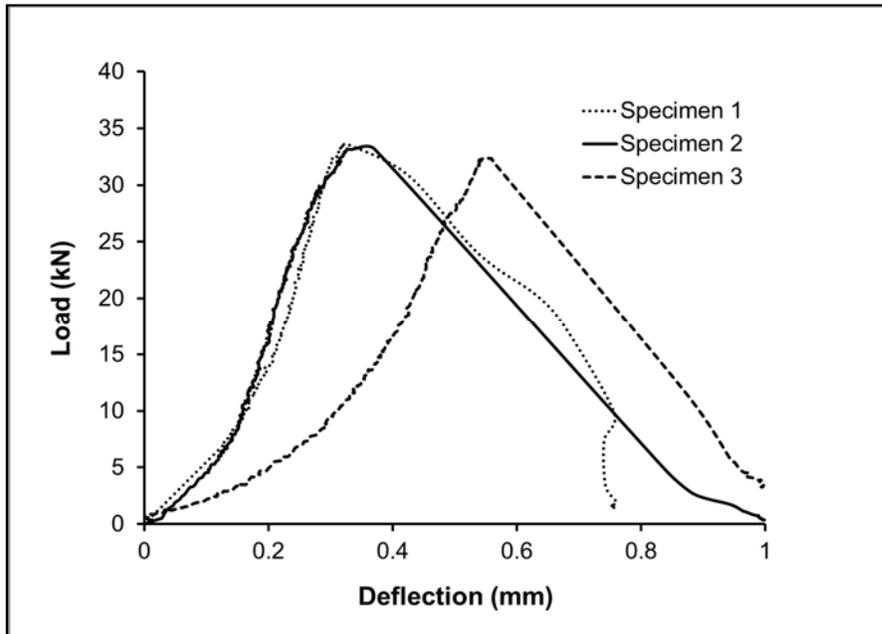


Figure 5.27: BF 12-8

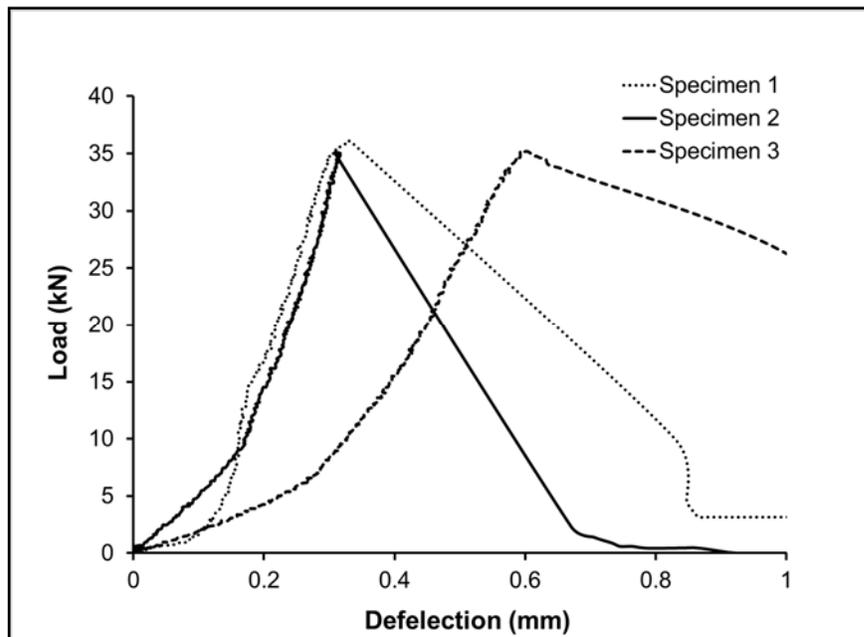


Figure 5.28: BF 12-12

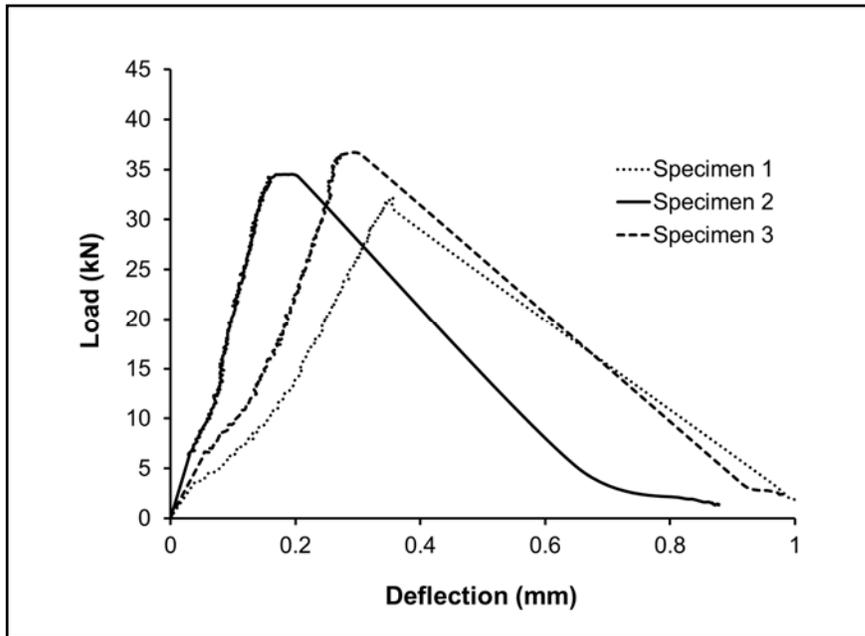


Figure 5.29: BF 36-4

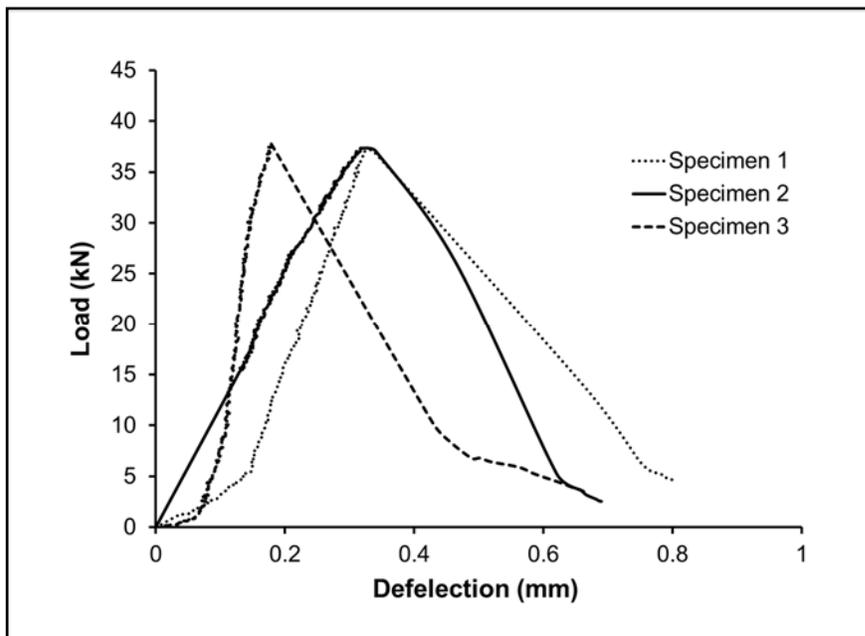


Figure 5.30: BF 36-8

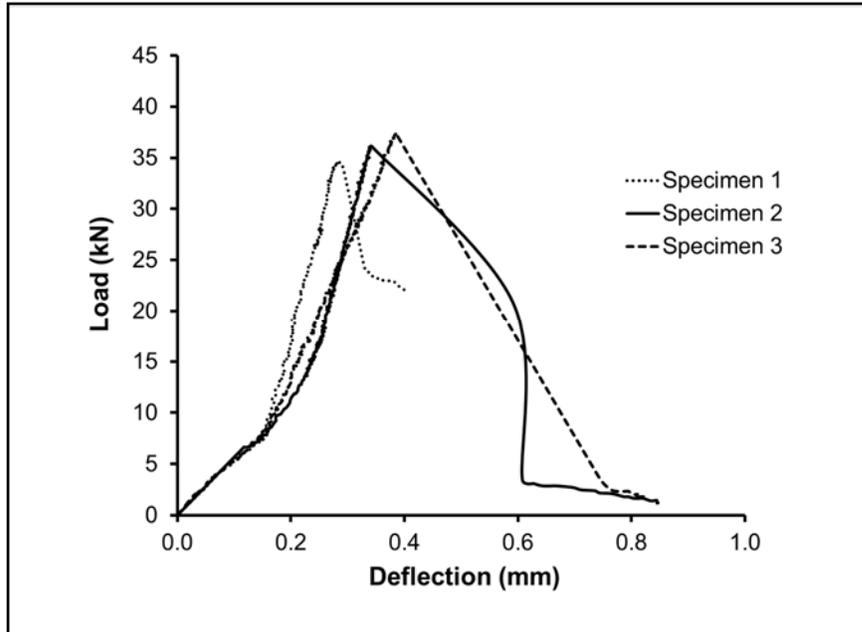


Figure 5.31: BF 36-12

