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PROPERTIES AND APPLICATIONS OF BASALT FIBRE REINFORCED CONCRETE

By

John-Sebastian Branston

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

2015

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PROPERTIES AND APPLICATIONS OF BASALT FIBRE REINFORCED CONCRETE

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DECLARATION OF CO-AUTHORSHIP AND PREVIOUS PUBLICATION

I. Co-Authorship Declaration

I hereby declare that this thesis incorporates material that is the result of joint research undertaken with Dr. Sara Kenno and Mr. Craig Taylor, of MEDA Limited, and my supervisor, Dr. Sreekanta Das, of the University of Windsor. In all cases, the key ideas, the primary contributions, and data analysis and interpretation were performed by the author of this thesis. The contributions of the co-authors were primarily focused on the provision of the study and suggesting possible directions. Results related to this research are reported in Chapters 2 and 3, inclusive.

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<tr>
<td>Chapter 2</td>
<td>Mechanical behaviour of basalt fibre reinforced concrete</td>
<td>Submitted, Construction and Building Materials</td>
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<tr>
<td>Chapter 3</td>
<td>Influence of basalt fibre on free and restrained plastic shrinkage</td>
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ABSTRACT

Basalt fibre has gained popularity in concrete reinforcing applications due to its excellent mechanical properties and an environmentally friendly manufacturing process. Research work presented in this thesis was undertaken to better understand potential applications of three different types of basalt fibre construction: filament and bundle dispersion fibres, and basalt fibre reinforced polymer bars (minibars). Mechanical performance was evaluated by measuring the effect of the fibres on the pre- and post-cracking behaviour of concrete, and by investigating how the fibre-concrete interfacial properties influenced that behaviour. Durability was evaluated by measuring the effect of the fibres on unrestrained plastic shrinkage, and their ability to prevent shrinkage cracking when restraint is present. Results suggest that filament dispersion fibres can be used for early-age crack control, minibars can replace rebar in applications for which it is not vital, and further research is required on bundle dispersion fibres to enhance their effect on post-cracking behaviour.
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Concrete work is very labour intensive and I would not have been able to complete all of the work presented in this thesis without the skill and input of our lab technicians Mr. Lucian Pop, Mr. Matt St. Louis, and Mr. Patrick Seguin. Additionally, I’d like to express my gratitude for the advice and help I received from fellow students: Jamshid Zohreh Heydariha, Hossein Ghaednia, Sahan Jayasuriya, Jason Duic, and Emad Booya.

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CHAPTER 1

GENERAL INTRODUCTION

Concrete is arguably the most widely used construction material in the world. Therefore, it comes as no surprise that a vast amount of research has been undertaken to enhance its performance; making it possible to build larger, safer, and more economical structures that are durable in a wider range of environments. One area of research that has been growing in the last few decades is the use of discrete, randomly distributed fibres to produce a composite material called fibre reinforced concrete (FRC). However, the idea of reinforcing brittle materials with fibres dates back to ancient times, where straw was used to reinforce mud bricks [1]. Even then the benefits of the composite system were apparent, in which the fibres are effective in restricting the development of cracks, and as a result, preventing sudden, potentially catastrophic, brittle failures due to the low tensile strength and strain capacity of plain concrete (PC).

More recently, asbestos fibre cement products were used successfully at a commercial scale during the early 1900s. Health concerns about asbestos during the 1950s sparked the introduction of steel fibre reinforced concrete (SFRC). Although well received, steel fibre reinforcement suffered from a few problems, namely difficulty with mixing, handling and placing fresh concrete with high fibre dosages, and susceptibility to corrosion. Consequently, a substantial amount of further experimental work has since been undertaken into alternative materials, which will be the topic of further discussion in the following sub-sections.
**1.1 INTRODUCTION TO FIBRE REINFORCED CONCRETE**

In general, areas of improvement in FRC over PC include: tensile strength, compressive strength, elastic modulus, crack resistance, crack control, durability, fatigue life, resistance to impact and abrasion, shrinkage, expansion, thermal characteristics and fire resistance [1]. Some commonly used types of fibres are shown below in Table 1.1.

**Table 1.1 Properties of commonly used fibres [2]**

<table>
<thead>
<tr>
<th>Fibre Type</th>
<th>Diameter (μm)</th>
<th>Specific Gravity</th>
<th>Elastic Modulus (GPa)</th>
<th>Tensile Strength (GPa)</th>
<th>Elongation at Break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>5-500</td>
<td>7.84</td>
<td>200</td>
<td>0.5-2</td>
<td>0.5-3.5</td>
</tr>
<tr>
<td>Glass</td>
<td>9-15</td>
<td>2.6</td>
<td>70-80</td>
<td>2-4</td>
<td>2-3.5</td>
</tr>
<tr>
<td>Asbestos</td>
<td>0.02-0.4</td>
<td>2.6-3.4</td>
<td>164-196</td>
<td>3.1-3.5</td>
<td>2-3</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>20-400</td>
<td>0.9-0.95</td>
<td>3.5-10</td>
<td>0.45-0.76</td>
<td>15-25</td>
</tr>
<tr>
<td>Aramid (Kevlar)</td>
<td>10-12</td>
<td>1.44</td>
<td>63-120</td>
<td>2.3-3.5</td>
<td>2-4.5</td>
</tr>
<tr>
<td>Carbon</td>
<td>8-9</td>
<td>1.6-1.7</td>
<td>230-380</td>
<td>2.5-4</td>
<td>0.5-1.5</td>
</tr>
<tr>
<td>Nylon</td>
<td>23-400</td>
<td>1.14</td>
<td>4.1-5.2</td>
<td>0.75-1</td>
<td>16-20</td>
</tr>
<tr>
<td>Cellulose</td>
<td>-</td>
<td>1.2</td>
<td>10</td>
<td>0.3-0.5</td>
<td>-</td>
</tr>
<tr>
<td>Acrylic</td>
<td>18</td>
<td>1.18</td>
<td>14-19.5</td>
<td>0.4-1</td>
<td>3</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>25-1000</td>
<td>0.92-0.96</td>
<td>5</td>
<td>0.08-0.6</td>
<td>3-100</td>
</tr>
<tr>
<td>Wood Fibre</td>
<td>-</td>
<td>1.5</td>
<td>71</td>
<td>0.9</td>
<td>-</td>
</tr>
<tr>
<td>Sisal</td>
<td>10-50</td>
<td>1.5</td>
<td>-</td>
<td>0.8</td>
<td>3</td>
</tr>
<tr>
<td>Cement Matrix</td>
<td>-</td>
<td>1.5-2.5</td>
<td>10-45</td>
<td>0.003-0.007</td>
<td>0.02</td>
</tr>
</tbody>
</table>

The physical and mechanical properties of the fibres are not the only aspects that should be considered when evaluating their potential use in FRC. Factors such as the chemical durability of the fibres in the alkaline environment of concrete, and the increased difficulty of working with the fresh FRC also require careful consideration when selecting the most suitable type of fibre for a specific application. However, these factors are not as straightforward to quantify as those presented in Table 1.1. For example, the influence of fibres on fresh concrete properties (e.g. workability) will
change when using different concrete mixes or production methods. Moreover, due to the uncertainty of accelerated testing, it can take many years of in-situ observation to evaluate the durability of the fibres, or that of the FRC composite as a whole. Therefore, it can be difficult to assess if the benefits of adding fibres are justified in the long-term. The following sub-sections will discuss the basic mechanics of FRC and some typical applications of some commonly used fibres, before delving into more detail on basalt fibre.

1.1.1 Basic Mechanics of Fibre Reinforced Concrete

The major draw of using FRC is the enhancement of post-cracking behaviour by restricting crack growth. As a result, the addition of fibres has two primary beneficial effects [2]:

1. Increase in the strength of the composite by transferring stress across the cracks. This behaviour is characterized by an ascending stress-strain curve following the first-crack, or strain hardening.

2. Increase in the toughness of the composite by providing an energy absorption mechanism. The mechanism is the result of the gradual pull-out of the fibres, which is reflected in the descending part of a stress-strain curve, or strain softening.

The behaviour of the composite following the first-crack depends on the load bearing capacity of the fibres. After cracking, a number of outcomes are possible depending on the material used. For example, using fibres with an elastic modulus and tensile strength greater than the concrete (matrix) would result in an increase in the pre-cracking strength, and then the toughness post-cracking depending on the fibre-matrix bond strength.
However, if the fibre elastic modulus was lower than that of the matrix, the fibre would deform with the matrix, and offer no increase to first-crack strength. On the other hand, a fibre that has a poor bond with the matrix would pull-out shortly after cracking occurs, and thus, not offer much increase in toughness. These types of variations in behaviour are illustrated in Fig. 1.1.

![Fig. 1.1 Typical post-cracking behaviour of FRC][1]

Apart from the use of different materials, the behaviour of FRC composites can be altered by a number of methods. The post-cracking behaviour can be enhanced by modifying the fibre-matrix contact area. This can be achieved by changing the fibre length or diameter (aspect ratio), or by introducing mechanical anchorage through different geometries (e.g. fibrillated or hooked end fibres). The load bearing capacity of the composite can be enhanced by increasing fibre quantity (without adversely effecting consolidation), or by favourable orientation of the fibres (e.g. spray-up process versus random orientation from traditional mixing). Finally, behaviour can also be altered by changes to the matrix, such as the use of different cements, aggregates, material proportions, and production methods.
Independent of these methods, the behaviour of the composite can also be expected to change over time. The material properties of concrete change due to on-going curing and environmental interaction, and the load bearing capacity of the fibres can change depending on their chemical stability in the alkaline environment of concrete.

1.1.2 Steel Fibre Reinforced Concrete

The most significant benefits of steel fibre reinforced concrete (SFRC) are an increase in toughness and reduction in cracking severity. Increases in first-crack strength with SFRC are relatively small [2]. Thus, the most typical application of SFRC is to replace traditional steel rebar when it is not essential for the safety and integrity of the structure, such as slabs-on-grade, pavements, and tunnel linings [1]. Steel fibres are also useful in flexural members as a secondary reinforcement, in which they can enhance resistance to dynamic loads (impact, fatigue, blast, and seismic loading) and changes in temperature and humidity [2].

Although steel fibres can decrease construction costs by reducing the required thickness of structures and eliminating the labour required to install mesh and rebar, the cost of steel fibres at a modest dosage of 1% (by volume) can double the material cost of the concrete [3]. For this reason, the use of SFRC has been limited to speciality applications, such as large industrial floors and airport pavements. Moreover, steel fibres are susceptible to corrosion due to the ingress of water and chlorides, and they increase the dead-load of the structure.

1.1.3 Glass Fibre Reinforced Concrete

Glass fibres are lighter and stronger than steel fibres (see Table 1). Hence, glass fibre reinforced concrete (GFRC) has been used primarily to produce thin, light-weight
architectural elements. Most notable is façade panels, which make up 80% of GFRC production [4]. Glass fibres can also be mixed into concrete at higher dosages than steel fibres. As a result, the first-crack strength of GFRC is considerably higher than that of the unreinforced matrix [2].

