INVESTIGATION OF MECHANICAL AND DURABILITY PROPERTIES OF CEMENT MORTAR AND CONCRETE WITH VARYING REPLACEMENT LEVELS OF CRUMB RUBBER AS FINE AGGREGATE

by

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Abstract

Waste rubber materials are increasing over time with the increase in rubber tire production. These huge piles of waste are contributing to environmental degradation. As such, environment friendly substitutes are required in minimizing the adverse impact. Reuse of these materials in various alternatives are in research for the last few decades; however, major outputs in structural construction material industries are still discouraging. This research primarily focuses on the reuse of crumb rubber in both cement mortar and concrete by replacing 10%, 20%, 30%, 40% and 50% volume of sand aggregates. The experiments and analyses are done in terms of fresh properties, i.e. workability, setting time, and air content as well as hardened characteristics, i.e. compressive strength, splitting tensile strength, flexural strength, stress-strain behavior, unit weight, and water absorption. Moreover, durability aspects, in particular freeze-thaw resistance and rapid chloride permeability test, are examined. The experimental results confirmed low compressive strength of rubber-based mortar; however, crumb rubber up to 10% replacement performed the best with a cement to sand ratio of 1: 2.5. On the other hand, crumb rubber up to 20% replacement in concrete surpassed 35 MPa designated compressive strength, showing comparable results with the control (without any crumb rubber) specimens. Moreover, rubber-based concrete outperformed natural aggregate based concrete in terms of long-term durability performance, creating potentials of using this construction material in harsh environment.
Preface

Major portions of this research are submitted for possible publications in peer-reviewed conference proceedings and technical journals. The author executed all the experiments, analyzed the results, and wrote initial drafts of the articles listed below. His research supervisor provided valuable guidance and facilitated in the development of the final versions of the publications.

Publications arising from this thesis are as follows:


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Dedicated to my loving mom and superhero dad
Chapter 1

Introduction

1.1 General

For the last few decades, waste disposal management has become a serious issue because of substantial increase in day-to-day commodities and goods. Environmental pollution and degradation are the direct effects of improper waste disposal management. In addition, lack of proper management diminishes the recycling and reusing potential of solid wastes. Consequently, managing disposable waste in an environment friendly way has become a demanding research topic, thereby creating scopes for future development (Islam et al., 2015).

Rubber-based products; especially used rubber tires from vehicles fill a significant portion of landfill spaces among all the waste materials (Meherier et al., 2015). This is due to its non-degradable or non-decomposed characteristics consisting of small molecular weight additives, such as adhesives, stabilizers, colorants, plasticizers, and other fibers. These small but destructive molecular weight additives from discarded waste rubber tires may leach to the soil surface and cause severe environmental and soil pollution. Usually a rubber tire that is discarded or disposed at the end of its service life consists less than 1% abraded rubber (Adhikari et al., 2000). However, the main component in a tire consists of 41% mixed synthetic and natural rubber (RMA, 2014). Therefore, a huge amount of waste is being generated every year from waste rubber tire. Consequently, many unwanted pests, rats, and mosquitoes can make their breeding ground in these huge piles of waste rubber materials. They can also be a source of devastating fire (Naik and Singh, 1991; Singh, 1993). Researchers and scientists all around the world are considering this alarming issue and working in finding a viable option for reusing and recycling rubber waste materials into resourceful alternatives and protect the environment as such.
One of the potential usages of crumb rubber is the replacement of naturally sourced aggregates in concrete and cement mortar (El-Gammal et al., 2010; Ling et al., 2010; Pierre, 2013). Both fine and coarse aggregates were replaced in partial or in full in most of the above-mentioned studies. However, poor mechanical properties made it an inferior construction material compared to conventional concrete (Al Bakri et al., 2007; Ling et al., 2009; IRSG, 2014). Moreover, very few studies were reported on the properties of cement mortar with varying replacement levels of crumb rubber (Eldin and Senouci, 1993; Raghavan et al., 1998; Meherier et al., 2015). In contrast, substantial studies can be found on rubber-based concrete (Fedroff et al., 1996; Khatib and Bayomy, 1999; Bravo and Brito, 2012; Dong et al., 2013; Holmes et al., 2014; Su et al., 2015).

Previous studies revealed inconsistencies in terms of material properties of rubber-based cement mortar and concrete. The sources and sizes of crumb rubber mostly influenced the mechanical and durability properties. Moreover, very few studies were found on rubber usage in concrete based on Canada’s waste rubber products, especially crumb rubber. Currently, in construction industry, there is no guideline for constructing and designing concrete members using rubber-based concrete. This creates scope in doing research and finding the possibility of using crumb rubber as a replacement of natural aggregates.

1.2 Objectives

The overall motivation of this research is to investigate whether crumb rubber can be used effectively in cement mortar and concrete as fine aggregates conforming Canadian design standards or requirements. Although studies have been performed on the properties of rubber-based concrete, its viable structural applications are yet to be accomplished. Moreover, rubber tires from different origins differ in their chemical composition thereby making significant changes in concrete properties. The following objectives are pursued in this study.

• Performing chemical analysis of crumb rubber and finding its chemical compositions. In terms of cement mortar, fresh and hardened properties were
explored with varying replacement levels of crumb rubber as fine aggregate substitution. Moreover, the effects of changing cement to aggregate (i.e. sand and crumb rubber) ratio was also examined.

- Investigating fresh, hardened, and durability properties of concrete made with different percentages of crumb rubber by replacing sand as fine aggregates.

- Feasibility of using crumb rubber in cement mortar and concrete as well as finding an optimum replacement percentage with comparable mechanical and durability properties.