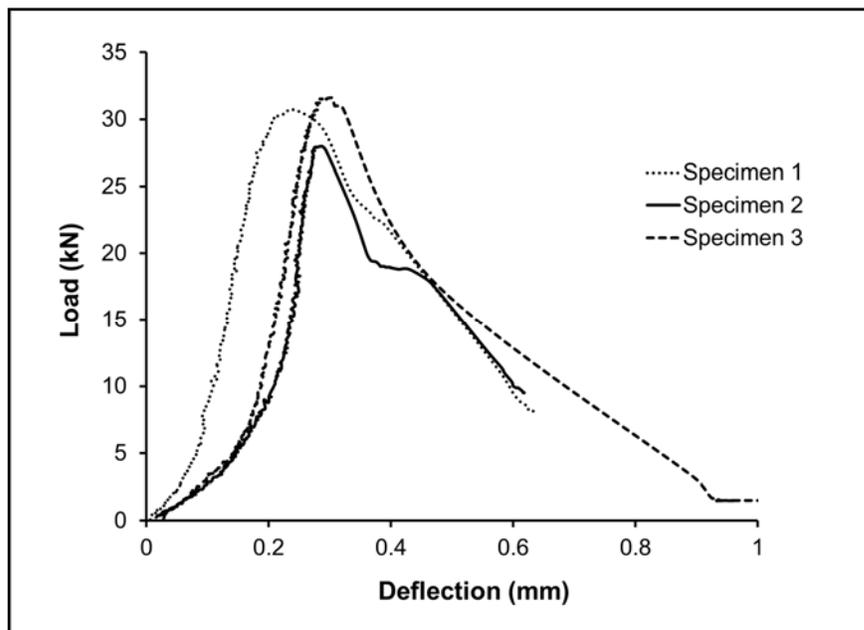


Figure 5.32: BF 50-4

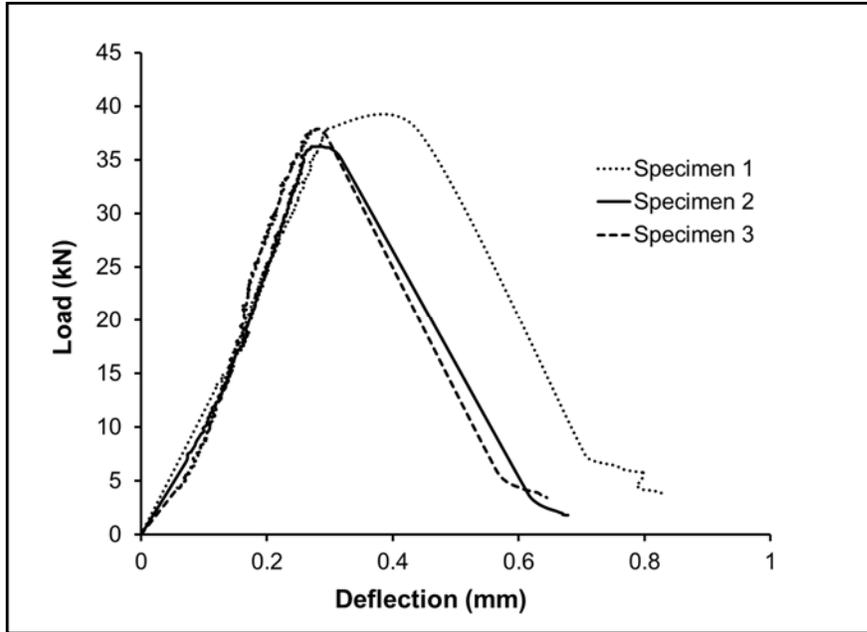


Figure 5.33: BF 50-8

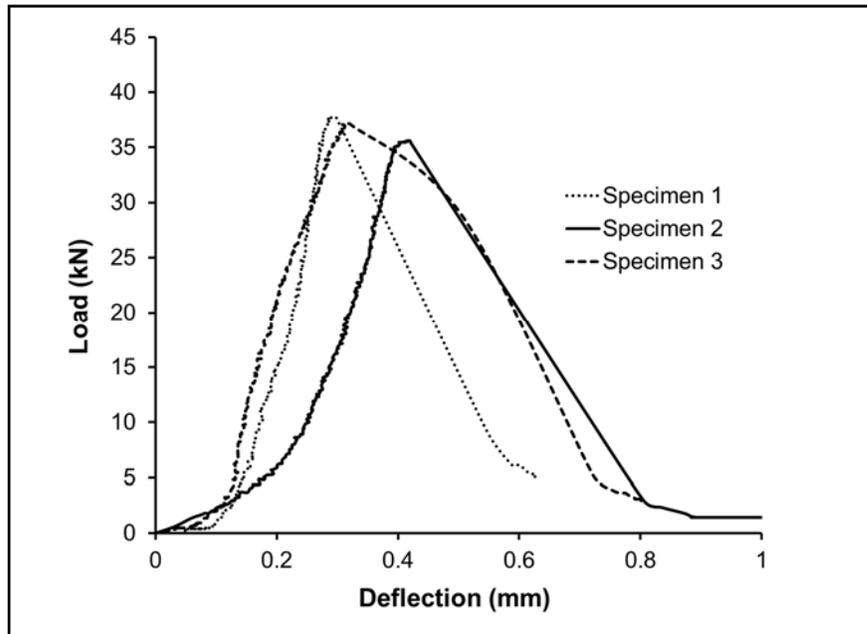


Figure 5.34: BF 50-12

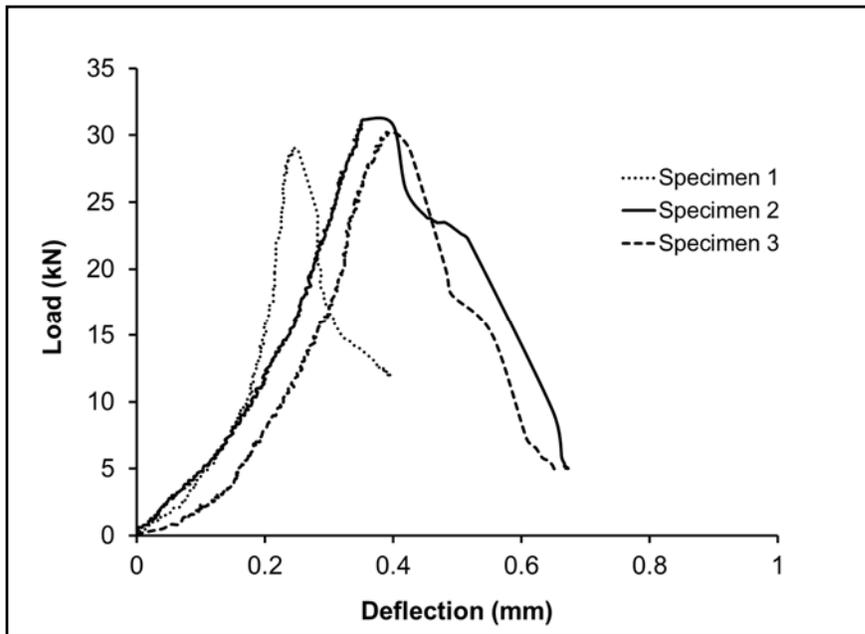


Figure 5.35: BB 12-4

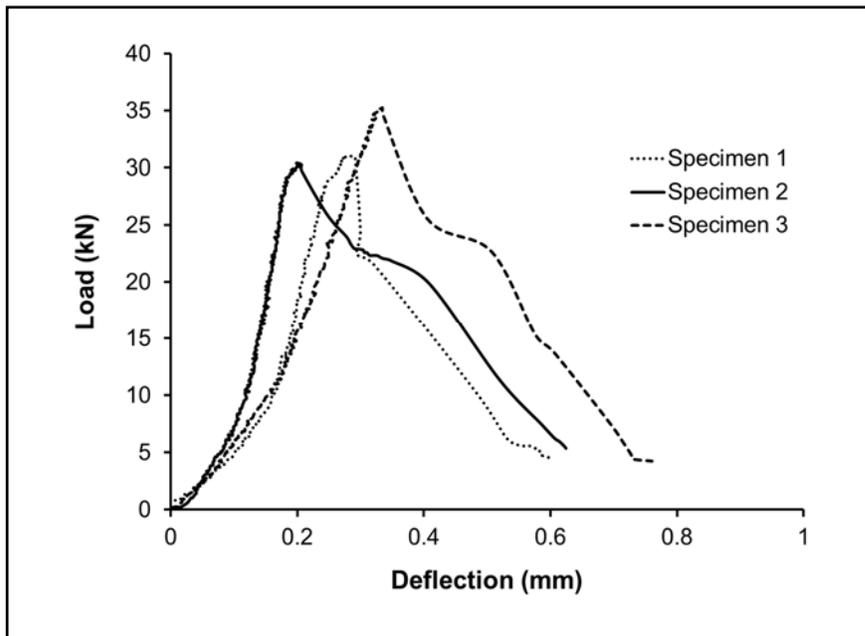


Figure 5.36: BB 12-8