However, applications of GFRC have largely been limited to architectural applications due to the poor chemical stability of the fibres in concrete. It has been well established that regular E-glass fibres will lose their tensile strength due to high alkalinity. To overcome this problem, alkali-resistant glass fibres (AR-glass) were developed by adding zirconia to the fibres during manufacturing. Additionally, the use of high-alumina cements and the addition of pozzolans (e.g. metakaolin) has been shown to increase the durability of GFRC [5, 6]. Despite these advances, the long-term performance of GFRC remains a primary concern.

1.1.4 Synthetic Fibre Reinforced Concrete

A variety of synthetic fibres, with a broad spectrum of mechanical properties, have been developed for concrete reinforcing applications. The fibres are generally categorized by their modulus of elasticity with respect to that of the matrix: if it is higher they are called high modulus fibres, and if it is lower they are called low modulus fibres. The key difference being that high modulus fibres can increase the first-crack strength of the composite, whereas low modulus fibres can not [2].

1.1.4.1 High Modulus Synthetic Fibre

The majority of research in this area has focused on aramid (Kevlar) and carbon fibres. FRC made with these fibres exhibits comparable mechanical behaviour to steel FRC, but the primary benefits of using these fibres are an increase in first-crack strength
and good durability [7, 8]. However, widespread application has been prohibited due to their high cost. One method to get cost-effective benefit from the fibres is by using a hybrid reinforcing system. Li et al. [9] found that a combination of steel and carbon fibres was very effective in increasing both strength and toughness. In that case, the smaller, well distributed carbon micro-fibres increased the first-crack strength by preventing the propagation of micro-cracks, and the steel fibres increased the toughness due to their high ultimate strain capacity. Current application of these fibres is limited to speciality structures where light-weight and stiffness is desirable, such as single and double curvature membrane structures and scaffold boards [1].

1.1.4.2 Low Modulus Synthetic Fibre

Commonly used low modulus synthetic fibres include: polypropylene, polyethylene, and nylon. The main draw of the fibres is their good alkaline resistance and low cost. However, they suffer from a lack of fire resistance, and a poor bond with the cement matrix [2]. For these reasons, the most typical use of low modulus synthetic fibres has been for crack control. Low dosages of polypropylene fibres (< 0.3% by volume) have been shown to eliminate cracking due to plastic shrinkage [10]. However, Song et al. [11] found that nylon fibres outperform polypropylene fibres in the reduction shrinkage cracking and attributed it to their higher tensile strength. The use of nylon fibres may be limited to low dosages for crack control, since they are hydrophilic and absorb mix water, which can be problematic at the higher dosages necessary to enhance mechanical behaviour [2]. In regards to mechanical properties, polyethylene fibres were shown to outperform polypropylene fibres in terms of flexural strength and impact resistance, likely due to a higher elastic modulus [12]. It is believed that a lot of research
in regards to enhancing the properties of these fibres is done in the private sector and not available in open literature. However, one obvious method that has been adopted is the use of fibrillations in the fibre to enhance the mechanical bond with the matrix.

1.1.5 Natural Fibre Reinforced Concrete

In general, research into the use of natural fibres has been undertaken to develop an economical and environmentally friendly alternative to manufactured fibres and traditional rebar. A lot of research is inspired by the idea of taking advantage of abundant, low-cost, locally available materials to enhance construction in the developing world. There are many types of natural fibres, and thus, discussion in this sub-section only provides a broad overview. Biagiotti et al. [13] categorized some commonly used natural fibres, as can be seen below in Fig. 1.2.

Fig. 1.2. Classification of natural fibres [13]

Natural fibre reinforced concrete follows the same type of behaviour as discussed in the previous sub-sections. Mechanical properties, such as the modulus of rupture, and toughness, are further enhanced with higher fibre dosages [1]. However, workability and proper consolidation puts an upper limit on the dosage. Fibres with a comparatively high...
tensile strength and elastic modulus, such as flax, jute, and hemp, are typically best for increasing flexural strength and elastic modulus. On the other hand, coarser fibres, such as sisal and coir, are better in terms of increasing toughness [13]. In regards to durability, flax, sisal, coconut, and cellulose fibres have been shown to prevent early age cracking due to shrinkage [14-16]. In general, the greatest drawbacks of natural fibres are their lack of durability in concrete due to alkalinity and biological attacks, and inconsistency in mechanical properties [2].

1.2 INTRODUCTION TO BASALT FIBRE

1.2.1 Manufacturing Process

Basalt is an igneous rock found in abundance throughout the world. Basalt rock is crushed, loaded into a furnace and liquefied. Next, basalt filaments are drawn through platinum-rhodium bushings. As the filaments cool, they are coated with a sizing agent. The sizing agent is necessary to prevent abrasion during transportation; however, it also provides manufacturers with a way to differentiate their fibre from their competitor’s. For example, the performance of E-glass fibre depends on parameters such as fibre volume and aspect ratio, but the fibre itself differs little from manufacturer to manufacturer. In regards to interfacial properties (e.g. bond strength and alkaline resistance), sizing is the primary variable [17]. Basalt fibres used in this study were manufactured with two different sizings. The first type of sizing keeps bundles of filaments together during transportation and handling, but allows them to disperse uniformly when mixed into the concrete. The second type of sizing has stronger adhesive properties and keeps the bundles of filaments together during mixing. These two types of fibre are called filament dispersion and bundle dispersion fibres, respectively. Basalt filaments can also be used to
reinforce polymers to produce fibre reinforced polymer (FRP) rebar. A similar technique has recently been applied on a smaller scale to produce basalt minibars [18]. The minibars are an epoxy based resin reinforced with basalt filaments. They are more rigid than plain chopped fibres and have similar dimensions to standard steel fibres. Fig. 1.3 shows some common basalt fibre products developed for reinforcing concrete.

![Fig. 1.3 Basalt fibre products developed for concrete reinforcing](image)

In general, the manufacturing process and chemical composition of basalt fibre is similar to that of glass fibre [19]. A comparison of the chemical composition of the fibres is shown in Table 1.2.

<table>
<thead>
<tr>
<th>Fibre Type</th>
<th>Weight % of compound</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SiO₂</td>
</tr>
<tr>
<td>Basalt</td>
<td>52-58</td>
</tr>
<tr>
<td>E-glass</td>
<td>52-56</td>
</tr>
</tbody>
</table>

Glass fibre is currently used to a much greater extent in concrete reinforcing applications. Therefore, further discussion will use glass fibre as a basis of comparison for basalt fibre.
1.2.2 Beneficial Aspects of Basalt Fibre

Basalt fibres can be manufactured directly from a single raw material (basalt rock) without the need for additives, making the process simpler than that of glass fibre [20]. As a result, the fibres can be manufactured with conventional processes and equipment, and less energy, which offers an economic advantage [21]. Moreover, the fibres are considered 100% natural, have no toxic reaction with air or water, and the fiberization process is said to be more environmentally friendly than that of glass fibre [19]. In terms of mechanical and physical properties, basalt fibre has gathered attention due to its high elastic modulus, high strength, corrosion resistance, high temperature resistance, and light-weight [19]. Table 1.3 compares some physical and mechanical properties of basalt and E-glass fibres.

<table>
<thead>
<tr>
<th>Table 1.3 Comparison of basalt and E-glass fibres [21]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre Type</td>
</tr>
<tr>
<td>Basalt</td>
</tr>
<tr>
<td>E-glass</td>
</tr>
</tbody>
</table>

In general, research into using basalt fibre as a concrete reinforcing material has grown in popularity because of its potential to replace glass fibre. Basalt fibre is often reported to offer better mechanical properties and a more economical, environmentally friendly manufacturing process. With such good characteristics, and its manufacturing process dating back to 1923 [19], it seems to be quite a mystery as to why its use has been so limited in the FRC industry; the following sub-section will discuss some possible reasons for this shortcoming.
1.2.3 Problems to Overcome

A key concern with basalt fibre is its chemical durability. Its alkaline resistance is often said to be good, on the basis that it may be better than that of E-glass. For example, one basalt fibre manufacturer states the fibre is very durable based on a weight loss of only 0.35% after immersion in a cement solution, in comparison to E-glass fibre that lost 4.5% of weight [22]. However, this is very indirect justification, since focus should be on the stability of the mechanical properties and matrix-fibre bond strength over time, when considering their application in concrete reinforcing. Lee et al. and Rabinovich et al. [23, 24] have shown basalt fibre loses tensile strength over time in a calcium hydroxide solution intended to replicate hydrating cement. In these cases, basalt fibre generally retained more strength than E-glass fibre. However, the improvement may be considered trivial when after 90 days, the basalt fibres still lost more than 50% of its tensile strength. There is a lack of research into the fibre-matrix bond strength, and how it changes with time. This will be discussed further in Chapter 2.

The issue of chemical durability may be further complicated by differences in basalt fibre produced by different manufacturers. Although production from a single raw material can be considered beneficial, it also means that manufacturers have less control over the consistency of the final product. The chemical composition and crystalline structure of basalt rock varies greatly by geographical location. Therefore, only select basalt rock can produce filaments with desirable properties [17]. As a result, the market share of basalt fibre has been reduced due to variability in the material properties of fibres manufactured with raw material from different locations [25]. Furthermore, manufacturers use proprietary sizings to give their fibres a competitive advantage in the
market. Thus, it may be difficult to quantify interfacial properties, since they may differ significantly when using fibres purchased from different manufacturers.

1.3 OBJECTIVE

The objective of this research is to evaluate the relative merit of basalt bundle dispersion fibres, filament dispersion fibres, and minibars in enhancing the mechanical behaviour and durability of concrete. Based on the results, suggestions for the most suitable application of each type of fibre are made.

1.4 METHODOLOGY

The experimental work in this thesis was completed in three distinct phases. Lab work was undertaken to quantify the effect of fibre type, length and dosage on the mechanical behaviour of concrete, and then on the durability. Additionally, an old deteriorated concrete bridge structure was repaired using basalt fibre reinforced concrete.

The mechanical behaviour of basalt fibre reinforced concrete was evaluated through four fundamental properties: compressive strength, split-tensile strength, flexural strength and, impact resistance. The influence of the fibres on the first-crack strength and the post-cracking behaviour was measured and then compared with that of unreinforced control specimens, as well as specimens reinforced with industry standard hooked-end steel fibres. Moreover, fibre-matrix pull-out testing was completed, and scanning electron microscopy was used, in order to better understand how the fibre-matrix interfacial properties influenced the mechanical behaviour of the composite.

The durability of basalt fibre reinforced concrete was evaluated by shrinkage testing. Early-age (plastic) shrinkage testing was completed in two phases. In the first
phase, concrete specimens were unrestrained in order to study the influence of the fibre on the free plastic shrinkage strain. In the second phase, a high-strength concrete sub-base was used to restrain the shrinkage movement in order to study the effect of the fibres on reducing plastic shrinkage cracking. The influence of the fibres on the unrestrained, long-term (drying) shrinkage was also studied for 120 days.