1.3 Research Significance

Sustainable construction and infrastructure are pivotal elements in overall development strategy of Canada. Canada processed 240 thousand metric tons of waste tire rubber in 2003 (Pehlken and Essadiqi, 2005); however, the number increased enormously over the next decade and reached 391 thousand metric tons (CATRA, 2015). Every year this huge amount of scrap tires are utilized in the end use market for producing tire derived fuel (TDF), tire derived products (TDP) like rubber flooring, rubber tiles, parking curbs, etc., and various civil engineering applications. The rubber flooring manufacturing industries contribute in large to British Columbia’s economy compared to other provinces in Canada.

The present research aims to utilize rubber waste and turn it into new construction materials. Building material industry, construction firms, government organizations including municipalities, federal, and provincial are all involved with the development of new construction and rehabilitation of infrastructure projects. These sectors would directly benefit from the outcomes of the proposed research. Moreover, this research will help Canada save substantial amount of natural resources by reusing waste rubber products thereby contributing directly to the Canadian economy by improving the GDP (gross domestic product). This research will lead Canada to a sustainable solution for the recycling/reusing of waste rubber products especially crumb rubber.
1.4 Thesis Outline

This thesis consists of six chapters focusing on different aspects of investigation. Chapter 1 introduces the inspected topic along with the objectives, research significance, and thesis outline. Chapter 2 provides an extensive literature review based on previous studies and publications. This chapter primarily gives an overview of scrap tire generation around the world with latest available data. Moreover, various applications of waste rubber materials as well as fresh, mechanical, and durability aspects of both rubber-based mortar and concrete are presented. Chapter 3 describes the experimental procedure along with the experimented results of fresh and hardened properties of rubber-based cement mortar with different replacement levels and cement to aggregate ratio. Moreover, Scanning Electron Microscopic (SEM) and Energy Dispersive Spectroscopy (EDS) chemical analysis of crumb rubber is also presented for having a broad idea about the used rubber material. Chapter 4 portrays the experimental procedure of rubber-based concrete samples in addition to the results of mechanical properties. Chapter 5 depicts the durability properties of different replacement levels of crumb rubber based concrete including freeze-thaw resistance and chloride permeability. Chapter 6 concludes the study with limitations and future recommendations.
Chapter 2

Literature Review

2.1 General

The use of sustainable materials in construction industry is gaining popularity, as environmental preservation is becoming a primary societal concern globally. The use of waste rubber materials in sustainable concrete production is a relatively new concept and gradually gaining a lot of interest in recent years. The newly produced material would definitely pave the way for a greener environment, even though the idea is still in its conceptual phase due to lack of technical knowledge in its behavior in concrete. Since the origin of waste rubber materials varies, their mechanical properties may fluctuate over a wide range. Therefore, proper guideline on the use of rubber in producing concrete and mortar is yet to be established.

This chapter presents a detailed summary of the existing literature on comparative analysis of fresh, hardened, and durability properties of rubber-based concrete and concrete without rubber as aggregate. Additionally, detailed summary of past and current status on scrap tire generation in the world and Canada, in particular, is presented in a systematic manner in order to have a better overview of the current situation. Since this concept is not yet introduced to the construction industry due to lack of technical knowledge, research is ongoing all over the world in order to enhance its properties efficiently.

2.2 Overview of Scrap Tire Generation

Since the number of vehicles like buses, trucks, cars, and aircrafts is increasing, the demand for rubber tire is growing at the same rate. Likewise, number of discarded and disposed waste rubber tires is going up. This has been the case globally, regardless of developed and developing countries. A brief summary with statistical information
related to rubber tire production, consumption, and consequently, waste rubber tire growth rate is presented in this section for a better overview of the whole condition.

2.2.1 Scrap tire generation around the world

Rubber generation around the world is increasing in order to feed the ever-demanding tire production. Consequently, waste management associated to waste rubber tire is growing alarmingly. To understand the scenario, rubber production around the world was examined in different studies.

The rubber is produced in two forms, i.e. Natural Rubber (NR) and Synthetic Rubber (SR). Around 26.3 million metric tons (in weight) of NR and SR were produced in 2011 (Amutio et al., 2012). According to Rubber Manufacturers Association (RMA), in 2012, more than 26.7 million metric tons of rubber were produced globally and it increased to more than 27 million metric tons in the year 2013 (RMA, 2014). In addition, production of SR is more in number than NR because of its ease in production and reduced cost. The International Rubber Study Group (IRSG) provided a broad overview of rubber production and consumption amount from 2000 to 2014 (IRSG, 2015). Figure 2.1 shows the increasing trend and summarizes the production amount of rubber (including both NR and SR) and their consumption amount (in million metric tons). It can be seen that production amount and consumption amount of rubber in 2000 was 17.7 million metric tons and 17.9 million metric tons, respectively. Both the production and consumption amount started to grow over the years and became 28.8 million metric tons (62.6%) and 28.9 million metric tons, respectively (61.2%). These values represent the year 2014.

The production rate and consumption rate of rubber over the years is presented in Table 2.1. The rate, however, decreased in 2001 but started to rise thereafter with the escalation of demand. The production growth rate reached 62.6% in 2014 as well as the consumption development rate reached 61.2% in the same year. Malaysia is one of the key rubber manufacturing countries; however, it produced 927 thousand metric tons of rubber in 2000 and gradually it reduced to 668 thousand metric tons in 2014.
(Al Bakri et al., 2007). As the country started to import more rubber from Thailand, its own rubber production went down.