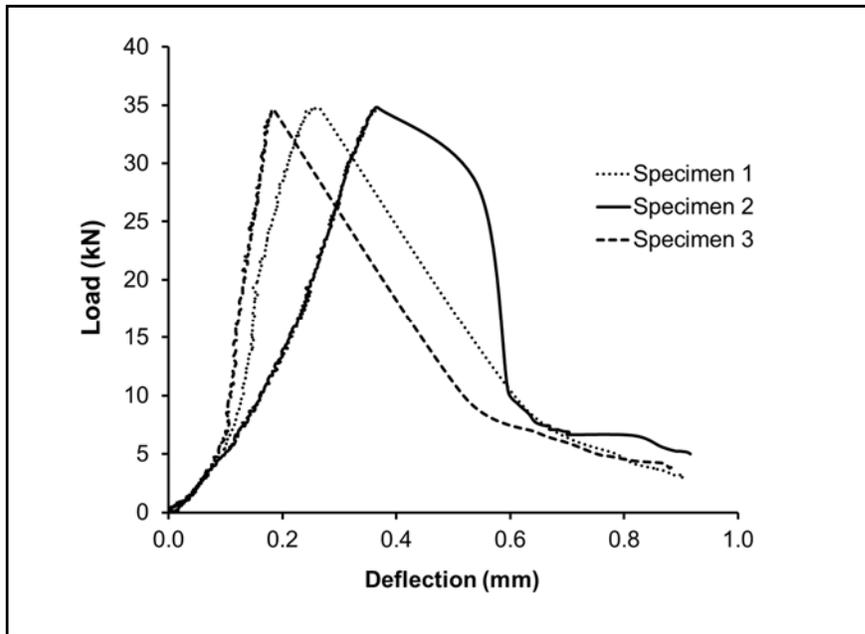


Figure 5.37: BB 12-12

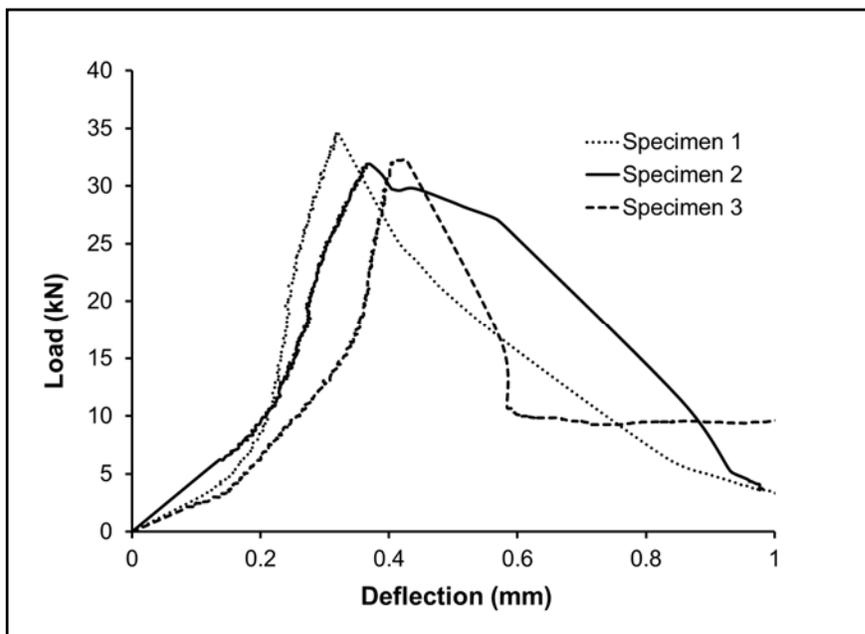


Figure 5.38: BB 36-4

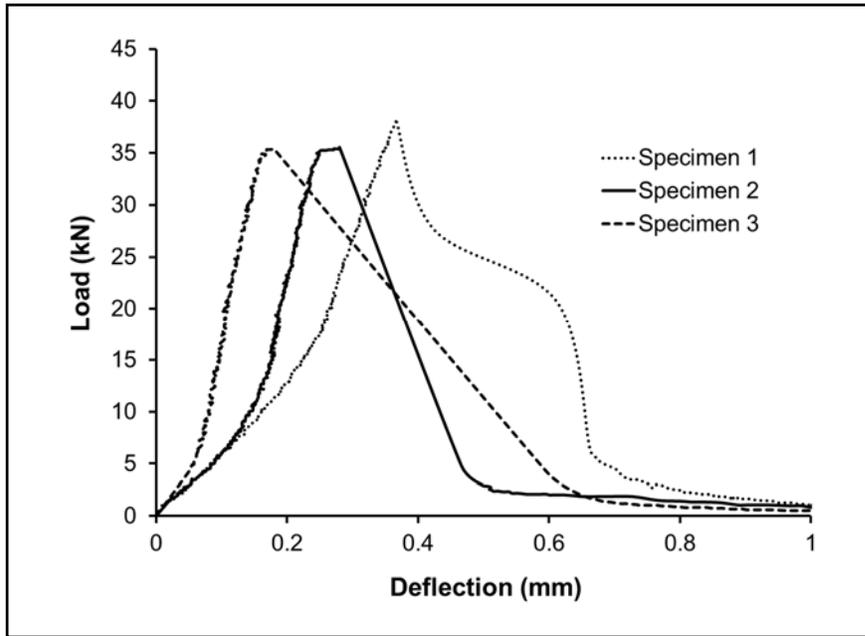


Figure 5.39: BB 36-8

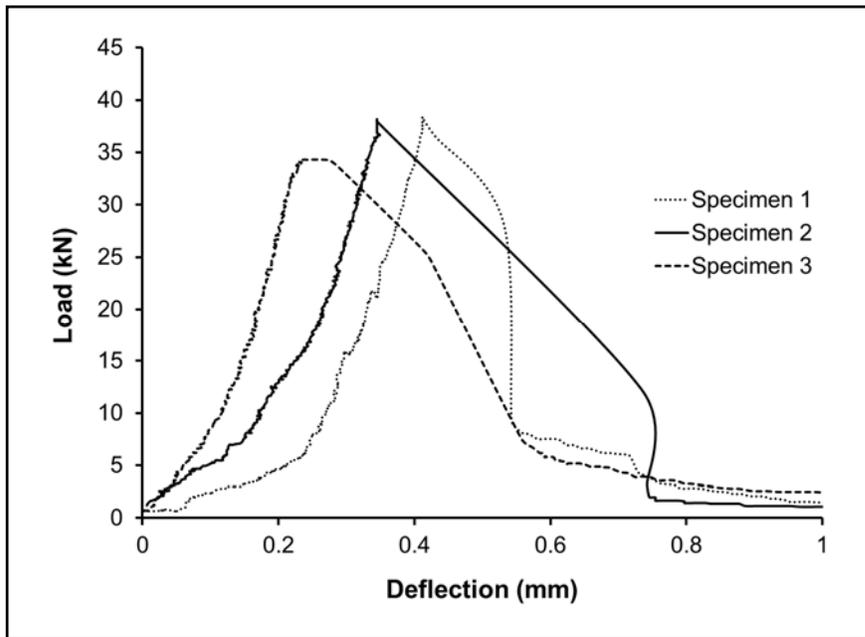
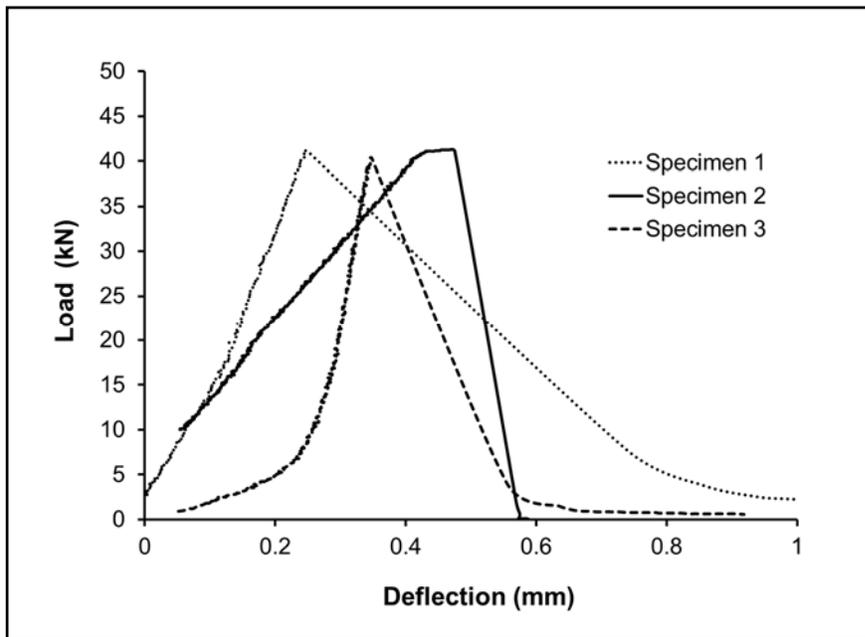
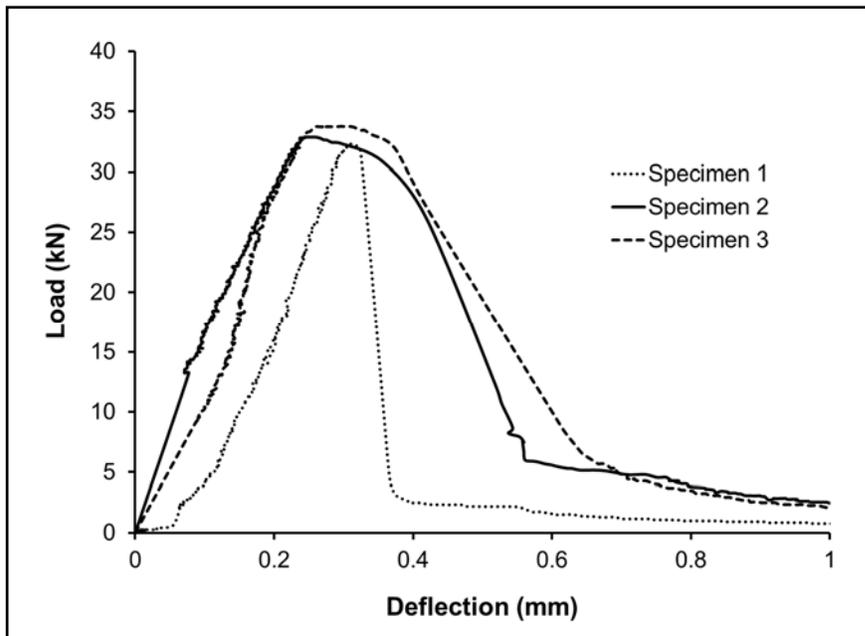