The practicality of basalt fibre reinforced concrete was evaluated by repairing a concrete bridge structure (box culvert) constructed sometime between the 1950s and 1960s. Sprayed-on patching repairs on the abutment walls and soffit were made with a cement-based mortar material reinforced with basalt fibre. Approximately 1 m$^3$ of deteriorated concrete at the end of the bridge deck was replaced with cast-in-place basalt fibre reinforced concrete. Measurements were made after one year by visual comparison between areas reinforced with basalt fibre versus those that were not.

1.5 ORGANIZATION OF THE THESIS

This thesis is written in paper format and it consists of five chapters. The first chapter provides a general introduction into fibre reinforced concrete and introduces the potential role of basalt fibre.

The second chapter investigates the pre- and post-cracking behaviour of basalt fibre reinforced concrete under flexural and impact loading, and how the interfacial properties influence that behaviour.

The third chapter investigates the influence of the fibres on the development of shrinkage strain (unrestrained shrinkage), and their ability to restrict the development of cracks when the shrinkage is restrained.
The fourth chapter highlights repair work completed on an old bridge structure, and examines the durability of those repairs after one year.

The fifth chapter provides a summary of how the previous chapters are related, general conclusions, and recommendations for future application and research work.

1.6 REFERENCES


CHAPTER 2

MECHANICAL BEHAVIOUR OF BASALT FIBRE REINFORCED CONCRETE

2.1 INTRODUCTION

Plain concrete (PC) is a brittle material with low tensile strength. Consequently, PC is susceptible to cracking due to tensile stress. When mixed into concrete, randomly distributed fibres are able to bridge these cracks and arrest their development. By this mechanism, it has been well established that the addition of fibres can enhance the mechanical behaviour of PC. Although a variety of fibre reinforcing materials exist, fibre reinforced concrete (FRC) used for structural applications is most often made with steel fibres. The most beneficial properties of steel fibre reinforced concrete (SFRC) are improved flexural toughness, flexural fatigue endurance, and impact resistance [1]. As a result, steel fibres are able to totally or partially replace traditional steel rebar in many applications, such as industrial floors and pavements. However, SFRC poses several issues, such as: increased dead-load, reduced workability, fibre balling at high dosages, and susceptibility to corrosion. For these reasons, glass fibre is a popular alternative. Glass fibre reinforced concrete (GFRC) has been used extensively to produce thin, lightweight architectural elements, most notably exterior facade panels. However, GFRC has been largely limited to architectural applications due to durability concerns with the fibres in the alkaline environment of concrete. It should be noted FRC made with a variety of natural and synthetic fibres, including carbon, aramid, polypropylene, and wood fibres has been shown to exhibit similar enhancements to the mechanical behaviour
of concrete [1]. However, these fibres are not currently used as commonly as steel and glass fibres in practical applications.

Basalt fibre has recently gained popularity as a potential competitor in concrete reinforcing applications due to its excellent mechanical properties and an environmentally friendly manufacturing process [2]. The fibres typically have a tensile strength slightly higher than E-glass fibres and many times greater than steel fibres. In addition to plain, chopped basalt fibres (BF), a new basalt concrete reinforcement product called minibars (MB) has recently been developed. The minibars are essentially a scaled down version of basalt fibre reinforced polymer rebar.

The research into basalt fibre reinforced concrete (BFRC) has largely been focused on fundamental mechanical properties: compressive, split-tensile, and flexural strength. In the case of BF, the research shows general agreement with the addition of fibres being beneficial up to approximately 0.3-0.5% by volume and detrimental thereafter [3-5]. However, optimum fibre dosages vary significantly in different types of concrete, such as geopolymer [6] and high-strength concretes [7]. By comparison, MB have been shown to be beneficial at dosages up to 4% by volume [8]. The influence of BF and MB on compressive strength is typically not significant [3, 5-10], although it has been shown to increase by as much as 31% with filament dispersion BF [4]. The primary benefit of BF and MB in concrete under compression is the shift from a brittle failure mode to a more ductile one [5, 7, 8, 10].

It has been shown that both BF and MB can significantly increase the tensile strength of concrete [3-9]. However, it is difficult to assess the magnitude of the increase in tensile strength because of discrepancies in values derived from direct tension, split-
tensile, and flexural tests. An increase of 43% in direct tensile strength was found using BF with added zirconia, in comparison to a 14% increase without zirconia [9]. Zirconia is added to E-glass fibre to produce alkaline resistant glass fibre. This may suggest that the BF is susceptible to a similar mechanism of degradation as glass fibre in concrete. Moreover, Jiang et al. [5] found the beneficial effects of BF diminished significantly after 90 days.

Research related to characterizing the post-cracking performance of BFRC has been limited. This is a problem because in many practical applications, first-crack strength is not increased. Rather, the most significant enhancement from the addition of fibres is the post-cracking response [1]. Both BF and MB have been shown to enhance the flexural toughness of concrete [5, 6, 8, 10]. However, it is difficult to assess the relative merit of each product since results are based on different test methods. It was found using the ACI Committee 544 recommended drop-weight test for impact resistance [11] that BF can significantly enhance performance after cracking [10]. However, the conclusion is based on data from four or six specimens per concrete mix. The test method is notorious for large variations, requiring approximately 40 specimens per mix to keep the percent error of measured mean values below 10% [12, 13]. Li and Xu [14] found BF can significantly increase the energy absorption capacity of geopolymer concrete under impact loading by using a Split-Hopkinson pressure bar system. However, the performance of BFRC under impact in general is still largely unknown. Since impact test results obtained by different test methods are generally not comparable [15], the results from a simple test method may provide a more practical reference for which future comparison can be made. This is particularly useful for BFRC because it is a relatively
new composite and further development is expected to enhance its material properties for concrete applications.

The purpose of the experimental work presented in this paper is to compare the pre- and post-cracking mechanical behaviour of concrete reinforced with plain chopped basalt fibres (BF), basalt minibars (MB), and commonly used hooked end steel fibres (SF). Comparative performance is evaluated by flexural and drop-weight impact testing. Interfacial properties are also investigated by scanning electron microscopy. It should be noted that two types of plain chopped BF are available: filament dispersion and bundle dispersion. Bundle dispersion fibres are manufactured with a sizing that holds bundles of basalt filaments together during mixing, whereas filament dispersion fibres will disperse into individual filaments. In this study, bundle dispersion fibres were selected since filament fibres are typically used for crack control. Compressive strength was measured as a means of quality control (see Appendix A). However, the data is not discussed further since it has been well established that the influence of fibres on compressive strength is generally insignificant.

2.2 EXPERIMENTAL PROCEDURE

2.2.1 Materials

All concrete was made with type 10 general use Portland cement conforming to the Canadian standard CSA A3001 [16], regular drinking water, and well-graded aggregates purchased locally. Superplasticizer was used in higher dosage FRC mixes.

Two different lengths of chopped BF were used: 36 mm and 50 mm. The BF bundles are flat, approximately 0.6 mm wide and made of 16 μm diameter filaments. The MB used in this study are an epoxy based resin reinforced with 17 μm diameter basalt
filaments. The composite is 43 mm in length and approximately 0.65 mm in diameter. By comparison with the BF, the MB are more rigid. The SF used in this study are 38 mm in length, 0.9 mm in diameter and have hooked ends. The fibres used in this study are shown in Fig. 2.1.

2.2.2 Concrete Mix Design

Concrete specimens used in this study were cast with a 0.5 w/c ratio and proportions of 1:1.4:2.8 by mass of cement, fine aggregate, and coarse aggregate. Three different dosages were used for each type of basalt reinforcement, ranging from a low dosage to the maximum mixable dosage. Despite the use of superplasticizer, it was found that dosages beyond 12 kg/m³ and 40 kg/m³ for BF and MB, respectively, led to fibre balling and difficulty achieving proper consolidation. A summary of the mix types used in this work is shown in Table 2.1. Mix designation is labelled according to fibre type, fibre length, and dosage. For example, mix designation BF-36-8 indicates chopped basalt bundle dispersion fibres of 36 mm length were used at a dosage of 8 kg per 1 m³ of plain concrete (8 kg/m³).
Table 2.1. Test Matrix

<table>
<thead>
<tr>
<th>Mix Designation</th>
<th>Fibre Type</th>
<th>Length (mm)</th>
<th>Dosage kg/m³</th>
<th>Volume (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>No fibre</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>BF 36-4</td>
<td>Bundle dispersion</td>
<td>36mm</td>
<td>4</td>
<td>0.15</td>
</tr>
<tr>
<td>BF 36-8</td>
<td></td>
<td></td>
<td>8</td>
<td>0.31</td>
</tr>
<tr>
<td>BF 36-12</td>
<td></td>
<td></td>
<td>12</td>
<td>0.46</td>
</tr>
<tr>
<td>BF 50-4</td>
<td></td>
<td>50mm</td>
<td>4</td>
<td>0.15</td>
</tr>
<tr>
<td>BF 50-8</td>
<td></td>
<td></td>
<td>8</td>
<td>0.31</td>
</tr>
<tr>
<td>BF 50-12</td>
<td></td>
<td></td>
<td>12</td>
<td>0.46</td>
</tr>
<tr>
<td>MB 43-6</td>
<td>Minibar</td>
<td>43mm</td>
<td>6.2</td>
<td>0.31</td>
</tr>
<tr>
<td>MB 43-20</td>
<td></td>
<td></td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>MB 43-40</td>
<td></td>
<td></td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td>SF 38-40</td>
<td>Steel</td>
<td>38mm</td>
<td>40</td>
<td>0.51</td>
</tr>
</tbody>
</table>

2.2.3 Test Methods

Flexural testing was completed following the guidelines of ASTM C1609 [17]. Concrete prisms 610 mm in length and 152 mm by 152 mm in cross-section were subjected to third-point loading using a compression testing machine with a 2,200 kN capacity. Mid-span deflection was measured using a 25 mm linear displacement transducer (LDT). Mean values reported for each mix designation are based on three specimens tested after 28 days of curing. The test setup is shown in Fig. 2.2.
Impact resistance was evaluated using a modified version of the ACI Committee 544 recommended drop-weight impact test [11], as recommended by Badr and Ashour [12]. Concrete was cast in standard 152 mm diameter by 305 mm cylindrical moulds with 25.4 mm triangular pieces of wood attached to each side to form notches. Test specimens 51 mm in thickness were cut from the notched cylinders using a diamond blade saw. The number of blows from a 4.54 kg compaction hammer with a 457 mm (18 in.) drop required to cause a visible surface crack and subsequent failure were recorded for each specimen. Failure was defined by either complete separation of the specimen, separation such that the specimen is touching both sides of the fixture, or the impact piston was fully embedded in the concrete. Moreover, only specimens that cracked through a line between the notches were included in the data. Mean values reported for each mix designation are based on 24 specimens tested after 28 days of curing. The number of specimens tested was based on the statistical analysis of other researchers using this method [12, 18]. The test setup is shown in Figs. 2.3 and 2.4.