![Figure 2.1: Global production amount and consumption amount of rubber over the years (Data collected from IRSG, 2015)](image-url)

Globally, the major consumers of produced rubber are tire-manufacturing industries that consume around 70% of the generated rubber (Meherier et al., 2015). As a result, waste rubber tire, also known as scrap tire, is piling up with the increased amount of rubber tire production. Moreover, the rest 30% of the generated rubber is consumed by General Rubber Goods (GRGs) industries. Some of the manufactured products of GRGs are rubber floor covering and mats, surgical gloves, rubber made tubes, pipes and hoses, transmission and conveyor belts, gaskets, washers, etc. Germany, France, Japan, USA, UK, and Sweden are the top manufacturing countries of GRGs in the world (ETRMA, 2014). For Malaysia, in spite of slow production rate, rubber consumption amount grew rapidly every year and it increased from 419 to 801 thousand metric tons during the years of 2000 to 2014 (DOS, 2015). Tire industries in the European countries consumed 74% of natural rubber in the year 2013. In terms of
tire production, these countries produced 4.9, 4.7, 4.5, 4.6, and 4.6 million metric tons of rubber tire in 2006, 2008, 2010, 2012, and 2013, respectively (ETRMA, 2014). Moreover, China is the market leader in consuming both the NR and SR followed by the European countries, the USA, and India.

Table 2.1: Global production rate and consumption rate of rubber over the years

<table>
<thead>
<tr>
<th>Year</th>
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<td>62.6%</td>
<td>61.2%</td>
</tr>
</tbody>
</table>

All the manufacturing units consume rubber and generate rubber products, including tire and GRGs. Since tire manufacturing industries consume majority of the produced rubber, their cumulative waste generation is also high. Table 2.2 resembles a typical composition of passenger and truck tire in North American. As it is shown in the table, a total 41% constituent by weight of a tire is rubber. In terms of waste rubber tire generation, developed countries are well ahead than the developing countries as the demand for tires is much higher in the former countries. The United States of America (USA) alone produced 270 million (amount in number) scrap tire that is approximately 3.6 million metric tons in weight. France, one of the leading scrap tire producer, generated 10 million (amount in number) scrap tire a year (Siddique and Naik, 2004). It has been reported that the entire North America, China, and European Union produced 2.5, 1, and 2.5 million metric tons, of scrap tire in 2005 respectively,
which is equivalent to 6 kilograms of waste rubber generated per resident per year in those countries (Sadaka et al., 2012).

Table 2.2: Typical composition of truck and passenger tires (RMA, 2014)

<table>
<thead>
<tr>
<th>Composition</th>
<th>Truck Tire</th>
<th>Passenger Tire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Rubber</td>
<td>27%</td>
<td>14%</td>
</tr>
<tr>
<td>Synthetic Rubber</td>
<td>14%</td>
<td>27%</td>
</tr>
<tr>
<td>Carbon Black</td>
<td>28%</td>
<td>28%</td>
</tr>
<tr>
<td>Steel</td>
<td>14-15%</td>
<td>14-15%</td>
</tr>
<tr>
<td>Fiber, Fillers, Accelerators, Antiozonants, etc.</td>
<td>16-17%</td>
<td>16-17%</td>
</tr>
</tbody>
</table>

2.2.2 Scrap tire generation in Canada

In all the provinces of Canada, dumping tires in landfills are banned and the authorities are in the process of cleaning up the leftover to eliminate the potential hazards from waste tire rubber. During the year of 2003 to 2004, Canada processed 240 thousand metric tons of scrap tire (Pehlken and Essadiqi, 2005). This number, however, increased over the years with the growing demand for waste tire derived fuel and products. Moreover, the provincial governments aid the tire-recycling program and strives to make the projects successful throughout the nation. In 2010, all the provinces of Canada collected more than 380 thousand metric tons of scrap tires (Table 2.3). However, the collection amount dropped in the following three years and started to rise in 2014.

Table 2.3: Scrap tire generation and recycling data of Canada a, b

<table>
<thead>
<tr>
<th>Data</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scrap tire collected</td>
<td>383,802</td>
<td>373,029</td>
<td>378,468</td>
<td>380,269</td>
<td>393,291</td>
</tr>
<tr>
<td>Tire – derived product (TDP)</td>
<td>276,995</td>
<td>320,984</td>
<td>329,494</td>
<td>357,309</td>
<td>341,624</td>
</tr>
<tr>
<td>Tire – derived fuel (TDF)</td>
<td>22,452</td>
<td>15,421</td>
<td>32,883</td>
<td>21,337</td>
<td>22,483</td>
</tr>
<tr>
<td>Recycling rate</td>
<td>78%</td>
<td>90%</td>
<td>96%</td>
<td>100%</td>
<td>93%</td>
</tr>
</tbody>
</table>

a Amount in weight (metric tons)  
b Data collected from Canadian Association of Tire Recycling Agencies (CATRA, 2015)
Table 2.3 demonstrates the recycled (tire – derived product, TDP) and energy recovered (tire – derived fuel, TDF) scrap tires from the collected ones over the years. Recycling rate is calculated by dividing the summation of tires recycled (metric tons) and those sent to energy recovery (metric tons) by the tires collected (metric tons) during that year. The data shows 78% of the scrap tires were recycled into TDF and TDP in 2010. The recycling rate increased quite significantly and stayed above 90% over the following years. An amazing 100% recycling rate was recorded in 2013. In spite of 100% recycling rate in 2013, accumulation of dumped tires from previous years still threatened the environment and thereby created scope in reducing waste rubber materials.