Figure 5.40: BB 36-12



**Figure 5.41: BB 50-4**



**Figure 5.42: BB 50-4 – Repeat mix**

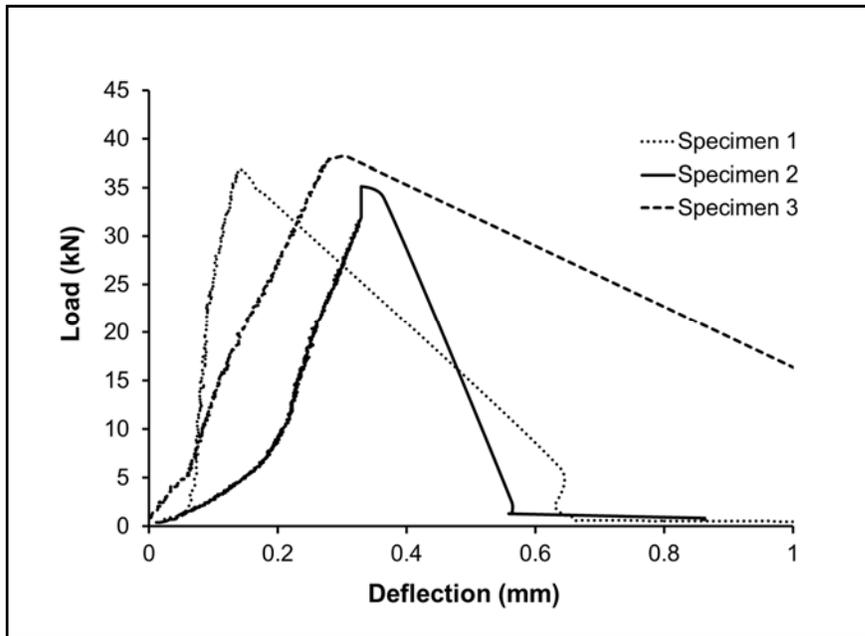


Figure 5.43: BB 50-8

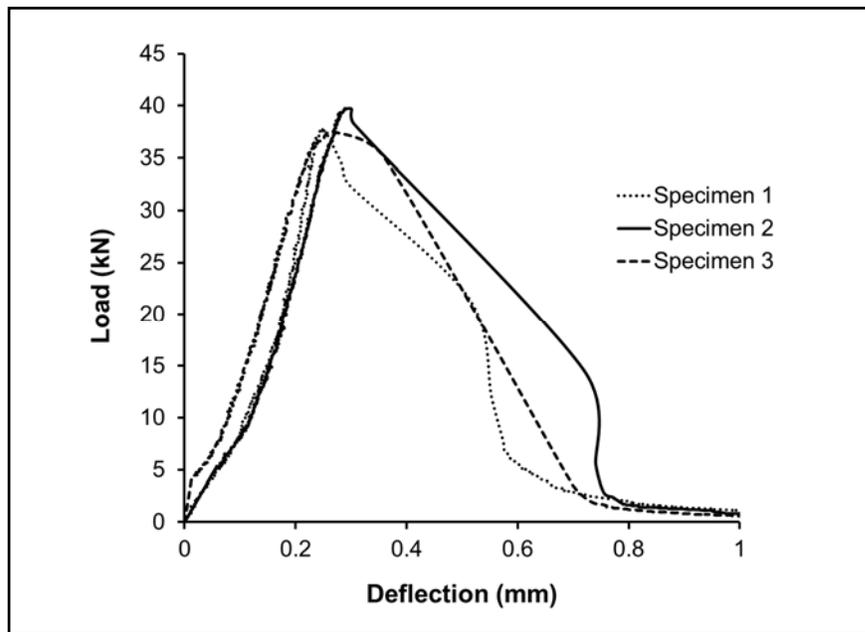
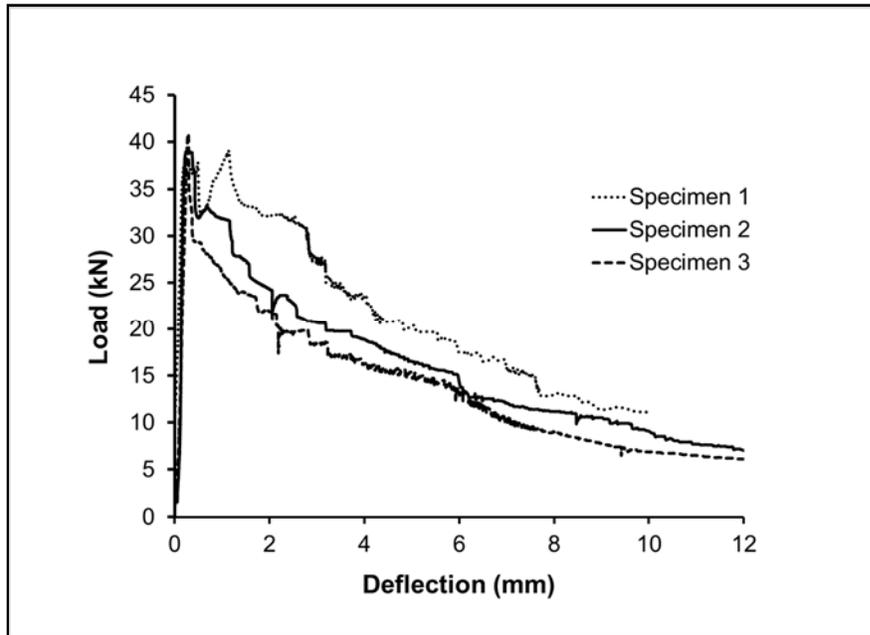
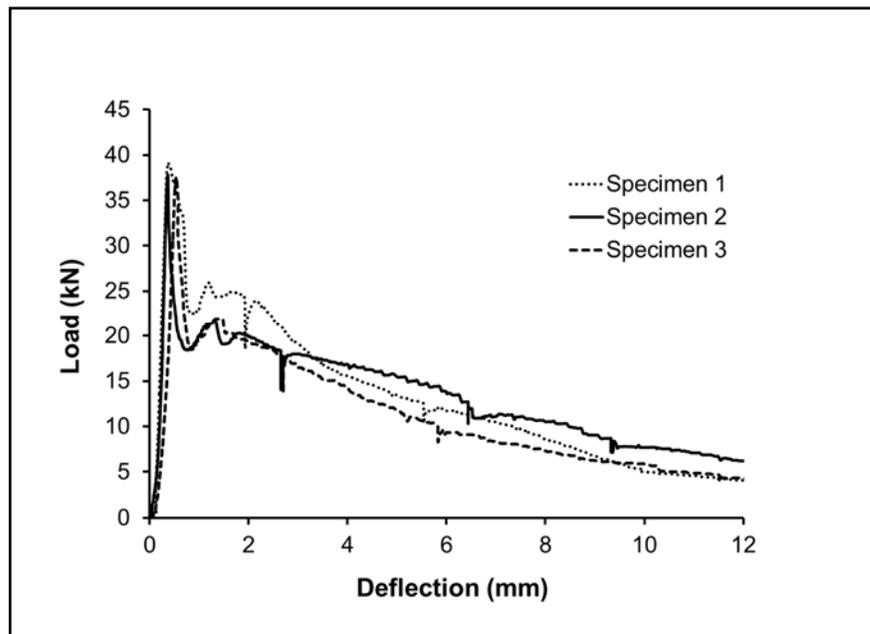


Figure 5.44: BB 50-12



**Figure 5.45: SF 38-40**



**Figure 5.46: PP 40-4.5**

## 5.5 MODULUS OF RUPTURE AND COMPRESSIVE STRENGTH – RELATION

The relationship between modulus of rupture ( $f_r$ ) and compressive strength ( $f'_c$ ) of plain concrete is shown in Equation 5.1 (CSA A23.3-04 Clause 8.6.4, 2010).

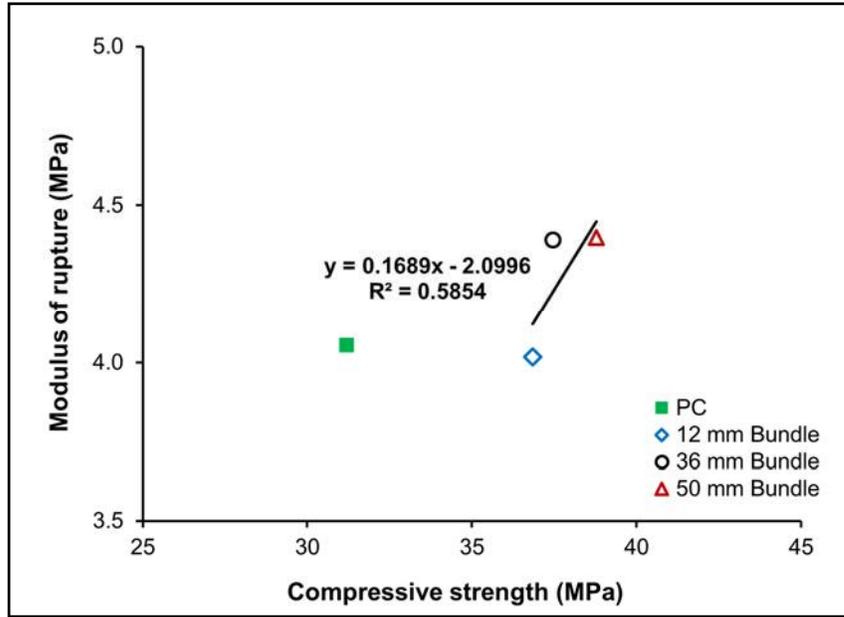
$$f_r = 0.6\lambda\sqrt{f'_c} \quad (5.1)$$

where  $\lambda = 1.0$  for normal density concrete.

Equation 5.1 is not applicable for fibre reinforced concrete. Hence, an attempt is made in this section to find the relationship between MOR and compressive strength for basalt fibre reinforced concrete (bundles and filaments) at fibre dosages of 4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>.

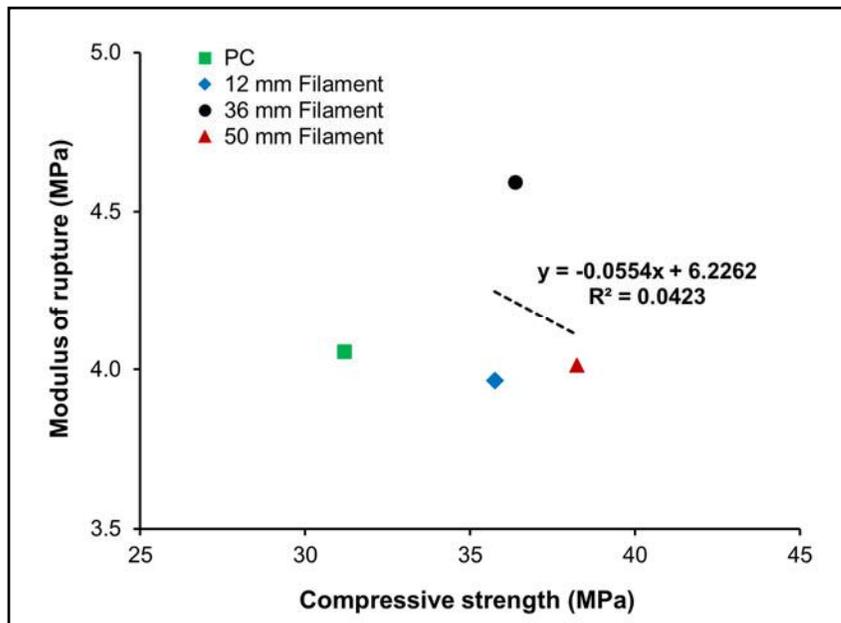
The regression line shows the relationship between modulus of rupture ( $f_r$ ) and compressive strength ( $f'_c$ ) for basalt bundles and filaments. The linear correlation coefficient ( $R$ ), is a measure of the linear correlation (dependence) between two variables. The coefficient of determination ( $R^2$ ) is a statistical measure of how well the regression line approximates the real data points. In other words, the coefficient of determination ( $R^2$ ) represents the percentage of data close to the regression line (line of best fit). An  $R^2$  of 1 indicates that the regression line perfectly fits the data and shows greater degree of association between the two variables.

Figure 5.47a shows the relationship between mean MOR and mean compressive strength of basalt bundled fibres (12 mm, 36 mm, and 50 mm) at 4 kg/m<sup>3</sup>. It was observed that  $R^2 = 0.5854$  which means that only 58.5% of the variation in modulus of rupture is explained by the variation in compressive strength (or the regression line). Hence, there is no strong relationship between MOR and compressive strength of basalt bundles at 4 kg/m<sup>3</sup>.



**Figure 5.47a: Basalt bundles: MOR vs. Compressive strength – 4 kg/m<sup>3</sup>**

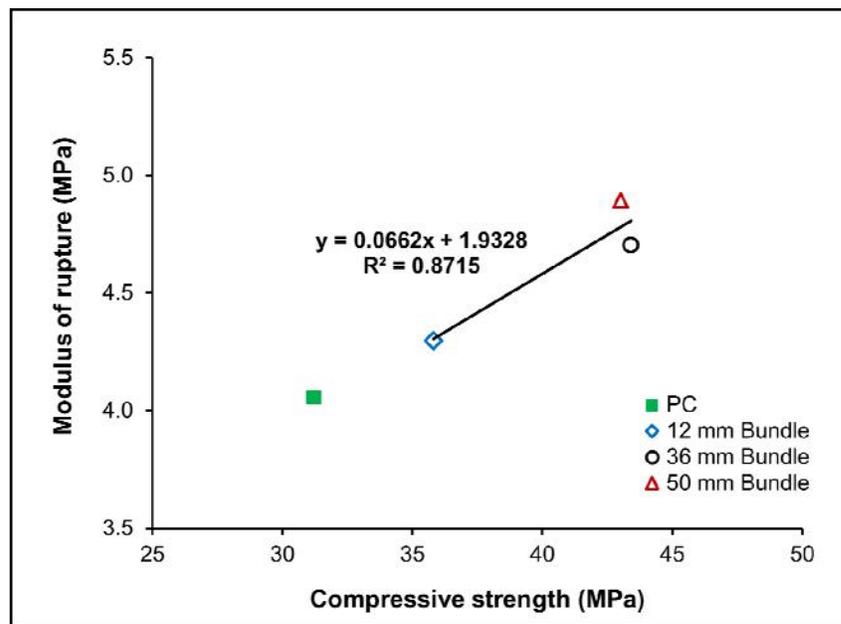
Figure 5.47b shows the relationship between mean MOR and mean compressive strength of basalt filaments (12 mm, 36 mm, and 50 mm) at 4 kg/m<sup>3</sup>. It was observed that  $R^2 = 0.0423$  which means that only 4% of the variation in modulus of rupture is explained by the variation in compressive strength (or the regression line). Hence there is no strong relationship between MOR and compressive strength of basalt filaments at 4 kg/m<sup>3</sup>.