Fig. 2.3. Impact test fixture
2.3 RESULTS AND DISCUSSION

2.3.1 Flexural Testing

It can be found from the load-deflection plot in Fig. 2.5 that BF specimens did not enhance post-cracking behaviour. BF was not observed bridging the cracks during testing and the specimens failed in the same brittle manner as PC. Conversely, Fig. 2.6 shows that MB specimens provided substantial post-cracking strength and ductility. Three distinct types of failure were observed in MB specimens depending on fibre dosage. At a low dosage (MB-43-6), the load capacity dropped after the concrete cracked, then increased again but remained below the first-peak load. At an intermediate dosage (MB-43-20), the load capacity also dropped when the concrete cracked; however, it quickly regained and increased beyond the first-peak load. At a high dosage (MB-43-40), it was unclear when the concrete first cracked since sudden drop in the load was not observed at any point and the load-deflection plot followed a smooth softening behaviour after reaching peak-load.
Fig. 2.5. Typical flexural test results for BF specimens

Fig. 2.6. Typical flexural test results for MB specimens
All the results are summarized in Table 2.2. In this table, \( f_1 \) is the first-peak stress value, \( d_1 \) is the deflection at first-peak stress, \( f_p \) is the maximum stress, and \( d_p \) is the deflection at maximum stress. The \( f_{L/600} \) is the residual strength at the deflection of \( L/600 \) and \( f_{L/150} \) is the residual strength at the deflection of \( L/150 \), where \( L \) is the beam’s span length. The \( R_{L/150} \) is the flexural strength ratio calculated as per ASTM 1609 [17].

<table>
<thead>
<tr>
<th>Mix Designation</th>
<th>( f_1 ) (MPa)</th>
<th>( d_1 ) (mm)</th>
<th>( f_p ) (MPa)</th>
<th>( d_p ) (mm)</th>
<th>( f_{L/600} ) (MPa)</th>
<th>( f_{L/150} ) (MPa)</th>
<th>( R_{L/150} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>4.05</td>
<td>0.32</td>
<td>0.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BF-36-4</td>
<td>4.39</td>
<td>0.37</td>
<td>1.19</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BF-36-8</td>
<td>4.70*</td>
<td>0.23</td>
<td>0.12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BF-36-12</td>
<td>4.93*</td>
<td>0.33</td>
<td>0.42</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BF-50-4</td>
<td>4.40*</td>
<td>0.28</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BF-50-8</td>
<td>4.89*</td>
<td>0.26</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BF-50-12</td>
<td>5.11*</td>
<td>0.27</td>
<td>0.31</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MB-43-6</td>
<td>4.01</td>
<td>0.17</td>
<td>2.12</td>
<td>2.11</td>
<td>54.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MB-43-20</td>
<td>3.42</td>
<td>0.17</td>
<td>6.14*</td>
<td>1.30</td>
<td>4.98</td>
<td>5.69</td>
<td>92.77</td>
</tr>
<tr>
<td>MB-43-40</td>
<td>2.63</td>
<td>0.33</td>
<td>9.22*</td>
<td>2.00*</td>
<td>7.54</td>
<td>8.66</td>
<td>93.74</td>
</tr>
<tr>
<td>SF-38-40</td>
<td>5.28*</td>
<td>0.60</td>
<td>3.33</td>
<td>1.65</td>
<td>32.79</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: * indicates effect of fibre is significant at 95% confidence interval (see Appendix B for MB specimens and [18] for SF and BF specimens).

The poor post-crack performance of BF (Fig. 2.5) was not surprising given the lack of visible fibres in the cracked cross-section, as shown in Fig. 2.7. Even at the highest dosages, BF was not visible by eye, and thus, some level of degradation in the chopped fibres was suspected. Regardless, the BF increased the first-peak stress, and therefore, provided some benefit. In most cases, the deflection at the first-peak stress was found to be lower in BF specimens in comparison with PC (Fig. 2.5 and Table 2.2). This would suggest the influence of BF is an increase in first-crack strength and modulus of elasticity as fibre dosage increases. Moreover, the increases are greater with fibers 50 mm in length than with fibers 36 mm in length. The MB specimens were also effective in
increasing first-peak load (Fig. 2.6). In this regard, MB-43-20 specimens had provided a similar increase as SF-38-40 specimens. Furthermore, MB specimens behaved in a ductile manner after cracking. As a result, the MB specimens were able to carry between 50% and 90% of peak-load at a deflection of 3 mm (L/150) and still had residual load capacity at a very large deflection of 10 mm. This is because the MB composites failed primarily by gradual fibre pull-out, evidenced by the lack of ruptured fibres observed in the cracked cross-section (Fig. 2.7). The post-cracking performance of MB-43-6 specimens was comparable to that of SF-38-40 (Table 2.2).

![Cracked cross-section of failed flexural test specimens](image)

**Fig. 2.7.** Cracked cross-section of failed flexural test specimens

### 2.3.2 **Impact Testing**

It was found after several preliminary tests that all 24 PC specimens cracked after a single blow and failed after one additional blow, if not already failed, when using the full drop height of the hammer (457 mm). A similar performance was observed with five specimens from all other mix designations (Table 1). Therefore, in the subsequent impact tests, the drop-height was reduced to 152 mm (6 in.). However, with the reduced drop-height of 152 mm, the MB-43 and SF-38 specimens required above 100 blows to fail, which was deemed impractical. Thus, after the first crack was observed in SF-38 and
MB-43 specimens, the hammer was dropped from the full height (457 mm) and compared with PC subjected to the same impact. Table 2.3 shows the mean number of blows until the first crack (N1) and subsequent number of blows until failure (N2).

<table>
<thead>
<tr>
<th>Mix Designation</th>
<th>152 mm Drop</th>
<th>457 mm Drop</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>N1: 5.0</td>
<td>N2: 3.2</td>
<td>N1: 1.0</td>
</tr>
<tr>
<td>BF-36-4</td>
<td>N1: 3.9</td>
<td>N2: 2.4</td>
<td>N1: -23.1</td>
</tr>
<tr>
<td>BF-36-8</td>
<td>N1: 4.0</td>
<td>N2: 3.0</td>
<td>N1: -19.8</td>
</tr>
<tr>
<td>BF-36-12</td>
<td>N1: 4.3</td>
<td>N2: 2.4</td>
<td>N1: -14.9</td>
</tr>
<tr>
<td>BF-50-4</td>
<td>N1: 4.9</td>
<td>N2: 3.8</td>
<td>N1: -2.5</td>
</tr>
<tr>
<td>BF-50-8</td>
<td>N1: 5.7</td>
<td>N2: 4.2</td>
<td>N1: 12.4</td>
</tr>
<tr>
<td>BF-50-12</td>
<td>N1: 4.4</td>
<td>N2: 3.3</td>
<td>N1: -13.2</td>
</tr>
<tr>
<td>MB-43-6</td>
<td>N1: 5.6</td>
<td>N2: 13.3</td>
<td>N1: 11.6</td>
</tr>
<tr>
<td>MB-43-20</td>
<td>N1: 8.0</td>
<td>N2: 19.4</td>
<td>N1: 59.5*</td>
</tr>
<tr>
<td>MB-43-40</td>
<td>N1: 9.3</td>
<td>N2: 30.6</td>
<td>N1: 84.3*</td>
</tr>
<tr>
<td>SF-38-40</td>
<td>N1: 6.7</td>
<td>N2: 19.7</td>
<td>N1: 32.2*</td>
</tr>
</tbody>
</table>

Note: * indicates change is significant at 95% confidence interval (see Appendix C)

Statistical analysis was completed with the Mann-Whitney U-test, since it was unclear if the data followed a normal distribution; something other researchers using the test method have also reported [12, 13, 19]. The results show BF does not have a statistically significant influence on first-crack strength (N1) and only in a few cases was found to significantly influence post-cracking performance (N2). At best, BF-50-8 was found to increase N2 by approximately 30%. On the other hand, BF-36-4 and BF-36-12 were found to decrease N2 by approximately 25%. It is believed these differences are the result of an insufficient sample size, since unlike the MB mixes, there was no obvious trend in the data and the BF was not visible bridging the crack. All of the data is presented graphically in Figs. 2.8 and 2.9. In these graphs, the ultimate resistance (sum of
N1 and N2) is depicted. The error bars shown represent one standard deviation on either side of the measured mean. Based on the size and overlap of the error bars, it can be seen visually from Fig. 2.8 that the differences in the mean values between PC and BF specimens are not significant in a practical sense. On the other hand, the differences in mean values in the MB specimens are clearly significant (Fig. 2.9).

![Fig. 2.8. Impact test results of BF specimens](image)

![Fig. 2.9. Impact test results of MB and SF specimens](image)
The cracked cross-sections shown in Fig. 2.10 are similar to those in Fig. 2.7, in which fibres are not visible in BF specimens, while fibres in MB specimens are clearly effective preventing separation by bridging the crack.

![Cracked cross-section of failed impact test specimens](image)

**Fig. 2.10.** Cracked cross-section of failed impact test specimens

An obvious trend in the data is present, where increasing dosages of MB resulted in increases in N2 ranging from approximately 1200% to 3000% (Table 2.3). MB-43-20 specimens had a similar performance to SF-38-40 specimens, with an increase in post-cracking impact strength (N2) of approximately 1900%. In both MB and SF specimens, observation of the cracked cross-section showed nearly all fibres failed by pull-out. Ruptured fibres were more prevalent in SF specimens, which is likely due to the increase in bond strength from the hooked ends of the SF. Moreover, MB and SF were also effective in increasing the first-crack strength of the concrete (N1). The increase in first-crack strength of MB-43-20 specimens was similar to that of SF-38-40 specimens. Although it should be noted that using the full drop-height (457 mm) during preliminary testing, the MB and SF specimens cracked after no more than two blows. Thus, first-crack strength under impact loading is likely most dependent on the concrete properties.
2.3.3 Interfacial Properties

The scanning electron microscope (SEM) image in Fig. 2.11 (a) shows the penetration of cement hydration products (likely calcium hydroxide – see Appendix D) in-between individual filaments of a BF bundle. This could explain the brittle nature of the BF composites observed in this work, whereby the growth of hydration products between the filaments increases the fibre-matrix bond strength beyond the tensile strength of the fibres, resulting in failure governed by fibre rupture. This is further evidenced by the lack of visible fibres in the failed cross-sections, as shown in Figs. 2.7 (a) and 2.10 (a). Preliminary fibre pull-out testing shows agreement with this idea, since initially the individual filaments in the bundle failed independently, but after 28 the entire bundle of filaments failed uniformly (see Appendix E). Moreover, deflection at peak-load is generally lower in BF-50 specimens than BF-36 specimens (Table 2.2). Thus, failure may be a combination of pull-out and rupture. In both cases, failure would be due to fibre rupture; however the 50 mm fibres probably slipped a little less than the 36 mm fibres due to increased bond strength from a greater contact area with the matrix. The same phenomenon is often reported in literature related to GFRC [20-22], though it is not agreed upon if the composites lose toughness primarily due to a physical mechanism, as suggested in this case, or by a chemical mechanism. In the case of MB specimens, the polymer appeared to be effective in preventing the penetration of hydration products. Some cracks were observed in the polymer, as shown outlined in a white broken line in Fig. 2.11 (b), that are likely the result of mechanical damage during mixing. Pull-out failure observed during testing would indicate it is unlikely the cracks have a significant influence on 28 day performance. However, they may become a durability issue over a
longer duration or in harsher mixing conditions. It should be noted the SEM images in Fig. 2.11 (a) and (b) are of different magnification.