Table 2.4: Scrap tire generation in different provinces of Canada

<table>
<thead>
<tr>
<th>Province</th>
<th>2003</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weight (metric tons)</td>
<td>By Province (%)</td>
</tr>
<tr>
<td>British Columbia</td>
<td>22,960</td>
<td>10.1%</td>
</tr>
<tr>
<td>Alberta</td>
<td>19,680</td>
<td>8.7%</td>
</tr>
<tr>
<td>Saskatchewan</td>
<td>9,020</td>
<td>4.0%</td>
</tr>
<tr>
<td>Manitoba</td>
<td>7,380</td>
<td>3.3%</td>
</tr>
<tr>
<td>Ontario</td>
<td>84,460</td>
<td>37.2%</td>
</tr>
<tr>
<td>Quebec</td>
<td>66,420</td>
<td>29.2%</td>
</tr>
<tr>
<td>New Brunswick</td>
<td>6,560</td>
<td>2.9%</td>
</tr>
<tr>
<td>Nova Scotia</td>
<td>5,740</td>
<td>2.5%</td>
</tr>
<tr>
<td>Prince Edward Island</td>
<td>1,640</td>
<td>0.7%</td>
</tr>
<tr>
<td>Newfoundland and Labrador</td>
<td>3,280</td>
<td>1.4%</td>
</tr>
<tr>
<td>Canada</td>
<td>227,140</td>
<td>100%</td>
</tr>
</tbody>
</table>

*a Data collected from Canadian Association of Tire Recycling Agencies (CATRA, 2015)*

Depending on the population density, tire demand varies significantly among the provinces. As such, scrap tire generation is directly co-related to tire consumption (Gray, 2012). The differences in provincial scrap tire generation in 2003 and 2014 is provided in Table 2.4. The table shows that in 2003, Ontario (37.2%) and Quebec (29.2%) were the highest generators of scrap tires among all other provinces. British Columbia (10.1%) and Alberta (8.7%) were positioned as third and fourth, respectively
in the same year. However, Alberta (17.6%) surpassed British Columbia (10.5%) and gained third position in scrap tire generation in the year 2014. Since the demand for heavy duty excavators increased with the oil industries in the province, scrap tire generation also picked up during the interim years. On the other hand, Ontario (34.9%) and Quebec (21.6%) still held their respective positions as first and second, respectively in 2014. It is also to note that within 10 years, Canada took a sharp increase in scrap tire generation. The amount shows a drastic increase to more than 390 thousand metric tons of scrap tires in 2014 from 227 thousand metric tons in 2003.

### 2.3 Applications of Waste Rubber Materials

Scrap tire generation has substantially increased between 2000 and 2014. As a result, different applications are explored and research is ongoing for finding efficient waste reduction techniques. Some of the widespread fields of application include but not limited to civil engineering, electricity co-generation, tire – derived fuel (TDF), tire – derived products (TDPs), highway pavement construction, tire – derived aggregates (TDAs), cement industry, industrial boilers, and pulp and paper industries. It is reported that these applications altogether consumed about 89.3% scrap tire in 2007 (Boustani et al., 2010). This section focuses on the broad concept of waste rubber applications in some of the major sectors.

#### 2.3.1 Waste rubber materials as Tire – Derived Fuel (TDF)

Used tire and other rubber-based products can be recovered as energy raw materials. It has a higher caloric value (36 MJ/kg) than most widely used fuel, i.e. coal (25 MJ/kg) (Gieré et al., 2006). Table 2.5 shows the energy content of some of the most popular fuel sources. In case of cement production, coal and petroleum coke, also known as fossil fuel, are two major thermal energy sources. However, cement industries are in the process of relying less on fossil fuel because of its high carbon emission (Sienkiewicz et al., 2012). As such, alternative sources of fuel input are under research and it has been reported that TDF can become a viable alternative due to its high caloric value and environment friendly characteristics. However, the combustion
process needs to be done in a controlled environment. Studies showed that tire combustion in a cement kiln is more environment friendly than fossil fuel; however, complete destruction of organic compounds is necessary in the kiln process (Conesa et al., 2008; Clauzade et al., 2010).

Table 2.5: Energy content of fuel sources

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Heating Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating Oil</td>
<td>42 MJ/kg</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>38 MJ/m³</td>
</tr>
<tr>
<td>Coal</td>
<td>25 MJ/kg</td>
</tr>
<tr>
<td>Wood Biomass</td>
<td>20 MJ/kg</td>
</tr>
<tr>
<td>Tires</td>
<td>36 MJ/kg</td>
</tr>
<tr>
<td>Plastic Waste</td>
<td>43 MJ/kg</td>
</tr>
</tbody>
</table>

aData collected from Archer et al. (2004)

In Canada, cement industries are the largest consumers of TDF. Around 20% recycled scrap tire is used as TDF nationwide (Pehlken and Essadiqi, 2005). British Columbia utilized 270 thousand scrap tire (amount in number) as TDF in cement plants in 2002. This number increased to 340 thousand in the following year, utilizing more recycled waste materials (CAC, 2010). The same report also stated that Quebec used more than 18 million scrap tire as TDF in cement industries during the years between 1993 and 2003. In terms of utilizing recycled scrap tire, the USA surpassed all other countries and used 130 million scrap tire as TDF in different manufacturing industries during the same period (EPA, 2005; RMA, 2011).