**Figure 5.47b: Basalt filaments: MOR vs. Compressive strength – 4 kg/m<sup>3</sup>**

Figure 5.48a shows the relationship between mean MOR and mean compressive strength of basalt bundled fibres (12 mm, 36 mm, and 50 mm) at 8 kg/m<sup>3</sup>. It was observed that R<sup>2</sup> = 0.8715 which means that 87% of the variation in modulus of rupture is explained by the variation in compressive strength (or the regression line). Hence, there exists a strong relationship between MOR and compressive strength of basalt bundles at 8 kg/m<sup>3</sup> given by Equation 5.2.

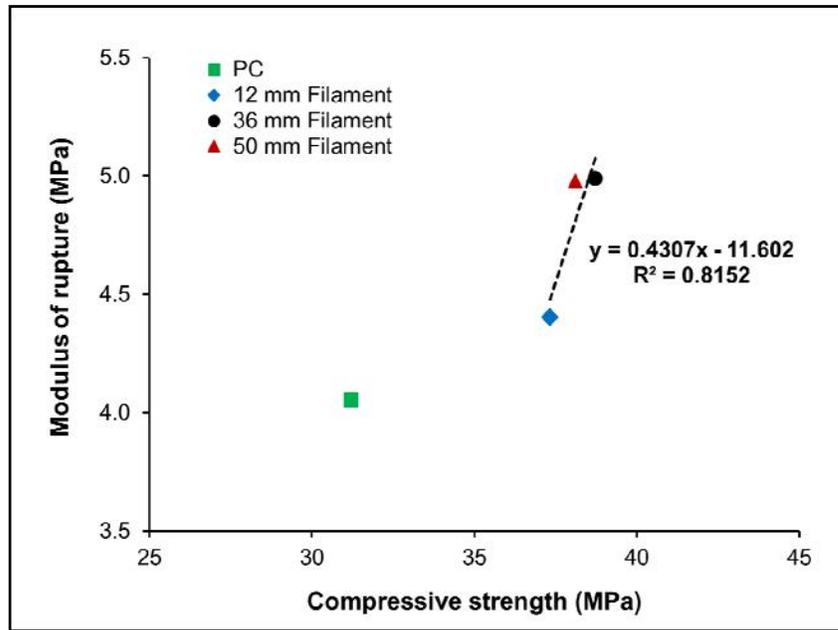
$$f_r = 0.0662f'_c + 1.9328 \quad (5.2)$$



**Figure 5.48a: Basalt bundles: MOR vs. Compressive strength – 8 kg/m<sup>3</sup>**

Figure 5.48b shows the relationship between mean MOR and mean compressive strength of basalt filaments (12 mm, 36 mm, and 50 mm) at 8 kg/m<sup>3</sup>. It was observed that R<sup>2</sup> = 0.8152 which means that 81% of the variation in modulus of rupture is explained by the variation in compressive strength (or the regression line). Hence, there exists a strong relationship between MOR and compressive strength of basalt filaments at 8 kg/m<sup>3</sup> given by Equation 5.3.

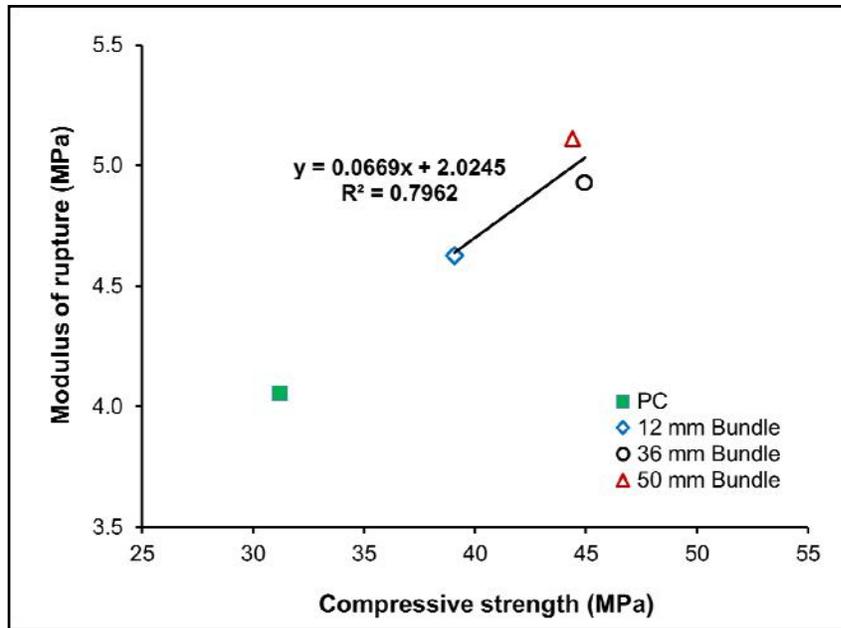
$$f_r = 0.4307f'_c - 11.602 \quad (5.3)$$



**Figure 5.48b: Basalt filaments: MOR vs. Compressive strength – 8 kg/m<sup>3</sup>**

Figure 5.49a shows the relationship between mean MOR and mean compressive strength of basalt bundled fibres (12 mm, 36 mm, and 50 mm) at 12 kg/m<sup>3</sup>. It was observed that  $R^2 = 0.7962$  which means that 79.6% of the variation in modulus of rupture is explained by the variation in compressive strength (or the regression line). Hence, there exists a strong relationship between MOR and compressive strength of basalt bundles at 12 kg/m<sup>3</sup> given by Equation 5.4.

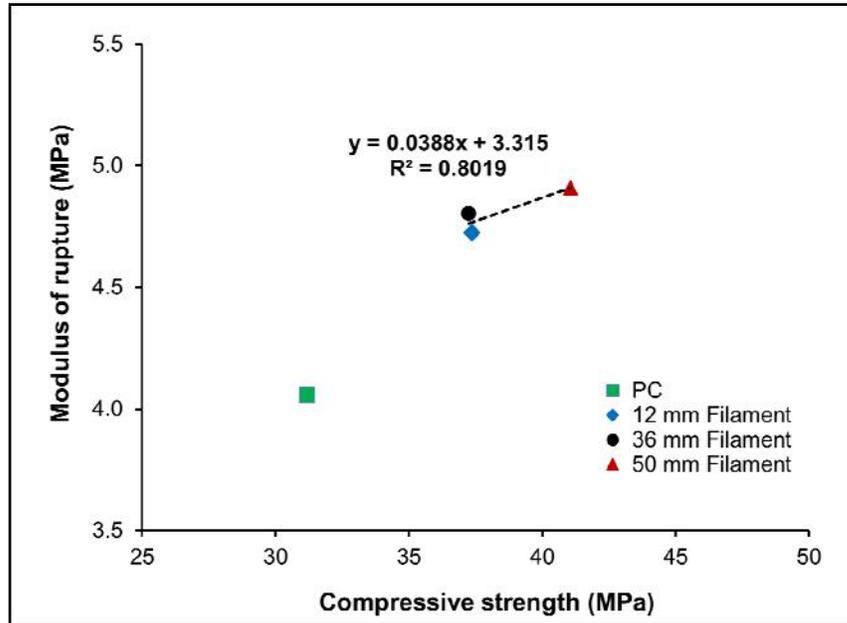
$$f_r = 0.0669f'_c + 2.0245 \quad (5.4)$$



**Figure 5.49a: Basalt bundles: MOR vs. Compressive strength – 12 kg/m<sup>3</sup>**

Figure 5.49b shows the relationship between mean MOR, and mean compressive strength of basalt filaments (12 mm, 36 mm, and 50 mm) at 12 kg/m<sup>3</sup>. It was observed that  $R^2 = 0.8019$  which means that 80% of the variation in modulus of rupture is explained by the variation in compressive strength (or the regression line). Hence, there exists a strong relationship between MOR and compressive strength of basalt filaments at 12 kg/m<sup>3</sup> given by Equation 5.5.

$$f_r = 0.0388f'_c + 3.315 \quad (5.5)$$



**Figure 5.49b: Basalt filaments: MOR vs. Compressive strength – 12 kg/m<sup>3</sup>**

### 5.5.1 SUMMARY

For both basalt bundled fibres and filaments at 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup> there exists a strong relationship between modulus of rupture (MOR) and compressive strength.

## **5.6 COMPARISON WITH SIMILAR TESTS ON BFRC**

This section compares the test results of mechanical properties (flexural strength, compressive strength, and split tensile strength) of basalt fibre reinforced concrete (BFRC) obtained from this research with similar research.

### **5.6.1 TEST 1**

Borhan (2013) investigated the mechanical properties of basalt fibre reinforced concrete using fibres 13  $\mu\text{m}$  in diameter and 25.4 mm in length. The following volume fractions of basalt fibre were used: 0.1%, 0.2%, 0.3%, and 0.5%. Results indicated that the compressive strength and the split tensile strength increase with the increase in fibre content until 0.3% by volume, then there was a slight reduction for 0.5% by volume of basalt fibre. There was up to 10% increase in split tensile strength for 0.3% by volume of basalt fibre and 4% reduction in split tensile strength for 0.5% by volume of basalt fibre, with respect to plain concrete. Similarly, there was up to 15% increase in compressive strength for 0.3% by volume of fibre and 10% reduction in compressive strength for 0.5% by volume of fibre, with respect to plain concrete.

#### **5.6.1.1 COMPARISON WITH TEST 1**

The compressive strength and split tensile strength test results of BFRC (16  $\mu\text{m}$  in diameter and 36 mm long filament) at 8  $\text{kg}/\text{m}^3$  and 12  $\text{kg}/\text{m}^3$  fibre dosages obtained from this research are compared with the test results of Borhan (2013). Fibre dosage of 8  $\text{kg}/\text{m}^3$  corresponds to 0.3% by volume of fibre and fibre dosage of 12  $\text{kg}/\text{m}^3$  corresponds to 0.46% by volume of fibre.

The test results from this research show that there was 24% and 4% increase in compressive strength and split tensile strength from PC with the increase in fibre dosage up to 8  $\text{kg}/\text{m}^3$ . However, there was 4% and 2.5% reduction in compressive strength and split tensile strength with the change in fibre quantity from 8  $\text{kg}/\text{m}^3$  to 12  $\text{kg}/\text{m}^3$ .

Hence, it was observed that the compressive strength and split tensile strength increases with the increase in fibre dosage up to  $8 \text{ kg/m}^3$ , and decreases with the change in fibre quantity from  $8 \text{ kg/m}^3$  to  $12 \text{ kg/m}^3$  for basalt filaments of medium length (36 mm). The test results from this research and the test results of Borhan's (2013) show similar trend. However, reduction in compressive strength and split tensile strength from PC observed in Borhan's study was not observed in this research. All basalt filament specimens provided compressive strength and split tensile strength higher than that of PC.