![SEM images of fibres in concrete after 7 days](image.png)

Fig. 2.11. SEM images of fibres in concrete after 7 days

Ongoing work at the University of Windsor has shown BF bundles will abrade more severely during mixing in the presence of higher quantities of coarse aggregate. Fig. 2.12 shows the typical appearance of the cracked cross-section of a BF-50-12 impact specimen. Not only could no fibres be found oriented in a manner that would suggest they were effectively bridging the crack, but the bundles had also clearly been separated into individual filaments. It is believed this is the result of a combination of abrasion during mixing and the ongoing growth of hydration products between the filaments. The work of Bentur [20] found that in brittle composites, spaces between filaments were at least partially filled with hydration products, while in the case of ductile composites, these spaces were largely empty. Therefore, future research should address how to mitigate this issue since ductility is a very desirable trait of FRC.
Jiang et al. [5] observed that the increases in compressive and flexural strength of BFRC diminished over time and attributed it to fibres de-bonding from the matrix. The hypothesis was based on the development of spaces between the fibre and matrix and a decrease in the density of cement on the fibre surface between 7 and 28 days. In some instances spaces were observed between the fibres and matrix, but it was believed to be the result of mechanical disruption due to testing or specimen preparation. Changes in cement density on the fibre surface after 7 and 28 days were not obvious. However, distinct differences were observed after 9 months. The differences are characterized well by Figs. 2.13 and 2.14. It can be found in Fig. 2.13 the amount of cement on the fibre surface appears to decrease. Additionally, as shown in Fig. 2.14, the roughened fibre surface after 9 months indicates a chemical reaction may have taken place.

**Fig. 2.12.** Cracked cross-section of BF-50-12 impact specimen after 9 months
Scheffler et al. [23] have shown BF corrodes in a cement solution, characterized by the development of small holes on the fibre surface after 7 days. Previous research has also shown basalt fibres will lose tensile strength over time when immersed in a solution of calcium hydroxide intended to replicate a hydrating cement medium [24, 25]. Therefore, the relative poor performance of BF observed in this work is believed to be
analogous to the well-established aging process of GFRC. The aging process of GFRC has two primary mechanisms: firstly, a physical mechanism characterized by the growth of hydration products between the filaments, and secondly, a chemical attack due to the high alkalinity of the cement matrix [26]. This is unsurprising given the similar manufacturing process and chemical composition of basalt and glass fibres. This research shows the use of a polymer is effective in overcoming these problems, and thus, MB are a promising alternative to steel fibres for concrete reinforcement. Although some research has been done to quantify the long-term durability of BFRP rebar [27], similar work should be undertaken for MB due to the substantial increase in surface area and the potential for damage during mixing. Finally, it should be noted that a vast amount of research exists on mitigating the aforementioned problems with GFRC by the addition of pozzolanic fillers to ordinary Portland cement concrete mixes, or with the use of alternative cements [26]. This would likely explain why Dias and Thaumaturgo [6] found BF performed better in a geopolymer concrete than in Portland cement concrete. Future research into BFRC can likely be expedited by taking advantage of the parallels drawn with GFRC and the enormous amount of work already published in that field.

2.4 CONCLUSIONS

The following conclusions are based on the results obtained from this research. Hence, may be limited to the specimens used in this study.

1. Fibre dosages beyond 12 kg/m³ and 40 kg/m³ of BF and MB, respectively, led to mixing problems due to fibre balling and resulted in difficulty handling, placing, and consolidating fresh concrete.
2. The addition of BF increased the first-crack strength of concrete subjected to flexural loading, but was not significantly influential when subjected to impact loading. In the case of flexural loading, the first-crack strength increases with increasing fibre dosage. The strength improvement was greater using longer, 50 mm BF than with 36 mm BF. A dosage of 12 kg/m$^3$ of 50 mm BF resulted in a first-crack strength that was comparable to a dosage of 40 kg/m$^3$ of SF.

3. The addition of MB increased the first-crack strength of concrete subjected to both flexural and impact loading. In both cases, the first-crack strength increased with increasing fibre dosage. However, at higher fibre dosages it was difficult to assess when the concrete cracked since the composite behaved in a ductile manner. A dosage of 20 kg/m$^3$ of MB resulted in a comparable increase in first-crack strength to that of SF with a dosage of 40 kg/m$^3$.

4. The addition of BF at any dosage did not have a meaningful effect on the post-cracking behaviour of concrete. On the other hand, MB had a significant benefit, which was further enhanced with increasing fibre dosages. Fibre dosages of 6 kg/m$^3$ and 20 kg/m$^3$ of MB resulted in a comparable post-cracking performance to SF at a dosage of 40 kg/m$^3$ under flexural and impact loading, respectively.

5. The poor post-cracking response of BF specimens was attributed to failure by fibre rupture, in comparison to the MB specimens which failed primarily by fibre pull-out. The ductile post-cracking behaviour in MB specimens was the result of failure by gradual pull-out.

6. Cement hydration products were observed in between the individual filaments of the bundles of BF. Moreover, physical changes to the BF surface were observed
after nine months and believed to be indicative of degradation to mechanical properties. Hence, the brittle behaviour of BF composites can be attributed to fibre rupture due to a combination of increased fibre-matrix bond strength and decreased fibre tensile strength.

2.5 ACKNOWLEDGEMENTS

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2.6 REFERENCES


CHAPTER 3

INFLUENCE OF BASALT FIBRE ON FREE AND
RESTRAINED PLASTIC SHRINKAGE

3.1 INTRODUCTION

Chopped basalt fibre is a relatively new concrete reinforcing material, with excellent mechanical properties and an environmentally friendly manufacturing process. The majority of research into basalt fibre reinforced concrete has focused on its mechanical properties [1-3]. In these studies, the results do not suggest that the fibres are particularly effective in enhancing the post-cracking response of the concrete though, which may be the most beneficial aspect of adding fibre to concrete [4]. Previous work has also indicated plain basalt fibres suffer from a lack of long-term durability in the alkaline environment of concrete [5, 6]. Based on these findings, a useful application of the fibre may be in enhancing the durability of concrete by reducing early age cracking due to plastic shrinkage.

Plastic shrinkage refers to the volumetric contraction of cement-based materials that occurs during the first few hours after placement, while the material is in a plastic state. The contraction is driven by a combination of autogenous mechanisms and capillary pressure that develops in the pore structure near the surface when the rate of water evaporating from the concrete exceeds the rate at which it can be replaced by rising bleed water. When restrained, shrinkage will induce tensile stresses. If those stresses exceed the tensile strength of the concrete, it will crack. Restraint is generally present to at least some degree in practical applications by internal factors, such as rebar and
aggregate, or by external factors, such as connections to walls and columns. Although initially shallow, plastic shrinkage cracks can grow to full-depth over time [7]. The cracks are not only unsightly, but they allow the penetration of deleterious substances, and consequently, can lead to the rapid deterioration of a structure. Most notable is the penetration of water and chlorides enabling the corrosion of embedded steel reinforcement. Shrinkage cracking is often attributed to severely reducing the serviceability of concrete structures, particularly those with a large surface area to volume ratio, including: slabs-on-grade, tunnel linings and repair overlays. Perhaps most detrimental is the reduced serviceability of bridge decks due to early age cracking. A number of reports published from various state departments of transportation (DOTs) in the United States of America, suggest that shrinkage is a major contributing factor to early age cracking [8-11]. In these reports, shrinkage refers to the strain that develops at both an early-age (plastic shrinkage), and over a longer duration after the concrete has hardened (drying shrinkage). However, according to the Transportation Research Board [12], the mechanisms that lead to plastic shrinkage cracks do not explain full depth cracks, and therefore, it is probable drying shrinkage can propagate plastic shrinkage cracks. Since cracks in concrete can propagate at a stress lower than that required to initiate them [13], the control of plastic shrinkage cracking should be a key design consideration in regards to preventing or reducing cracking, and in-turn, minimizing life-cycle costs.

It has been well established that the addition of short, randomly distributed fibres to the concrete mix is an effective method in mitigating plastic shrinkage cracking. The fibres are effective in this regard for two reasons: first, they reduce the overall shrinkage
strains and lower the possibility of tensile stresses exceeding tensile strength, and second, the fibres are able to restrict their development if they do occur [14]. According to Naaman et al. [15], the addition of any fibre with a diameter smaller than 40 microns, an aspect ratio above 200, in volume fractions of 0.2% to 0.4%, should effectively eliminate plastic shrinkage cracking in concrete. Hence, it is unsurprising such a wide variety of fibres have been shown to be beneficial in this regard, including: steel, glass, various synthetic fibres (polypropylene, polyethylene, polyvinyl, and carbon), and various natural fibres (sisal, coconut, flax, and cellulose) [15-20]. However, the mechanisms by which different fibres reduce plastic shrinkage strains, and the resultant cracking, are not as thoroughly studied. This is an important consideration in order to understand the circumstances in which the use of particular types of fibres is most effective.

Only one study, completed by the Florida Department of Transportation (FDOT) was found in regards to the influence of basalt fibre on early age shrinkage. The study concluded that stiff fibres, including basalt, steel, and glass should not be used for early age crack control since it was evident their stiffness initiated cracking sooner, and the cracks were wider [21]. The conclusions were based on the results of the ASTM C1581 [22] test method, in which a steel ring is used as a restraint element. In that case, the poor performance of the stiff fibres may be due to the inability of the fibres to bend and align with the circumference of the cracks that develop due to the circumferential shrinkage stress induced by the ring. The results in that study may not be a good representation of the development of plastic shrinkage cracks in structures with typical rectangular geometry, where shrinkage stresses would develop more linearly, and therefore more likely for fibres to transfer that stress in an optimal orientation. The test method has
previously been criticized for producing an unrealistic stress field in regards to repair overlays [14].

The purpose of the experimental work reported in this paper is to evaluate the influence of three different types of basalt fibre on the plastic shrinkage of concrete. The basalt fibres used in this study are: bundle dispersion fibres (BD), filament dispersion fibres (FD), and minibars (MB). The influence of the fibres is quantified by measurement of the strain when the specimen is unrestrained (free shrinkage), and measurement of crack tendencies in specimens that are restrained from shrinking using a realistic restraint element. It should be noted that the term concrete in this paper refers to both mortar (cement and fine aggregate) and traditional concrete (cement, fine aggregate, and coarse aggregate). Long-term drying shrinkage of fibre specimens was also measured (see Appendix F), however the results showed the fibres did not have a useful effect, and therefore not discussed further in this chapter.