Cement industries are the highest consumers of TDF in North America, whereas other industries are producing steam and electricity utilizing scrap tire. In addition, paper mills, lime and steel factories are using TDF as a vital source of energy input. Most importantly, coal and ground rubber (fine granules of scrap tire) can be co-combusted to improve thermal efficiency of furnaces and steam boilers without exceeding permissible limits of exhaust gases (Levendis et al., 1996; Courtemanche and Levendis, 1998; Singh et al., 2009).
2.3.2 Waste rubber materials as Tire – Derived Product (TDP)

In case of product manufacturing, different sizes of shredded rubber particles are used. In this case, the size of the shredded rubber particles matter the most and therefore removal of other impurities such as reinforcing steel and fiber contained in the tire is necessary. In terms of final product, asphalt rubber is produced as one of the major products. It consists 18 – 22% of crumb rubber along with asphalt cement and extender oil (Navarro et al., 2004). Additionally, asphalt rubber can also be used as an elastic binder additive; the addition of crumb rubber at an elevated temperature with asphalt cement (Hicks, 2002).

New products based on rubber-plastic blend have gained popularity due to its superior performance compared to the conventional blended materials (plastic or thermoplastics and rubber). However, the process required a surface modification of rubber particles in order to enable its properties to combine with plastic (Riggle, 1994). It is advantageous in terms of environmental benefits and lowering specific weight compared to rubber. Some of the examples include making shoe soles, molded epoxy coatings, industrial wheels made with solid cast polyurethane, and wheelchair tires. Moreover, automotive industries are making their parts using the rubber-plastic blend instead of using virgin plastic and rubber for superior performance and durability (Bandyopadhyay et al., 2008).

In case of using recycled rubber, these waste materials can be used in making new tires. However, the percent of using recycled rubber is still limited (up to 5 % in weight) due to inferior qualities of new tires, reduced tire tread life, higher rolling resistance, and poor wet traction (RMA, 2003). Canada has found different alternatives in using the waste scrap tire. More than 40% of the total scrap tire, equivalent to almost 100 thousand tons in weight, are used in producing rubber-based finished products, i.e. rubber tiles, rubber mats, and parking curbs (Pehlken and Essadiqi, 2005).
2.3.3 Civil Engineering applications

Tire derived aggregates (TDAs) and crumb rubber are one of the widely used varieties of recycled scrap tire in the context of civil engineering (El-Gammal et al., 2010; Pierre, 2013). Some of the civil engineering applications include landfill construction and operation, road construction, septic system drain fields, subgrade fill and embankments, backfill for walls and bridge abutments, subgrade insulation for roads, and highway crash barriers (Humphrey and Blumenthal, 1998; RMA, 2003). Since waste rubber would be contained in concrete as aggregates, environmental degradation due to leaching could be avoided. Besides, the growth rate of using waste rubber in civil engineering applications is expected to raise more over the years. TDAs and crumb rubber differ in sizes and so these materials can be used in cement concrete and cement mortar, replacing conventional aggregates in different percentage based on various applications. Moreover, the concept of rubber concrete pavement block (RCPB) is gaining more acceptance because of its non-structural applications.

2.3.3.1 Rubber aggregates in cement mortar

Finer particles of waste rubber, commonly known as ground rubber and crumb rubber, are used in cement mortar as a replacement of conventional fine aggregate, i.e. sand (Meherier et al., 2015). Volumetric and weight based replacement of fine aggregate with crumb rubber was done in previous studies. Their fresh, mechanical, thermal, hardened, and durability properties were examined and compared with the specimens without any rubber particles. All the studies showed a sharp decline in compressive strength; however, showed positive output in thermal and durability aspects (Eldin and Senouci, 1993; Raghavan et al., 1998).

Crumb rubber was used to produce and investigate the lightweight (1.2 – 1.6 gm/cc) flowable fill (Pierce and Blackwell, 2003). It showed satisfactory flowable consistency with a compressive strength of 0.02 to 0.09 MPa. Some of the applications of flowable fill are bridge abutment fills, trench fills, and foundation fills. In a different approach, tire rubber ash (TRA), residue of burned tire rubber chips at a controlled 850 °C, was used in producing mortar. The product had a superior compressive
strength, tensile and flexural strength, and delayed initial and final setting time. However, workability reduced significantly with the increase of TRA (Al-Akhras and Smadi, 2004).

### 2.3.3.2 Rubber aggregates in cement concrete

Concrete industries are the most viable options for utilizing waste rubber materials as aggregate. The conventional filler materials, i.e. gravel and sand, can be replaced partially or fully with rubber particles and thus rubber concrete can be produced having some superior qualities over conventional cement concrete. However, its significant compressive strength reduction made it an inferior construction material with very limited applications, mostly non-structural elements (Al Bakri et al., 2007; IRSG, 2014; Ling et al., 2009). TDAs are mostly used as coarse aggregate whereas crumb rubber, size distribution of 1 mm – 5 mm, is used as fine aggregate in concrete (Ling et al., 2009; Ling et al., 2010).

Previous studies reported the significance of using waste rubber materials as rubber concrete pavement block (RCPBs). Ling et al. (2010) reported that less than 20% of the rubber content in RCPBs can be used for trafficked pavement desiring more strength whereas more than this percent can be used in sidewalks and playgrounds. Researchers also derived equations using statistically significant parameters in order to predict the behavior of rubberized pavement blocks; however, inconsistency in the results were significant (Ling, 2011).

### 2.3.3.3 Pavement construction

The major constituent of transportation network, i.e. roadways have a huge potential of using waste rubber materials as a resource. The incorporation of rubber shows superior qualities over conventional asphalt concrete and so its acceptance is increasing globally. In case of constructing highways and roadways, crumb rubber can be utilized as modifiers to asphalt paving mixtures by replacing conventional aggregates (Maupin Jr, 1996; Troy et al., 1996; Tahmoressi, 2001; Shu and Huang, 2014). The US department of transportation (USDOT) and Federal highway administration (FHWA) were the world leaders in utilizing recycled scrap tire for
constructing its regional highways during 1980s and early 1990s (Heitzman, 1992; FHWA, 1993; Epps, 1994). Rubber-based pavements showed improved mechanical properties, lowered reflective cracking, increased durability, and reduced fatigue resistance. More to that, the constructed rubber-based pavement improved surface safety by increasing surface friction (Pehlken and Essadiqi, 2005).