## **5.6.2 TEST 2**

Jun and Ye (2010) conducted flexural strength tests on basalt fibre reinforced concrete using fibres  $15 \mu\text{m}$  in diameter and 30 mm in length. The following volume fractions of basalt fibre were used: 0.1%, 0.15%, 0.2%, 0.25%, 0.3%, and 0.35%. Results showed that there was up to 12.3% increase in flexural strength from plain concrete for 0.3% by volume of basalt fibre. However, slight reduction (0.5%) in flexural strength was observed for 0.35% by volume of basalt fibre from 0.3% by volume of basalt fibre.

### **5.6.2.1 COMPARISON WITH TEST 2**

The flexural strength of BFRC ( $16 \mu\text{m}$  in diameter and 36 mm long filament) at  $8 \text{ kg/m}^3$  (0.3% by volume) obtained from this research are compared with the test results of Jun and Ye (2010). The test results from this research show that there was 23% increase in flexural strength from plain concrete at  $8 \text{ kg/m}^3$  (0.3% by volume) fibre dosage. However, slight reduction (1%) in flexural strength was observed for  $9 \text{ kg/m}^3$  (0.35% by volume of basalt fibre) from  $8 \text{ kg/m}^3$  fibre dosage.

Hence, it was observed that the test results of Jun and Ye (2010) and the test results from this research show increase in flexural strength from plain concrete up to  $8 \text{ kg/m}^3$  fibre dosage and a slight reduction in flexural strength with further addition of basalt fibre ( $9 \text{ kg/m}^3$ ).

### **5.6.3 TEST 3**

Flexural and compressive strength tests were conducted with 16  $\mu\text{m}$  diameter and 24 mm long basalt fibre reinforced concrete by KNUCA (2011) for Technobasalt-Invest LLC. The results showed that the flexural strength and the compressive strength increased by 29% and 14%, respectively from plain concrete specimen; by adding 5  $\text{kg}/\text{m}^3$  (0.19% by volume) of basalt fibre to 29 MPa concrete.

#### **5.6.3.1 COMPARISON WITH TEST 3**

The flexural strength and compressive strength of BFRC (16  $\mu\text{m}$  in diameter and 36 mm long filament) obtained from this research are compared with the test results of KNUCA (2011). The test results from this research show that there was 16% increase in flexural strength and 18.5% increase in compressive strength from plain concrete at 5  $\text{kg}/\text{m}^3$  (0.19% by volume) fibre dosage. This was obtained by interpolating the test results of 36 mm filament at 4  $\text{kg}/\text{m}^3$  and 8  $\text{kg}/\text{m}^3$ .

Hence, it was observed that the test results of KNUCA (2011) and the test results from this research show higher flexural strength and compressive strength at 5  $\text{kg}/\text{m}^3$  if compared with plain concrete. Both studies show that the flexural strength and compressive strength follow an increasing trend with the addition of basalt filaments (up to 5  $\text{kg}/\text{m}^3$ ).

## 5.7 CONCLUSIONS

All basalt fibre beam and cylinder specimens (bundle and filament) failed in a brittle, and sudden manner after the first crack, similar to PC. However, there was improvement in the peak strength (flexural, compressive, and split tensile). Steel fibre and macro synthetic fibre control specimens failed in a ductile manner after the first crack. The tested basalt fibre, steel fibre, and macro synthetic fibre specimens are shown in Appendix B.

### 5.7.1 BASALT BUNDLES

- The medium length (36 mm) and long (50 mm) bundled fibres at high fibre dosage of  $12 \text{ kg/m}^3$  have consistently performed (flexural strength, compressive strength, and split tensile strength) better than all other basalt fibre specimens. The flexural strength and compressive strength of these specimens are comparable with SF 38-40.
- Compared to PC, 36 mm bundled fibre at  $12 \text{ kg/m}^3$  provided 22% increase in MOR, 44% increase in compressive strength, and 27% increase in split tensile strength. Similarly, 50 mm bundled fibre at  $12 \text{ kg/m}^3$  provided 26% increase in MOR, 42% increase in compressive strength, and 25% increase in split tensile strength compared to PC.
- The long (50 mm) bundled fibre at  $8 \text{ kg/m}^3$  provided flexural strength similar to PP 40-4.5 and compressive strength similar to SF 38-40. It shows 21% increase in MOR, 38% increase in compressive strength, and 14% increase in split tensile strength if compared with PC.
- The increase in strength (flexural, compressive, and split tensile strength) for 50 mm bundled fibre with the change in fibre dosage from  $8 \text{ kg/m}^3$  to  $12 \text{ kg/m}^3$  is not statistically significant. Hence, the optimum fibre dosage for 50 mm bundled fibre is  $8 \text{ kg/m}^3$ .
- Satisfactory workability could be maintained even at high volume fractions (up to  $12 \text{ kg/m}^3$ ) of long basalt bundle fibres (36 mm and 50 mm) which dispersed uniformly in the concrete mix.

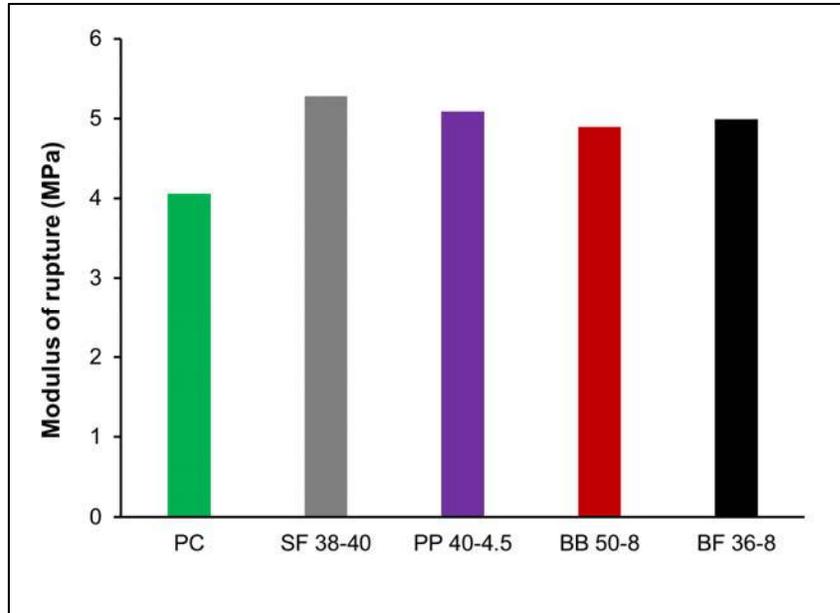
### **5.7.2 BASALT FILAMENTS**

- The medium length (36 mm) filament at 8 kg/m<sup>3</sup> and long (50 mm) filament at 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup> provided flexural strength similar to PP 40-4.5 control specimen. The MOR of BF 36-8, BF 50-8, and BF 50-12 are 23%, 23% and 21% higher than that of PC, respectively.
- None of the basalt filament specimens provided flexural strength similar to SF 38-40 control specimen.
- The short (12 mm) filament at high fibre dosage of 12 kg/m<sup>3</sup> showed 20% increase in compressive strength and split tensile strength when compared with PC.
- The medium length (36 mm) and long (50 mm) filaments tend to lump at high fibre dosage (8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup>).

### **5.7.3 BASALT BUNDLES vs. BASALT FILAMENTS**

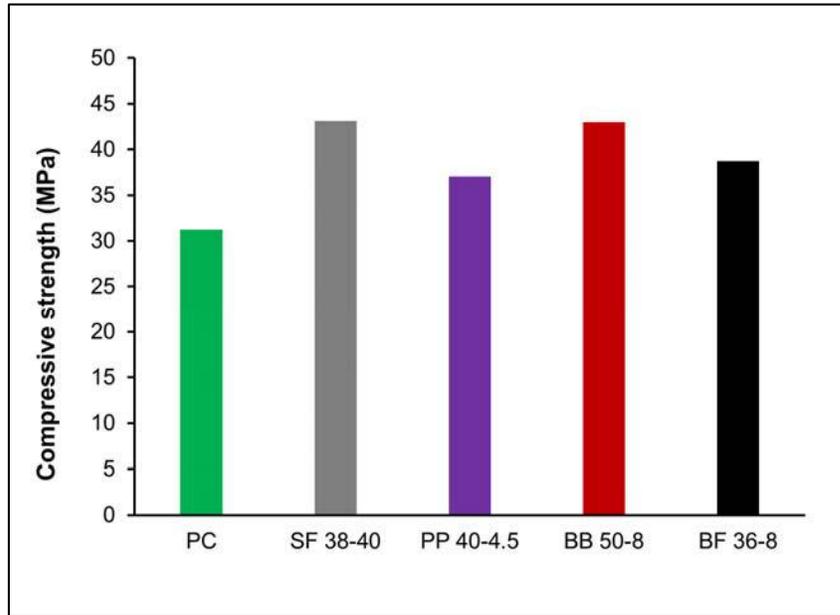
- The flexural strength of 36 mm filament is 6% higher than that of 36 mm bundles at 8 kg/m<sup>3</sup>.
- The compressive strength of 36 mm bundle at 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup> are 12% and 20% higher than that of 36 mm filament. The compressive strength of 50 mm bundle at 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup> are 13% and 8% higher than that of 50 mm filament. Bundles have consistently performed better than filaments in compression.
- The split tensile strength of 36 mm bundled fibre is 25% higher than that of 36 mm filament at 12 kg/m<sup>3</sup>.

Figure 5.50 shows the comparison of mean MOR of basalt bundle (BB 50-8) and filament (BF 36-8) fibre specimens which provided the optimum performance along with PC, SF 38-40, and PP 40-4.5 control specimens.



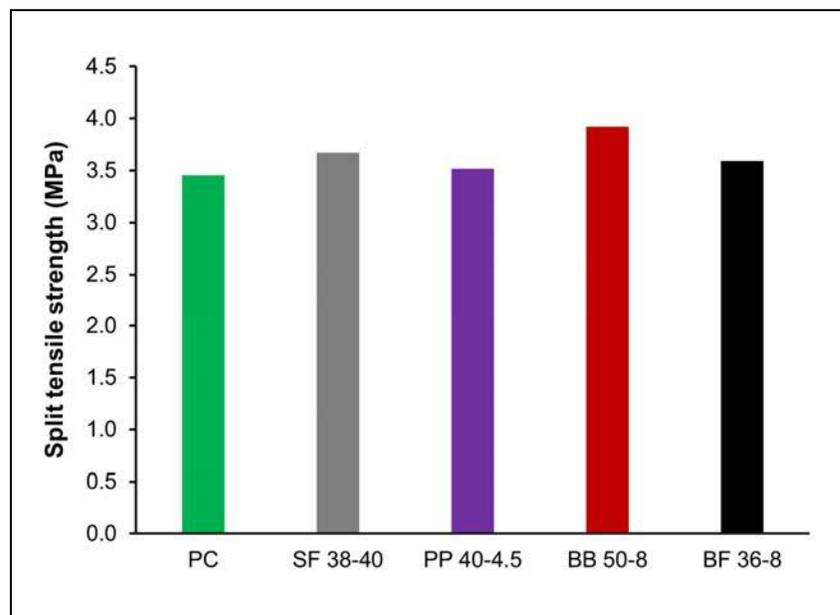
**Figure 5.50: Modulus of rupture (MOR): Comparison of basalt fibre specimens with control specimens**

Figure 5.51 shows the comparison of mean compressive strength of basalt bundle (BB 50-8) and filament (BF 36-8) fibre specimens which provided the optimum performance along with PC, SF 38-40, and PP 40-4.5 control specimens.