3.2 EXPERIMENTAL PROCEDURE

3.2.1 Environmental Chamber

All testing was done in an environmental chamber that operated at a temperature of 48 °C (± 2 °C) and relative humidity of 15% (± 3%). This was achieved by connecting a heater fan to a temperature and humidity controller capable of reading temperature accurate to ± 1.5 °C and relative humidity to ± 2%. These conditions resulted in an evaporation rate of approximately 0.75 kg/m²/h. The environmental chamber is depicted in Fig. 3.1.
3.2.2 Free Shrinkage Testing

The test setup for the free (unrestrained) shrinkage testing was developed based on similar methods used by other researchers [23, 24]. Concrete specimens measuring 500 mm in length and 80 mm by 80 mm in cross-section were cast. The interior of the forms were lined with a thick polypropylene sheet (vapour barrier) that was lightly coated with Teflon spray. A Teflon plate was placed at one end of the form with a 9.5 mm diameter bolt threaded into it that extended 30 mm into the form. The Teflon plate was loose fitting so that it could move with minimal resistance. As the concrete contracted, the plate was moved by the bond between the bolt and the mortar. The displacement of the plate was measured with a 5 mm linear displacement transducer (LDT) that is accurate to 5 µm. A 25 mm thick piece of foam was placed behind the Teflon plate so that movement due to thermal expansion was also possible. The forms were placed in the environmental chamber and data was collected for four hours. Free shrinkage test results
reported in this study are the mean values calculated based on three specimens per fibre dosage. The setup is illustrated in Fig. 3.2.

![Diagram of test setup](image)

**Fig. 3.2.** Free plastic shrinkage test setup

### 3.2.3 Restrained Shrinkage Testing

The test setup for restrained shrinkage testing closely followed the method proposed by Banthia and Gupta [14], with two exceptions: the length of the restraint element (Fig. 3.3(a)) was increased from 300 mm to 500 mm to match that of the free shrinkage testing, and the thickness of the mortar overlay was reduced from 60 mm to 35 mm to represent a typical concrete cover so that the results could be applied directly to a rehabilitation project in the field. The restraint elements had an average 28 day compressive strength of approximately 60 MPa. The mortar overlay was placed over the restraint element and then the form was placed in the environmental chamber for four hours. The form was carefully removed after 1.5 hours in order to increase the exposed surface area of the mortar, and in-turn, the severity of the cracking. Fig. 3.3b depicts the development of cracks after removing the specimen from the environmental chamber. The cracks were measured using a 240x magnification digital microscope. The total area
of all cracks on the surface for each specimen was measured, and the largest crack width was recorded. Restrained shrinkage test results reported in this study are the mean values calculated based on three specimens per fibre dosage.

3.2.4 Materials and Specimen Preparation

All mixes were made with type 10 general use Portland cement conforming to CSA A3001 [25], regular drinking water, and well-graded aggregates. Mortar was generally used in this study to increase the magnitude of shrinkage strain and cracking severity, so that the influence of the fibre could be more readily measured. The concrete mixes in Table 3.1 show the proportions (by mass) of each type of mix used in this work, along with a description indicating the purpose of the mix.
### Table 3.1. Mass proportions of concrete mixes used

<table>
<thead>
<tr>
<th>Designation</th>
<th>Cement</th>
<th>Water</th>
<th>Fine Agg.</th>
<th>Coarse Agg.</th>
<th>Superplasticizer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>1</td>
<td>0.5</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>Control mix</td>
</tr>
<tr>
<td>M2</td>
<td>1</td>
<td>0.35</td>
<td>2</td>
<td>0</td>
<td>varied</td>
<td>Low w/c ratio</td>
</tr>
<tr>
<td>M3</td>
<td>1</td>
<td>0.5</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>Coarse aggregate</td>
</tr>
<tr>
<td>M4</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>Increase cracking</td>
</tr>
<tr>
<td>M5</td>
<td>1</td>
<td>0.35</td>
<td>1</td>
<td>0</td>
<td>varied</td>
<td>Low w/c ratio</td>
</tr>
</tbody>
</table>

Three types of basalt fibre were evaluated: filament dispersion (FD), bundle dispersion (BD) and minibars (MB). Filament dispersion fibres disperse into individual filaments during mixing, whereas bundle dispersion fibres have a sizing that keeps the filaments together as a bundle. Minibars are an epoxy based polymer reinforced with basalt filaments; essentially a scaled down version of basalt fibre reinforced polymer rebar. The filament and bundle dispersion fibres consist of filaments 16 µm in diameter and the minibars are constructed with filaments 17 µm in diameter. A summary of the fibre dosages used in this work is shown in Table 3.2. Designations are labelled according fibre type, fibre length, and dosage. For example, the designation BD-25-0.1 indicates basalt bundle dispersion fibres of 25 mm length at a dosage of 0.1% by volume.
Concrete was mixed in a standard electric drum mixer until the fibres were uniformly dispersed. The flow of the mortar mixes was measured as per ASTM C1437 [26]. In the case of the reduced w/c ratio mixes (M2 and M5), superplasticizer was added to the mix such that the flow was approximately equal at all fibre dosages. In all cases, the fibres mixed without any noticeable balling or clumping. Differences in fibre dispersion are shown in Fig. 3.4.

![Image](image1.jpg)  
(a) BD-25-0.3  
(b) FD-25-0.3  
(c) MB-43-1.0

**Fig. 3.4.** Difference in dispersion of fibres used in this study
3.3 RESULTS AND DISCUSSION

3.3.1 Mortar Flow

The flow of the control mix (M1) and the mix with a reduced w/c ratio (M2), reinforced with 25 mm filament dispersion fibres is shown in Table 3.3, since that type of fibre had the greatest effect on the flow. In this table, \(D_i\) is the initial diameter of the mortar and \(D_f\) is the diameter of the mortar after dropping the plate 25 times within 15 seconds.

<table>
<thead>
<tr>
<th>Mix Designation</th>
<th>FD-25 Dosage (%)</th>
<th>Super-plasticizer (mL)</th>
<th>(D_i) (mm)</th>
<th>(D_f) (mm)</th>
<th>Flow (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>255*</td>
<td>≥ 155</td>
</tr>
<tr>
<td></td>
<td>0.05</td>
<td>0</td>
<td>90</td>
<td>255*</td>
<td>≥ 178</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>0</td>
<td>85</td>
<td>230</td>
<td>171</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0</td>
<td>70</td>
<td>195</td>
<td>179</td>
</tr>
<tr>
<td>M2</td>
<td>0</td>
<td>40</td>
<td>75</td>
<td>200</td>
<td>167</td>
</tr>
<tr>
<td></td>
<td>0.05</td>
<td>45</td>
<td>75</td>
<td>200</td>
<td>167</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>60</td>
<td>70</td>
<td>200</td>
<td>186</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>110</td>
<td>70</td>
<td>195</td>
<td>179</td>
</tr>
</tbody>
</table>

Note: * indicates mortar spilled off the plate before 25 drops

Results for other types of fibre followed the same trend shown in Table 3.3, and are thus, they are not shown in this table. However, it should be noted that the order from greatest to least in terms of their effect on the flow was: FD-25, FD-12, BD-25, and MB-43. In the cases where the mortar spilled off the plate before being dropped 25 times, the flow could not be accurately calculated. The effect of the fibres is evident by the decreasing value of \(D_i\) with increasing fibre dosages in M1. Moreover, the number of drops required to cause the mortar to spill increased from 17 without fibre, to 22 when a
fibre dosage of 0.05% was used. At fibre dosages of 0.1% and 0.3% it did not spill. In the case of M2, superplasticizer was added to each mix in an attempt to produce an equivalent flow for all fibre dosages. To achieve this, greater dosages of superplasticizer were required as fibre dosage increased. The idea being that the most efficient use of materials would be using the smallest amount of superplasticizer to achieve a minimum flow, or workability. In this case, that was a flow of approximately 170%.

3.3.2 Free Plastic Shrinkage

Preliminary testing showed free shrinkage stabilized between three and four hours after placement. Shrinkage strains measured after 24 hours in several specimens were insignificant in comparison with those occurring in the first few hours, regardless of fibre dosage. Thus, free shrinkage testing was stopped after 4 hours or 240 minutes for all other specimens (Fig. 3.5). Plots based on the mean values of strain measured over time for M1 specimens reinforced with BD-12, FD-25, and FD-12 fibre at a dosage of 0.1% by volume are shown in Fig. 3.5.

![Graph showing strain development over time](image)

**Fig. 3.5.** Mean curves for development of strain over time
In general, the behaviour depicted in Fig. 3.5 shows good agreement with the findings of other researchers using similar test methods [17, 20, 23, 24, 27]. The mean shrinkage strains after four hours are depicted in Fig. 6 for all fibre dosages used in the control mix (M1). The error bars represent one standard deviation on either side of the mean.

**Fig. 3.6.** Mean strain values measured after four hours in control mix (M1)

Based on their work with steel fibres, Mangat and Azari [27] suggested that the reduction in shrinkage strain is the result of a frictional force between the fibre-cement interface that restrains the movement of the cement as it slides past the fibres. Experimental results presented in Fig. 3.6 strongly agree with this explanation. The increase in contact area between fibres and cement when using filament dispersion fibres, as opposed to bundle dispersion fibres or minibars, should theoretically increase frictional resistance, and thus, explains the greater reduction in free shrinkage strain. It is not clear as to why the 12 mm filament dispersion fibres were less effective than the 25 mm
filament dispersion fibres, although the differences may simply be the result of variation in the data (Fig. 3.6). Reduction in free shrinkage also correlates with the effect on the flow. That is, the effect of each type of fibre ordered from greatest to least is the same in both flow and free shrinkage reduction.

It was found that the 25 mm filament dispersion fibres had the greatest beneficial influence on the free shrinkage (Fig. 3.6). Hence, these fibres were used in a low w/c ratio mortar mix (M2), and a concrete mix (M3), to determine if they were still effective in reducing free shrinkage in differently proportioned mixes. A plot comparing the development of shrinkage strains in M2 and M3, as well as the influence of FD-25-0.3 in both mixes, is shown in Fig. 3.7. Additionally, the mean shrinkage strains after four hours are depicted in Fig. 3.8 for all fibre dosages used in M2 and M3. The error bars represent one standard deviation on either side of the mean.

Fig. 3.7. Comparison between reduced w/c ratio mix (M2) and concrete mix (M3)
It can be found from Figs. 3.7 and 3.8 that the reduction of water content in M2, and the addition of coarse aggregate in M3, resulted in approximately the same reduction in the free shrinkage from the control mix (M1), which had shrinkage strain of about 2400 micro-strain as shown in Fig. 3.6. In the case of M2, a fibre dosage of 0.3% did not significantly reduce the free shrinkage strain (Figs. 3.7 and 3.8(a)). On the other hand, when that same fibre dosage was used in M3, a significant decrease was observed (Figs. 3.7 and 3.8(b)). This is most likely due to the addition of superplasticizer to the M2 mixes, which was not used in M3 mixes. The superplasticizer seems to reduce the frictional effects of the fibres, thereby reducing their effect on flow; however, this simultaneously negated their beneficial effect on the free shrinkage strain. Superplasticizer is a key component in concrete mixes with a low w/c ratio (e.g. high strength concrete). Thus, the addition of fibres in these types of mixes will only be useful

Fig. 3.8. Mean strain values measured after four hours

<table>
<thead>
<tr>
<th>Fibre vol. (%)</th>
<th>Designation</th>
<th>Strain ($10^{-6}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>M2</td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>FD-25</td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fibre vol. (%)</th>
<th>Designation</th>
<th>Strain ($10^{-6}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>M3</td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>FD-25</td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
in regards to plastic shrinkage if they are effective in restricting the development of cracks. Even small fibre dosages will require additional superplasticizer in low w/c ratio concrete mixes, since it is most cost-effective to use the lowest amount of superplasticizer to achieve a minimum flow, or workability. In regards to the concrete mix (M3), a previous study has shown that the addition of filament dispersion fibres does not have a significant effect on the workability of regular strength concrete (w/c of 0.5 and compressive strength of 30-40 MPa) until dosages of approximately 0.46% by volume [2].