In terms of overall cost benefit, life cycle cost analyses were done in order to prove its feasibility. Moreover, USA undertook a pavement rehabilitation project under Arizona department of transportation (ADOT) and reported that in spite of high construction and material cost at the project initiation phase, asphalt rubber-based pavement prevailed over conventional pavement during the life time of the project (Jung et al., 2002). Overall expenses of this pavement were reduced to 80% of conventional materials based pavement for an analysis period of 30 – 40 years. Moreover, natural resources and energy can be saved because of the reduced layer thickness required for rubber-based pavement.

2.4 Properties of Rubber Mortar and Rubber Concrete

The volume of concrete is mostly occupied by aggregates for at least three-quarters. As a result, the quality of aggregates is of immense importance, even though it was assumed to be inert and have no effect on concrete. Moreover, aggregates with undesirable properties reduce the strength of concrete as well as adversely affect its durability and other mechanical characteristics. Since waste rubber aggregate is being explored very recently for potential use in construction material, there is a gap in technical specifications and guidelines for producing rubber-based mortar and concrete. As such, researchers all over the world are doing extensive research on this topic to find concrete properties incorporating waste rubber materials as aggregate. The following sections cover fresh, hardened, and durability properties of rubber-based mortar and concrete based on previously published documents.
2.4.1 Fresh Properties

The following sub-sections cover fresh properties, slump and workability, air content, normal consistency, and setting time, of rubber-based cement mortar and concrete. The fresh properties are reported within 24 hours of casting the cement mortar and concrete.

2.4.1.1 Slump and workability

Incorporating rubber particles largely influence the slump; hence, workability of rubber-based cement concrete. In most of the previous studies, increasing rubber content decreased the slump value; thereby made the cement matrix less workable (Fedroff et al., 1996; Khatib and Bayomy, 1999; Dong et al., 2013). Different researchers provided their opinions in terms of reasoning the behavior of reduced workability. Increase in inter-particle friction between rubber and cement matrix could be the pivotal reason for low slump value (Holmes et al., 2014). Moreover, it was reported that both fine and coarse aggregate replacement lowers the slump value by increasing the stiffness of the cement matrix (Mavroulidou and Figueiredo, 2010; Thiruppathi, 2013). However, the same study also denoted that fine ground rubber was found to be more workable than coarse-sized rubber chips. The recycling process also determines the workability of rubber-based concrete. In a study conducted by Bravo and Brito (2012), it was concluded that cryogenic ground tire aggregates showed higher slump value than mechanically ground tire aggregates due to low specific surface and roughness of ground tire aggregates in the cryogenic process. In a different study, higher water absorption of rubber particles was reported to be responsible for reduction in workability, irrespective of rubber particle size (Su et al., 2015).

The workability of rubber-based concrete can be improved by adopting some special measures. Rubber shreds can slightly increase the workability by partial replacement of fine and coarse aggregates, thereby making the control concrete fluid (Aiello and Leuzzi, 2010). Mixture of rubber powder and crumb rubber along with sufficient quantity of water reducing admixture showed improved workability of plain concrete (Elchalakani, 2015). Rubber chips, replacing coarse aggregates, can possibly
increase the workability of concrete. Up to 15% replacement of coarse aggregate was found to escalate the workability of rubber-based concrete but it can decrease with further percentage of replacement (Pacheco-Torgal et al., 2012).

2.4.1.2 Air content

Air content is also an important parameter in concrete as it projects the compressive strength of the specimens. Increasing air content would result in less compressive strength after designated curing period (Raghavan et al., 1998). In terms of rubber-based concrete, addition of crumb rubber resulted in increased air content in the cement matrix (Fedroff et al., 1996; Khatib and Bayomy, 1999; Kaloush et al., 2005). Rubber particles entrapped air in their rough surface and showed non-polar properties thereby escalating the amount of air with the increase in crumb rubber in concrete (Khaloo et al., 2008). Most importantly, increased air content means reduced strength in concrete. It was reported that 8% air could reduce 45% compressive strength of concrete specimens (Neville, 2011), which might be one of the primary causes of reduced compressive strength of rubber-based concrete.

2.4.1.3 Penetration and setting time

Penetration test is done in order to investigate the adequate amount of water necessary to prepare hydraulic mortar paste. On the other hand, setting time is defined as the time required for specimens to set. In this case, two different setting times are examined; one being the initial setting time and the other is final setting time. Very few studies have been found reporting on penetration test and setting time of rubber-based cement mortar and concrete. Similar to slump value, penetration value decreased with the addition of rubber in the matrix (Meherier et al., 2015; Al-Akhras and Smadi, 2002). Since rubber particle increased the inter-particle friction between rubber and cement matrix, slump value decreased, hence penetration value dropped (Holmes et al., 2014).

On the other hand, setting time is influenced with the incorporation of rubber particles. Setting time increased significantly with the addition of rubber particle as aggregates (Meherier et al., 2015; Pierce and Blackwell, 2003; Siddique and Naik,
2004). Crumb rubber repelled water and remained non-reactive with cement, thereby retarded the setting time of the mix (Meherier et al., 2015; Al-Akhras and Smadi, 2002).