**Figure 5.51: Compressive strength: Comparison of basalt fibre specimens with control specimens**

Figure 5.52 shows the comparison of mean split tensile strength of basalt bundle (BB 50-8) and filament (BF 36-8) fibre specimens which provided the optimum performance along with PC, SF 38-40, and PP 40-4.5 control specimens.



**Figure 5.52: Split tensile strength: Comparison of basalt fibre specimens with control specimens**

## 6. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

### 6.1 SUMMARY

The objectives of this research were the following.

- Determine the optimum fibre length and dose of basalt fibres required to improve the flexural strength, compressive strength, and split tensile strength of smart BFRC from plain concrete.
- Compare the performance (flexural, compressive, and split tensile strength of BFRC specimens) of bundled fibres with basalt filaments of various lengths (12 mm, 36 mm, and 50 mm) at various fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>).
- Compare the performance (flexural, compressive, and split tensile strength) of the bundled fibre specimens and the basalt filament fibre specimens with plain concrete, steel fibre, and macro synthetic fibre control specimens.

To accomplish these objectives, a total of 126 beam specimens and 252 cylinder specimens were cast and tested which includes control specimens (plain concrete, steel fibre, and macro synthetic fibre) and BFRC specimens (bundled fibre and filament). In each batch, 8 cylinders were prepared for compression tests (4 cylinders each for 7 day and 28 day tests), 4 cylinders were prepared for split tensile tests and 6 beams were cast for flexural tests.

In this research, a weight ratio of 1:1.4:2.8 (cement: fine aggregate: coarse aggregate) was used for all concrete mixes. The water-cement ratio was kept constant at 0.5 for the mixes. BFRC beam and cylinder specimens were cast using basalt fibres (bundles and filaments) of varying lengths (12 mm, 36 mm, and 50 mm) and varying fibre dosages (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>). Similarly, steel fibre control specimens were prepared using steel fibres 0.9 mm in diameter and 38 mm long at a fibre dosage of 40 kg/m<sup>3</sup>. Macro synthetic fibre control specimens were cast using 40 mm long polyolefin fibres with an aspect ratio of 90 at a fibre dosage of 4.5 kg/m<sup>3</sup>. Flexural strength, compressive strength, and split

tensile strength tests were conducted according to the Canadian standard, CSA A23.2 (2009a).

Statistical analysis were performed on the test results using one sample t-test and independent sample t-test (or paired t-test). The following is the summary of statistical analysis.

- *Basalt bundles:* Short bundled fibre (12 mm) showed significant change in flexural strength and compressive strength from plain concrete (PC) only at high fibre dosage of 12 kg/m<sup>3</sup>. The medium length (36 mm) and long (50 mm) bundled fibres at 8 kg/m<sup>3</sup> and 12 kg/m<sup>3</sup> showed significant influence (statistically) on flexural strength and compressive strength from PC. The 36 mm and 50 mm bundled fibres at 12 kg/m<sup>3</sup> are statistically similar to the steel fibre control specimen (SF 38-40) in flexural strength and compressive strength. The 36 mm bundled fibre at 12 kg/m<sup>3</sup> showed significant change in the split tensile strength from PC.
- *Basalt filaments:* Short filament fibre (12 mm) at high fibre dosage of 12 kg/m<sup>3</sup> showed significant change in flexural strength, compressive strength, and split tensile strength from plain concrete (PC). None of the basalt filament specimens had flexural strength similar to the steel fibre control specimen (SF 38-40). The medium length (36 mm) filament at 8 kg/m<sup>3</sup> provided flexural strength and compressive strength similar to the macro synthetic control specimen (PP 40-4.5). The long filament (50 mm) at 12 kg/m<sup>3</sup> provided flexural strength similar to the macro synthetic control specimen and compressive strength similar to the steel fibre control specimen.
- *Basalt bundles vs. Basalt filaments:* The flexural strength and compressive strength of both bundled and filament fibres of same length and quantity were statistically similar, except for 36 mm fibres at 8 kg/m<sup>3</sup>. The compressive strength and split tensile strength of both bundled and filament fibres were statistically similar, except for 36 mm fibres at 12 kg/m<sup>3</sup>.

## 6.2 CONCLUSIONS

The conclusions presented here are based on the results obtained from this research. Hence, the results might not be applicable for different concrete mix proportions and different water-cement ratios.

All basalt fibre beam and cylinder specimens (bundles and filaments) failed in a brittle and sudden manner after the first crack, similar to PC. However, there was improvement in the peak strength (flexural, compressive, and split tensile).

- *Basalt bundles:* The optimum fibre length and dosage for basalt bundled fibres which provided the best performance (flexural, compressive, and split tensile strength) is 50 mm bundled fibre at 8 kg/m<sup>3</sup>. It provided flexural strength similar to the macro synthetic fibre control specimen (PP 40-4.5) and compressive strength similar to the steel fibre control specimen (SF 38-40). It showed a 21% increase in flexural strength, 38% increase in compressive strength, and a 14% increase in split tensile strength compared to the plain concrete control specimen.
- *Basalt filaments:* The optimum fibre length and dosage for basalt filaments which provided the best performance (flexural, compressive, and split tensile strength) is the 36 mm filament at 8 kg/m<sup>3</sup>. It was similar to the macro synthetic fibre control specimen (PP 40-4.5) in flexural, compressive, and split tensile strengths. It showed 23% increase in flexural strength, 24% increase in compressive strength, and 4% increase in split tensile strength compared to plain concrete control specimen.
- *Basalt bundles vs. Basalt filaments:* The medium length (36 mm) and long (50 mm) filaments tend to lump at the high fibre dosage of 12 kg/m<sup>3</sup>. The 36 mm and 50 mm bundled fibres dispersed uniformly at 12 kg/m<sup>3</sup> and have performed (flexural, compressive, and split tensile strength) better than filament fibres of the same length and dosage.

### **6.3 RECOMMENDATIONS**

The basalt bundled fibres work satisfactorily in improving the flexural, compressive, and split tensile strength if compared with plain concrete without adversely affecting the workability. It is recommended to manufacture coarse monofilament basalt fibres (36 mm to 50 mm long) similar to macro synthetic fibre, which may stop dispersing of the bundles into individual filaments during mixing, in order to achieve better post-cracking ductility. These coarse monofilaments may be able to carry the load in tension after the first crack and hence, improve the ductility and ultimately failure mode.

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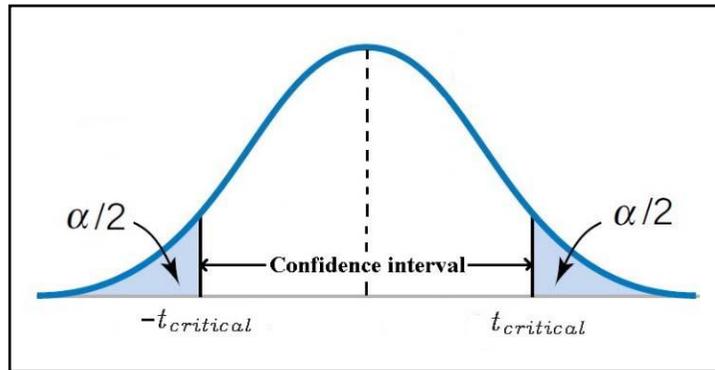
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## APPENDICES

### APPENDIX A

#### A.1 CRITICAL VALUES FOR T-DISTRIBUTION – TWO-TAIL TEST



**Table A.1 Critical values for t-distribution – Two-tail test**

| Confidence level | 80%   | 90%          | 95%          | 98%    | 99%    |
|------------------|-------|--------------|--------------|--------|--------|
| DF \ $\alpha/2$  | 0.1   | 0.05         | 0.025        | 0.01   | 0.005  |
| 1                | 3.078 | 6.314        | 12.706       | 31.821 | 63.656 |
| 2                | 1.886 | 2.92         | <b>4.303</b> | 6.965  | 9.925  |
| 3                | 1.638 | 2.353        | 3.182        | 4.541  | 5.841  |
| 4                | 1.533 | <b>2.132</b> | <b>2.776</b> | 3.747  | 4.604  |
| 5                | 1.476 | 2.015        | 2.571        | 3.365  | 4.032  |
| 6                | 1.44  | 1.943        | 2.447        | 3.143  | 3.707  |
| 7                | 1.415 | 1.895        | 2.365        | 2.998  | 3.499  |
| 8                | 1.397 | 1.86         | 2.306        | 2.896  | 3.355  |
| 9                | 1.383 | 1.833        | 2.262        | 2.821  | 3.25   |
| 10               | 1.372 | 1.812        | 2.228        | 2.764  | 3.169  |
| 11               | 1.363 | 1.796        | 2.201        | 2.718  | 3.106  |
| 12               | 1.356 | 1.782        | 2.179        | 2.681  | 3.055  |
| 13               | 1.35  | 1.771        | 2.16         | 2.65   | 3.012  |
| 14               | 1.345 | 1.761        | 2.145        | 2.624  | 2.977  |
| 15               | 1.341 | 1.753        | 2.131        | 2.602  | 2.947  |
| 16               | 1.337 | 1.746        | 2.12         | 2.583  | 2.921  |
| 17               | 1.333 | 1.74         | 2.11         | 2.567  | 2.898  |
| 18               | 1.33  | 1.734        | 2.101        | 2.552  | 2.878  |
| 19               | 1.328 | 1.729        | 2.093        | 2.539  | 2.861  |
| 20               | 1.325 | 1.725        | 2.086        | 2.528  | 2.845  |