The FDOT [21] found that the addition of low dosages of fibre (<0.3%) generally did not have a significant effect on the workability of a concrete mix with a low w/c ratio (<0.37). However, marginal decreases in the workability were found with stiffer fibres. Assuming all other parameters being identical, it seems intuitive that fibres with a higher elastic modulus would produce greater frictional resistance, and therefore, lead to a larger reduction in free shrinkage strain. Boghossian and Wegner [17] studied the effect of flax, polypropylene, and glass fibres on free shrinkage and found that glass fibres, having a higher elastic modulus than the other fibres, were the only type of fibres to consistently reduce the free shrinkage strain. This may suggest that the use of high modulus fibres like basalt comes with a trade-off: they are effective in decreasing the free shrinkage strain, but probably have a more adverse effect on workability than low modulus fibres (e.g. polypropylene).

3.3.3 Restrained Shrinkage

Preliminary testing showed that at the lowest dosage (0.05% by volume), 25 mm filament dispersion fibres completely eliminated shrinkage cracking in the control mix
M1. Thus, the amount of fine aggregate was reduced in mix M4, which in-turn increased the unit volume of cement and water, and therefore, resulted in greater shrinkage strain and more cracking. This allows the effect of the fibres to be more readily measured. Fig. 3.9 shows the typical appearance of fibre reinforced specimens with varying fibre dosages versus an unreinforced specimen after four hours. Additionally, the influence of the fibres on the total crack area and largest crack width are shown in Figs. 3.10 and 3.11, respectively.

Fig. 3.9. Crack reduction with increasing fibre dosage in M4

Fig. 3.10. Effect of fibres on total crack area on specimen surface in M4
Again, the 25 mm filament dispersion fibres had the greatest effect. In this case, they produced the greatest reduction of the crack area and the crack width. The results from the free shrinkage testing correlated well with both measured parameters: total crack area and largest crack width. In other words, the magnitude of shrinkage strain was very indicative of the crack severity. However, it is clear that the benefit of the fibres is not just because of their ability to reduce free shrinkage strain. The fibres are effective, at least partly, due to their ability to bridge cracks, as shown in Fig. 3.12.

**Fig. 3.11.** Effect of fibres on crack width on specimen surface in M4

![Graph showing the effect of fibre dosage on crack width](image)

**Fig. 3.12.** Crack development without fibre (a) and with fibre (b)
Further evidence of the crack bridging ability of basalt fibres is provided in Fig. 3.13, in which it can be found that the 25 mm filament dispersion fibres are also effective in reducing the crack area in the low w/c ratio mix (M5). Free shrinkage testing revealed that the fibres did not have a significant effect on the reduction in strain when both low w/c ratio and superplasticizer are used. Thus, their effectiveness in this case must be attributed to their ability to restrict the growth of cracks.

The performance of 12 mm filament dispersion fibres was very similar to that of the 25 mm filament dispersion fibres. It is likely the greater bond strength, resulting from the increased length of the 25 mm fibres, which makes them more effective in restricting crack growth. Banthia and Gupta [16] reported similar findings in their study on polypropylene fibres. In the case of bundle dispersion fibres and minibars, the fibres were not observed bridging the cracks. This makes sense, since cracks are more likely to develop where fibres are not present. The filament dispersion fibres cover a much greater area, and therefore, there is a higher probability they will bridge a developing crack.

Fig. 3.13. Effect of FD-25 on crack area in low w/c ratio mix M5

The performance of 12 mm filament dispersion fibres was very similar to that of the 25 mm filament dispersion fibres. It is likely the greater bond strength, resulting from the increased length of the 25 mm fibres, which makes them more effective in restricting crack growth. Banthia and Gupta [16] reported similar findings in their study on polypropylene fibres. In the case of bundle dispersion fibres and minibars, the fibres were not observed bridging the cracks. This makes sense, since cracks are more likely to develop where fibres are not present. The filament dispersion fibres cover a much greater area, and therefore, there is a higher probability they will bridge a developing crack.
Restrained shrinkage testing was not undertaken with the concrete mix (M3), since it would not provide realistic data given the scope of the test method. However, it would be reasonable to assume that basalt fibres would have a similar benefit in concrete mixes and this could be of interest to further research. The findings of the restrained shrinkage testing in this paper, in regards to the ability of basalt fibres to restrict the growth of plastic shrinkage cracks, disagree with those of the FDOT [21], who found basalt fibres were detrimental.

3.4 CONCLUSIONS

The results presented in this paper suggest basalt fibres are effective in mitigating plastic shrinkage cracking by reducing the magnitude of the shrinkage strain and by restricting crack propagation if they do occur. In the case of low w/c ratio mixes, it is the latter mechanism which is most prominent. Thus, it could be stated that the fibres are more efficient when w/c ratio is greater (e.g. regular strength concrete), but are still beneficial when the w/c ratio is low (e.g. high strength concrete).

The filament dispersion fibres were most beneficial, likely due to two reasons: an increased surface area resulting in higher frictional restraint, and a greater probability of bridging cracks because of the increased number of uniformly spaced filaments. Moreover, filament dispersion fibres 25 mm in length were more effective than fibres 12 mm in length, although, the difference was minor and may be a result of the inherent variability in both test methods used. From a manufacturing point of view, the fibre dosage required to eliminate cracking could likely be decreased by reducing the diameter of the filaments. This would increase the number of individual filaments and the surface area of the fibres as a whole, with respect to the quantity of material.
Filament dispersion fibres were able to completely prevent shrinkage cracking at a dosage of 0.1% by volume in all cases in this study. However, in practical applications, shrinkage cracking could likely be eliminated at even lower fibre dosages, since the environmental conditions and mix proportions used in this study were designed to exaggerate the effects of shrinkage. It has been well established that the workability decreases with increasing fibre dosages. Eliminating shrinkage cracking with the lowest possible fibre dosage could provide maximum benefit with minimal interference to the workability. Related literature suggests the effect on workability is more detrimental with higher modulus fibres like basalt. Therefore, it could be concluded that basalt fibres are likely best suited for use in regular strength concrete (e.g. higher w/c ratio, higher slump mixes), since they can eliminate cracking by restricting crack growth in addition to reducing strain, without requiring measures to restore workability. In low w/c ratio concrete mixes, basalt fibres are still effective, but it may be preferential to use low modulus fibres to reduce the impact to workability (e.g. polypropylene).

Although this study has concluded that bundle dispersion fibres and minibars are not optimal for plastic shrinkage cracking, they still clearly provided some benefit. Therefore, it may be of interest to pursue future research into the use of these fibres as secondary reinforcement with the intent of minor enhancements to both mechanical behaviour and reducing plastic shrinkage strains and cracking.

3.5 ACKNOWLEDGEMENTS

The authors appreciate the financial assistance received from OCE, NSERC, Connect Canada, and MEDA Limited. The authors also appreciate the technical assistance and donation of materials from MEDA Limited.
3.6 REFERENCES


CHAPTER 4

REHABILITATION OF A DETERIORATED CONCRETE BRIDGE STRUCTURE

4.1 INTRODUCTION

The poor condition of North American infrastructure has been a growing cause of concern for quite some time now. A lot of public infrastructure was built in the economically prosperous decades following the Second World War, and consequently, is now showing obvious signs of deterioration. The utility of structures like dams, roads, and bridges is something that often seems to be taken for granted in times of rapid technological advancement. Evidence of this outlook perhaps lies in the low grade assigned to the majority of areas evaluated in the Report Card for America’s Infrastructure; a study conducted by the American Society of Engineers every four years (since 2001) to assess the condition of various types of infrastructure. According to their 2013 release, an annual investment of $20.5 billion is required to eliminate the bridge deficient backlog in the United States by 2048, while only $12.8 billion is currently being spent [1]. Moreover, a study conducted in 2007 by the MMM Group reports that 14% of Ontario’s 12,000 bridges require immediate maintenance, and 26% require maintenance in 1-5 years, at an average cost of about $300,000 per bridge [2]. Of course concrete is not the only material used in bridge construction, however, it is quite reasonable to assume that a very significant portion of the repair figures cited can be attributed to deteriorated concrete elements (e.g. piers, abutment walls, decks). In any case, there is
clearly a significant amount of spending required for concrete repairs in general; with many of the required repairs being similar in nature on structures besides just bridges.

Unfortunately, concrete repairs are often treated as something so simple that anyone can do it. As a result of this view, there has been an endless “repair of repairs”, which is tarnishing the public’s image of concrete repairs [3]. Given the significant cost associated with these repairs, it is a rather serious problem that public funds may be effectively wasted due to poor practices. Vaysburd et al. [3] attribute the poor practices partly to outdated specifications that are not conducive to the selection of materials that are appropriate for specific situations. For example, cement-based materials are often selected based on a minimum compressive strength, instead of a parameter that may be more relevant in particular circumstances, like a drying shrinkage limit. Focus is often on using high-performance materials, without considering these materials require highly trained individuals to implement effectively. Consequently, the repairs are often little more than a cosmetic bandage, instead of serving a more practical purpose: to stop the problem and prevent it from re-occurring in the expected service life of the structure.

The objective of the work presented in this chapter is to evaluate the effect of chopped basalt fibres used to reinforce cement-based repair materials. Moreover, the potential benefit of applying the repair material onto the existing structure using a spraying technique (spraycrete) is investigated.

### 4.2 ORIGINAL CONDITION OF BRIDGE

The bridge structure repaired in this study spans a drainage ditch under Manning Rd. in Maidstone, Ontario, as shown in white in Fig. 4.1.
Five areas of the bridge were identified to be in need of repair (shown in Figs. 4.2-4.6.): the east-end wing walls, the mid-span of the abutment walls, the mid-span and west-end of the deck soffit, and the east-end of the deck.

(a) Major repair  
(b) Minor patch repairs

**Fig. 4.1.** Location of bridge (in white)

**Fig. 4.2.** East-end wing wall repairs
Fig. 4.3. Major continuous crack at mid-span of abutment walls

Fig. 4.4. Major continuous crack at mid-span of deck soffit
Fig. 4.5. West-end of deck soffit

Fig. 4.6. East-end of bridge deck
4.3 REPAIR METHODOLOGY

Three repair techniques were used: sprayed on patches (spraycrete), trowelled on patches, and cast-in-place concrete. The methods used at each location are summarized in Table 4.1.

The patch repairs were made with a commercial product (SikaTop), which is a fast-setting, corrosion inhibiting mortar with a high bond-strength that makes it ideal for overhead and vertical repairs. For the sprayed on repairs, a dosage of 8 kg/m³ of 12 mm basalt filament dispersion fibres were added. The trowelled on patches did not have any basalt fibre added and were used as a control.