2.4.2 Hardened Properties

The following sub-sections cover hardened properties such as compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, toughness, unit weight, water absorption, and shrinkage of rubber-based cement mortar and concrete. The hardened properties of the experimented samples were reported on different curing ages to determine the variability in their properties over time.

2.4.2.1 Compressive strength

Compressive strength of rubber-based concrete and mortar varies with the variation of size, proportions, and surface texture of rubber particles. Eldin and Senouci, (1993) explored the compressive strength reduction due to replacing both coarse aggregate and fine aggregate. The study showed 85% and 65% reduction in compressive strength with the incorporation of tire chips and crumb rubber, respectively. In different studies, it was reported that coarse aggregate replacement decreased the compressive strength more than replacing fine aggregate (Khatib and Bayomy, 1999; Topcu, 1995). Contradictory results were also reported where fine aggregate replacement reduced compressive strength more than coarse aggregate replacement (Ali et al., 2000; Fattuhi and Clark, 1996).

However, in almost every case incrementing rubber content negatively affected the compressive strength of concrete specimens (Ali et al., 2000; Rostami et al., 2000; Eldin and Senouci, 1993; Topcu, 1995). In most of the cases, the strength reduction was significant; therefore, researchers discouraged high natural aggregate replacement levels (Gesoglu et al., 2014a and 2014b; Meherier et al., 2015). Different studies recommended various maximum acceptable aggregate replacement percentage. Up to 20% replacement of the total aggregate content could avoid significant compressive strength reductions (Holmes et al., 2014). Youssf et al. (2014) reported a maximum 3.5% mineral aggregate replacement would not affect the
compressive strength, whereas Biel and Lee (1996) recommended a maximum of 17% replacement of total aggregate volume.

There might be multiple reasons for a rapid compressive strength reduction of rubber-based concrete and mortar. Cracks seemed to develop more around the aggregates containing soft rubber-based cement paste, thereby initiated rapid failure (Ganjian et al., 2009). Moreover, low specific gravity of rubber particles and lack of proper bonding between rubber particles and cement paste could also be the leading cause for low compressive strength (Meherier et al., 2015; Holmes et al., 2014; Eldin and Senouci, 1993; Thomas and Gupta, 2016; Siddique and Naik, 2004).

Since compressive strength deteriorates with the incorporation of rubber, researchers tried to enhance its property by modifying it. Studies revealed that changing smooth rubber surface texture to a rough surface might develop better bonding with the surrounding matrix; hence, improve compressive strength. Dong et al. (2013) coated rubber particles with a saline coupling agent. The resultant concrete showed better compressive strength compared to untreated rubber concrete. Silica fume also improved the compressive strength of rubber-based concrete as it filled the micro pores and helped in strength increment (Onuaguluchi and Panesar, 2014).

NaOH treated rubber particles showed an increase in compressive strength compared to rubber particles without any treatment. Youssf et al. (2014) reported an increase of 15% at 28 days after NaOH treatment compared to untreated rubber particles. Moreover, washing rubber aggregate before mixing with concrete showed a growth in strength gain. Approximately 16% higher strength gain was confirmed compared to unwashed crumb rubber (Rostami et al., 2000). A study was reported in using treated powdered tire rubber, as a binder, with the addition of cement (Segre and Joekes, 2000). The treated rubber powder showed an increase in rubber-matrix adhesion; hence, increased the compressive strength of concrete. Rubber ash improved the compressive strength of mortar specimens when restricted to 10% fine aggregate replacement. The strength gain was 14%, 21%, 29%, and 45% higher compared to normal mortar at a replacement level of 2.5%, 5%, 7.5%, and 10%, respectively (Al-Akhras and Smadi, 2004).
2.4.2.2 Flexural strength and splitting tensile strength

Similar to compressive strength, addition of rubber particles in the cement matrix adversely affects splitting tensile strength and flexural strength. A study reported 50% reduction in splitting tensile strength with the full replacement of coarse aggregate and fine aggregates with rubber chips and crumb rubber, respectively (Eldin and Senouci, 1993). Flexural strength was reported to reduce further when coarse aggregate was replaced with rubber aggregate compared to fine aggregate (Aiello and Leuzzi, 2000). Similar trend was reported in other studies where rubber aggregate replaced coarse aggregate instead of fine aggregate (Ganjian et al., 2009; Su et al., 2015). Since crumb rubber is small and can enhance the compactness of concrete, flexural strength tends to behave better with the addition of crumb rubber instead of coarse rubber chips.

Tensile strength can be increased by adding coated rubber aggregates (Onuaguluchi and Panesar, 2014). Moreover, tire-added latex concrete (TALC) showed an increase in flexural strength compared to rubber added concrete (Lee et al., 1998). Scanning electron microscopic (SEM) images further confirmed that latex improved the bonding between crumb rubber and cement paste. Even NaOH treatment and washing rubber aggregate also helped in reducing flexural strength and splitting tensile strength loss of rubber added concrete samples (Siddique and Naik, 2004, Segre and Joekes, 2000). Silica fume was reported to enhance the flexural strength of concrete by enhancing the interfacial transition zone bonding (Elchalakani, 2015).

The type of cement affects the splitting tensile strength of rubber-based concrete. It was reported that Magnesium oxychloride cement and Portland cement concrete specimens retained 34% and 25% of their splitting tensile strength, respectively after failure (Biel and Lee, 1996). In both of these cases, 25% of the total aggregate volume was replaced with fine rubber aggregate.