Degree of freedom for one sample t-test =  $n - 1$

Degree of freedom for independent sample t-test =  $n_A + n_B - 2$

## APPENDIX B

### B.1 TESTED SPECIMENS

#### B.1.1 BASALT FIBRE



**Figure B.1: Tested basalt fibre beam specimens**

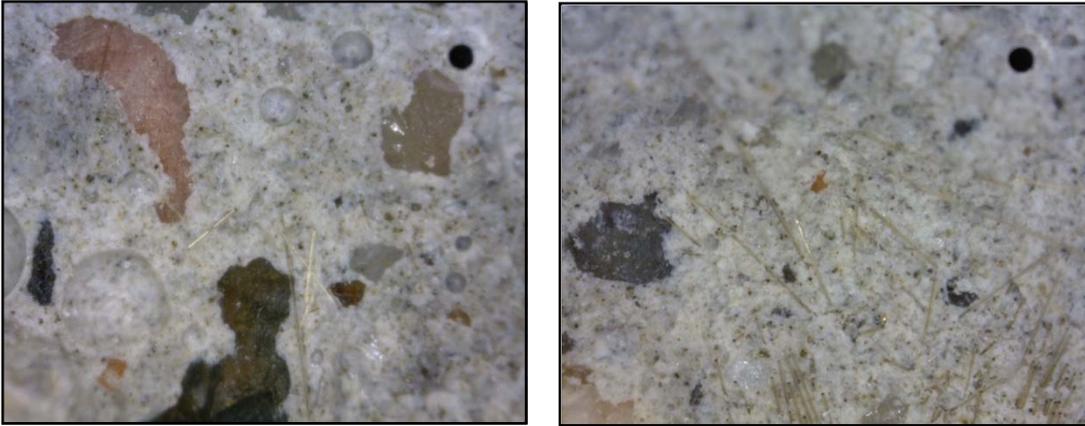


**Figure B.2: Tested basalt fibre cylinder specimen (Compression test)**



**Figure B.3: Tested basalt fibre cylinder specimen (Split tensile test)**

### B.1.1.1 MICROSCOPE IMAGES - BASALT FIBRE SPECIMENS



**Figure B.4: Microscopic images of tested basalt fibre specimens**  
(200 magnification)



**Figure B.5: Microscopic image of tested basalt fibre specimen**  
(500 magnification)



**Figure B.6: Microscopic image of tested basalt fibre specimen**

### B.1.2 STEEL FIBRE



**Figure B.7: Tested steel fibre beam specimens**



**Figure B.8: Tested steel fibre cylinder specimen (Compression test)**



**Figure B.9: Tested steel fibre cylinder specimen (Split tensile test)**

### B.1.3 MACRO SYNTHETIC FIBRE



**Figure B.10: Tested macro synthetic fibre beam specimens**



**Figure B.11: Tested macro synthetic fibre cylinder specimen (Compression test)**



**Figure B.12: Tested macro synthetic fibre cylinder specimen (Split tensile test)**

## APPENDIX C

### C.1 COMPRESSION TEST – 7 DAY TEST

#### C.1.1 BASALT BUNDLES

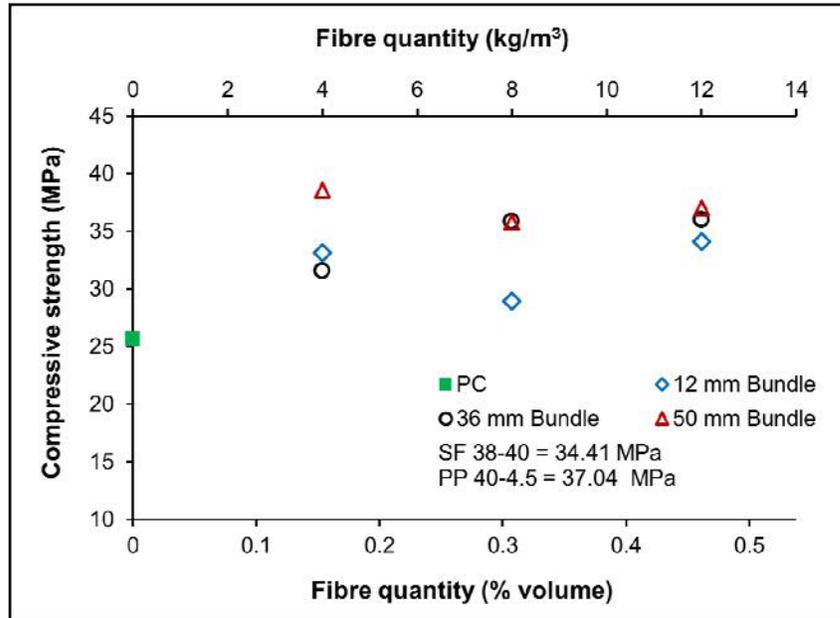


Figure C.1: Basalt bundles: 7 day Compressive strength

#### C.1.2 BASALT FILAMENTS

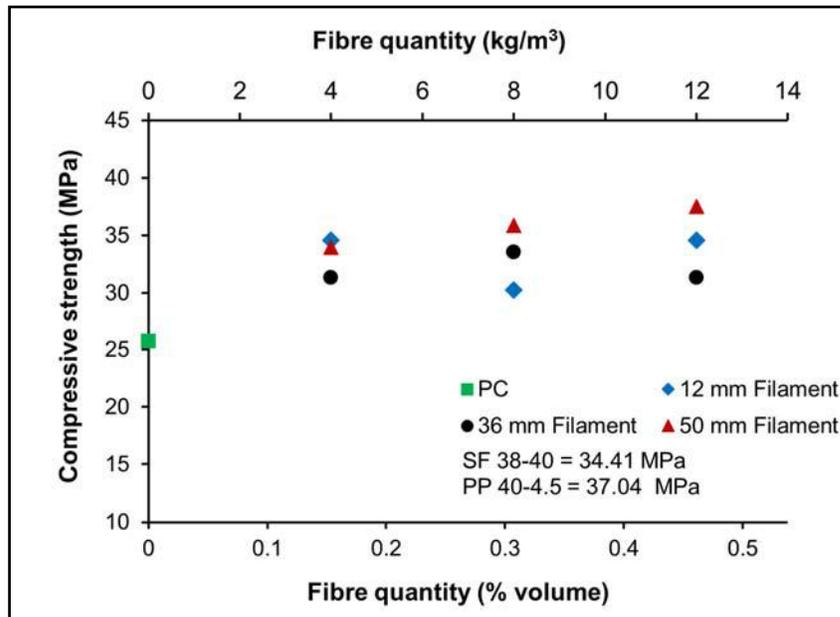


Figure C.2: Basalt filaments: 7 day Compressive strength

## APPENDIX D

### D.1 SLUMP

Figure D.1 and Figure D.2 show the decrease in slump for all fibre lengths (12 mm, 36 mm, and 50 mm) of basalt bundled fibres and basalt filaments with the increase in fibre dosage (4 kg/m<sup>3</sup>, 8 kg/m<sup>3</sup>, and 12 kg/m<sup>3</sup>).

#### D.1.1 BASALT BUNDLES

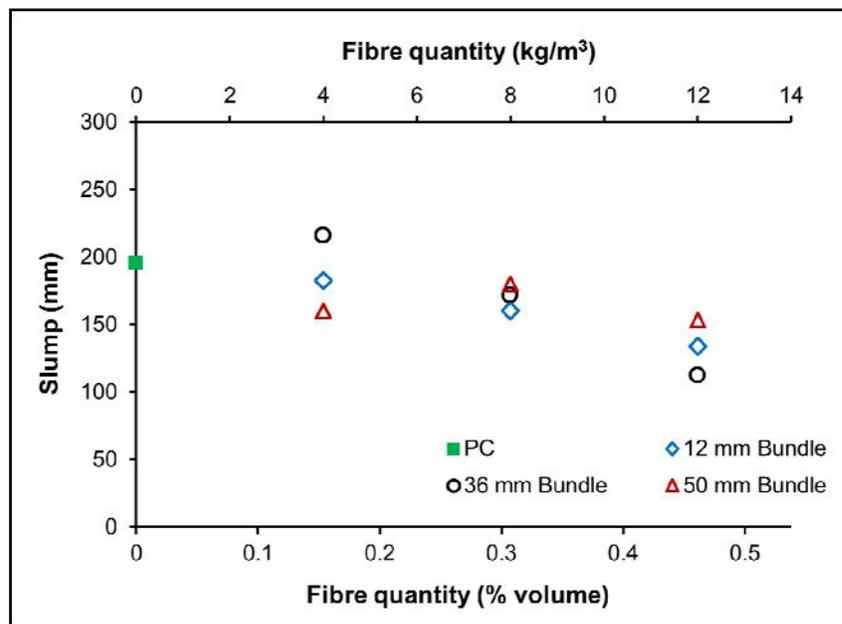


Figure D.1: Basalt bundles: Average slump

## D.1.2 BASALT FILAMENTS

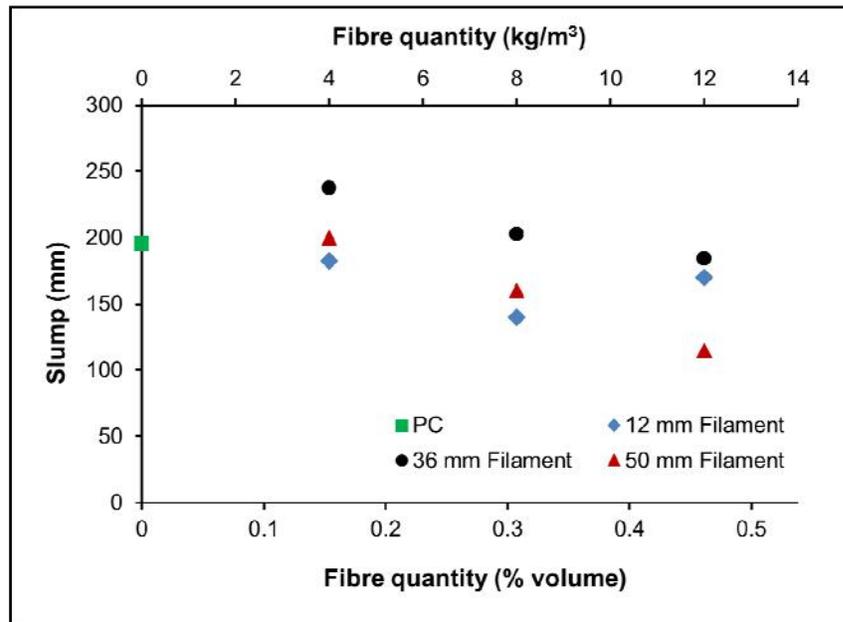


Figure D.2: Basalt filaments: Average slump

## APPENDIX E

### E.1 COPYRIGHT CLEARANCES

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To whomsoever it may concern

I referring to the contents of "*EFFECTIVE ELASTIC PROPERTIES OF FIBER REINFORCED CONCRETE WITH RANDOM FIBERS*" By Hasan Ahmad and Dimitris C. Lagoudas ( from *Journal of Engineering Mechanics*, Vol. 117, No. 12, December, 1991) in my Master's Thesis titled "Performance of Basalt Fibre Mixed Concrete". I am referring to the contents from this article only in my literature review chapter with proper reference to the source of the contents and is fully acknowledged in accordance with the standard referencing practices.

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Thank you,  
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