![Image](a) Mixing patching material  ![Image](b) Spraying on

**Fig. 4.7.** Patching repair methodology

The cast-in-place concrete was provided by a local ready mix plant. It was a standard, regular strength concrete mix, with an expected 28-day compressive strength of 35 MPa (without fibre added). A dosage of 8 kg/m³ of 36 mm basalt fibre was added into the mix by hand. Basalt rebar dowels 10 mm in diameter were inserted into drilled holes in the existing concrete with epoxy, to enhance the connection of the repair with the
existing structure. Additionally, 25 mm basalt mesh was placed on the fresh concrete halfway through placement as an extra crack control measure. A total of five cylinders (100 mm diameter by 200 mm height) were made on-site to test the compressive strength of the concrete after 28 days. All exposed rebar was coated with a corrosion inhibiting epoxy spray.

Fig. 4.8. Cast-in-place concrete repair
Table 4.1. Summary of repair techniques

<table>
<thead>
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<th>Location</th>
<th>Repair Technique</th>
<th>Chopped Basalt Fibre Added</th>
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</thead>
<tbody>
<tr>
<td>East-end Wing Walls</td>
<td>Sprayed on (Fig 4.2). Upper right corner cast-in-place with deck (Fig 4.2 (a)).</td>
<td>12 mm length at 8 kg/m³</td>
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<tr>
<td>Abutment Walls</td>
<td>Existing rebar epoxy coated then mortar sprayed on (Fig. 4.3).</td>
<td>12 mm length at 8 kg/m³</td>
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<tr>
<td>Mid-span Deck Soffit</td>
<td>Existing rebar epoxy coated then mortar sprayed on (Fig. 4.4).</td>
<td>12 mm length at 8 kg/m³</td>
</tr>
<tr>
<td>West-end Deck Soffit</td>
<td>Existing rebar epoxy coated then mortar trowelled on (Fig. 4.5).</td>
<td>No fibre</td>
</tr>
<tr>
<td>East-end Deck</td>
<td>Existing rebar epoxy coated. New basalt rebar dowels and mesh added. New concrete cast-in-place (Fig. 4.6)</td>
<td>36 mm length at 8 kg/m³</td>
</tr>
</tbody>
</table>

4.4 ASSESSMENT AFTER ONE YEAR

The sprayed on and trowelled on patches showed no obvious signs of deterioration after one year. The condition of the patch repairs for each location are shown in Figs. 4.9 to 4.13. These figures correspond to Figs. 4.2 to 4.6. That is, they show the before and after of the repair process. The mean 28 day compressive strength of the cast-in-place concrete was evaluated as per ASTM C39 [4] and found to be 17 MPa.
Fig. 4.9. East-end wing wall repairs after one year

(a) Major repair

(b) Minor patch repairs

Fig. 4.10. Major continuous crack at mid-span of abutment walls after one year

(a) Repaired crack in abutment wall

(b) Same crack on opposite side
Fig. 4.11. Major continuous crack at mid-span of deck soffit after one year

(a) Repaired crack in deck soffit  
(b) Same crack on opposite side

Fig. 4.12. West-end deck soffit after one year

Fig. 4.13. East-end deck after one year
4.5 DISCUSSION

The visual inspection one year after the repair revealed there were no obvious signs of deterioration to any of the patch repairs. This provides some evidence that the basalt fibre reinforced mortar repairs are durable. However, it is unclear (at least at this point) if there is any benefit to adding the fibre, since there is no obvious difference between patches made with and without fibre. The spray on technique was reported as beneficial by the contractors. It allowed material to be applied quicker than trowelling, particularly when spaces behind rebar needed to be filled (e.g. Fig. 4.4 (b)). During the overhead repairs (Fig. 4.4), the initial repair patch fell off the existing concrete (de-bonded) because it was too heavy. To overcome this problem, the patch was re-applied in two separate thinner layers. Minor sagging was also a problem in the repairs on the abutment and wing walls (Figs. 4.2 and 4.3). Further lab work could be completed to determine a maximum layer thickness before sagging and de-bonding become a problem. The effect of parameters such as air pressure, spraying distance, and material properties could be investigated.

The cast-in-place repair to the east-end of the deck (Fig. 4.13) demonstrated the potential for problems due to the effect of the fibres on workability. When the fibre was added to the concrete, the workability was severely reduced. To restore workability, a disproportionate amount of water was added due to miscommunication with the contractor on the volume of concrete in the truck. It has been well established that compressive strength and the w/c ratio are inversely related. As a result of adding water, the expected compressive strength (35 MPa) was reduced by approximately 50%. Moreover, the rough surface shown in Fig. 4.13 clearly indicates a segregation problem.
That is, the water (the material with the lowest density) rose to the surface, while the cement and aggregates settled at the bottom. The consequence is the very weak, porous surface layer shown in Fig. 4.13. In a general sense, the cast-in-place concrete could be described as low quality. These problems could have been avoided by using superplasticizer to restore workability (not available at the time), instead of adding more water.

The repairs made in this project may also further prove the view of Vasyburd et al. [3], in which too much focus is given to high-performance materials, instead of the implementation of those materials. This is evident in the repair to the east-end wing wall, shown in Fig. 4.14.

![Fig. 4.14. Rust deposit on surface of east-end wing wall repair](image)

(a) Before repair  
(b) One year after repair
As shown in Fig. 4.14, it is likely that the corner of the wing-wall had such significant deterioration because of the penetration of water and a number of freeze-thaw cycles. When water freezes, it expands by about 9%, inducing stresses that can cause cracking and crumbling [5]. Moreover, the presence of rust on the surface suggests that the embedded steel rebar is still corroding. Corroded steel rebar occupies more volume than that of un-corroded rebar, and exerts stresses on the concrete that can also cause cracking and crumbling. Finally, it is possible that the cast-in-place repair is quite porous due to the high w/c ratio. Therefore, the addition of basalt fibre to the concrete did not seem be effective in preventing the underlying problem causing the deterioration.

Chapter 3 indicates one useful aspect of adding basalt fibre to the material would be in decreasing the free shrinkage strain, which could be beneficial to the bond strength of the patch repairs. However, that was not known at the time the repairs were made, although it may be of interest in future work. Finally, the chopped fibres, mesh, and rebar will not contribute to further deterioration due to corrosion in the same way as steel rebar. The condition of the repairs will continue to be monitored.

4.6 REFERENCES

CHAPTER 5

GENERAL DISCUSSION AND CONCLUSIONS

The work in this thesis was undertaken in order to better understand the general behaviour of concrete reinforced with different types of basalt fibre, so that potential applications of those fibres can be better identified. This chapter summarizes the main findings for each type of fibre and provides recommendations for future work.

5.1 FILAMENT DISPERSION FIBRES

Filament dispersion fibres at a dosage of 0.1% by volume completely eliminated plastic shrinkage cracking. They were more effective at reducing free plastic shrinkage strain and restricting crack growth than bundle dispersion fibres and minibars. Moreover, fibres 25 mm in length were more effective than fibres 12 mm in length. This research suggests the most useful application of these fibres is in providing crack control at an early age. Prevention of cracks at an early age will be beneficial in enhancing the long-term serviceability of concrete structures with a large exposed surface area, such as bridge decks, and slabs-on-grade. The lab results provide strong evidence of the benefit of the fibres, and thus, future work should focus on real-world application. Although the long-term chemical durability of the fibres is unknown at this time, they will have achieved their intended purpose before degrading should that be a problem.

5.2 BUNDLE DISPERSION FIBRES

The bundle dispersion fibres were shown to increase the first-crack strength of concrete, but did not provide a meaningful benefit after cracking. Unfortunately, post-
cracking behaviour is generally the most important parameter when using fibre as a strengthening material. However, from a durability perspective, the bundle dispersion fibres were more effective than the minibars in reducing free plastic shrinkage strain and restricting crack growth. This research suggests the most useful application of these fibres is enhancing the mechanical behaviour and durability of architectural cement products (e.g. facade panels). Architectural elements typically would not have high-strength requirements, nor are susceptible to corrosion due to chloride penetration, since they are typically not reinforced with steel rebar. Future work should focus on how to prevent the penetration of cement hydration products between the individual filaments, in order to change the failure mode to fibre pull-out, and in-turn, enhance post-cracking behaviour. Moreover, the long-term chemical durability of the fibres should be quantified, so that even if alkaline attack is inevitable, it can at least be taken into account in design.

5.3 MINIBARS

The minibars were shown to provide the greatest enhancement to the pre- and post-cracking strength. On the other hand, they were least effective in reducing free plastic shrinkage strain and restricting crack growth. Therefore, this research suggests the most beneficial application of these fibres is in partially, or totally replacing traditional steel rebar in structures where tensile load carrying capacity is not vital (e.g. industrial floors and pavements). Future research should quantify the long-term chemical durability of the minibars if they are to reliably replace rebar.
APPENDICES

APPENDIX A

COMPRESSIVE STRENGTH

Table A.1. Compressive strength of BF specimens

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Table A.2. Compressive strength of MB and SF specimens

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Table B.1. Statistical analysis of flexural testing specimens

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APPENDIX C

IMPACT TESTING STATISTICAL ANALYSIS

Fig. C.1. Q-Q plot of PC specimens

Fig. C.2. Histogram with normal distribution curve overlayed (N1 of PC)
Fig. C.3. Histogram with normal distribution curve overlayed (N2 of PC)

Fig. C.4. Q-Q plot of BF-50-8 specimens
Fig. C.5. Histogram with normal distribution curve overlayed (N1 of BF-50-8)

Fig. C.6. Histogram with normal distribution curve overlayed (N2 of BF-50-8)
Fig. C.7. Q-Q plot of MB-43-20 specimens

Fig. C.8. Histogram with normal distribution curve overlayed (N1 of MB-43-20)
Table C.1. Statistical Analysis of N1

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Fig. C.9. Histogram with normal distribution curve overlayed (N2 of MB-43-20)
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Table C.2. Statistical Analysis of N2
APPENDIX D

EDS ANALYSIS OF SEM WORK

Fig. D.1. SEM images of fibre surface

(a) Fibre as received
(b) After 7 days in cement matrix

Fig. D.2. EDS spot analysis of fibre as received

Fig. D.3. EDS spot analysis of fibre after 7 days in cement
Table D.1. Change in chemical composition on fibre surface

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<th>Element</th>
<th>Weight % (initial)</th>
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<th>% Change</th>
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<td>Mg K</td>
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APPENDIX E

FIBRE PULL-OUT TESTING

Fig. E.1. Pull-out test setup

Fig. E.2. Test specimen

Fig. E.3. Load-deflection plot after 1 day (typical for 6/8 tests)

Fig. E.4. Load-deflection plot after 28 days (typical for 8/8 tests)
APPENDIX F

LONG TERM DRYING SHRINKAGE

Fig. F.1. Concrete prisms

Fig. F.2. Scale and length comparator

Fig. F.3. 120 day shrinkage of BD-25 and FD-25 specimens (representative of other fibre types)
Fig. F.4. 28 day shrinkage of FD-25 specimens

Fig. F.5. 28 day mass loss of FD-25 specimens
Appendix G

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Publication: Journal of Natural Fibers
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