Previous studies also reported an increase in flexural strength and splitting tensile strength after a certain replacement level of natural aggregate that is
contradictory to the previously mentioned studies. Ganesan et al. (2013) reported an increase in flexural strength of 15% and 9% with fine aggregate replacement of 15% and 20%, respectively. In case of rubber-based mortar, flexural strength increased with fine aggregate replacement of up to 10% by rubber ash. In all of these cases, rubber-based samples were compared to specimens without rubber aggregate. Moreover, adding rubber as fiber up to 20% of the total aggregate volume increased the flexural strength of concrete, showing slow and incomplete breakdown (Yilmaz and Degirmenci, 2009). However, increasing the fiber amount beyond 20% showed a decline in strength gain.

2.4.2.3 Modulus of elasticity and toughness

Rubber aggregate influences the modulus of elasticity and toughness of concrete. Because of low compressive strength of softer material, the modulus of elasticity of rubber-based concrete behaves differently than normal concrete. Previous studies reported that rubber aggregate reduced the modulus of elasticity with the decrease in compressive strength (Gesoglu et al., 2011, 2014a and 2014b; Ganjian et al., 2009; Dong et al., 2013; Pelisser et al., 2011). Moreover, increasing the rubber content would keep decreasing the modulus of elasticity (Dong et al., 2013). Ganjian et al. (2009) reported 17 – 25% reduction in modulus of elasticity while using chipped rubber as aggregate, whereas powdered rubber reduced 18 – 36% of elasticity compared to the specimens without rubber. In both these cases, 5 – 10% aggregate replacement was reported. An average 49% reduction in elastic modulus of rubber-based concrete was observed in a different study (Pelisser et al., 2011). Besides, dynamic modulus of elasticity and rigidity decreased with an increase in rubber content in concrete (Goulias and Ali, 1997). The same study also reported a decrease in damping capacity of concrete while rubber content was increased. Similar behavior was also found in other studies (Topcu and Avcular, 1997a and 1997b; Fattuhi and Clark, 1996).

Some superior behavior was observed in case of rubber-based concrete over conventional concrete in terms of toughness, flexibility, and ductility. Since rubber aggregate is soft and porous, crumb rubber based concrete showed ductile (Li et al.,
1998) and non-brittle failure (Kaloush et al., 2005). The failure pattern was more gradual compared to the explosive failure pattern of normal concrete. Moreover, rubber aggregate acted as tiny springs, withstanding large tensile deformations (Eldin and Senouci, 1993). Studies showed an increase in toughness of concrete incorporating rubber aggregate (Tantala et al., 1996).

### 2.4.2.4 Unit weight

Crumb rubber has a very low specific gravity compared to naturally sourced aggregates and as such, the unit weight or density of rubber-based concrete reduces significantly with the increase in rubber content. One of the studies reported that 50 lbs per cubic yard of crumb rubber reduced 6 lbs per cubic feet of rubber-based concrete (Kaloush et al., 2005). In one of the studies, it was found that density of rubber-based concrete reduced by 13% compared to normal concrete (Pelisser et al., 2011). However, the change in unit weight was negligible when rubber content was added less than 10 to 20 percent of total aggregate volume (Khatib and Bayomy, 1999). Change in unit weight was also reported in terms of changes in cement to sand ratio. A lower cement to sand ratio showed a unit weight of 1.40 gm/cc compared to 1.37 gm/cc, with a constant 75% crumb rubber replacing sand (Meherier et al., 2015).

Comparative study related to chipped rubber and crumb rubber addition showed that chipped rubber-based concrete had lower density compared to crumb rubber based concrete (El-Gammal et al., 2010). In a different study, it was reported that rubber replacing coarse aggregate and fine aggregate reduced the concrete’s density by 45% and 34%, respectively (Pacheco-Torgal et al., 2012). Because of lower density, lightweight concrete can be produced by adding rubber to concrete and the resultant concrete had superior characteristics in non-structural applications (Gesoglu et al., 2014a and 2014b).

### 2.4.2.5 Water absorption

Studies have been done in terms of water absorption capacity of rubber-based concrete and mortar. Studies showed that bigger rubber particles cause higher water absorption compared to smaller rubber particles (crumb rubber). The smaller
particles could fill the pores easily and thereby created less permeable samples (Gesoglu et al., 2014a and 2014b; Ganjian et al., 2009). Besides, well-graded crumb rubber increased water absorption capacity of rubber-based specimens compared to concrete without rubber as aggregate (Su et al., 2015). Low water-cement ratio can also enhance the water absorption capacity; hence, permeability. Studies showed medium and low permeability of samples with a water cement ratio of 0.45 and 0.3, respectively (Thomas et al., 2014).

Contradictory results have been found in terms of water absorption capacity of rubber-based concrete and mortar specimens. Some studies showed a decrease in water absorption with the addition of rubber particles in the matrix as rubber does not absorb water (Segre and Joekes, 2000; Oikonomou and Mavridou, 2009). However, other studies showed an increase in water absorption with the increase in rubber content (Meherier et al., 2015; Azevedo et al., 2012; Gesoglu and Guneyisi, 2011; Onuaguluchi and Panesar, 2014; Bravo and Brito, 2012; Sukontasukkul and Tiamlom, 2012). Since the rubber particles trap air bubbles at their surface due to non-polarity, the interface between cement and aggregate becomes porous and absorptive; hence, increase the water absorption capacity of the specimens.

A unique study was carried out by Meherier et al. (2015) and showed that water absorption capacity of mortar samples is dependent on cement to sand/crumb rubber ratio. A high cement to sand/crumb rubber ratio depicted a higher porosity of rubber mortar due to higher amount of rubber in the matrix. Seventy-five percent sand replacement with crumb rubber showed 13% and 12% water absorption capacity of samples having cement to sand ratio of 1:3 and 1:2.8, respectively. Besides, the control specimens had 7% water absorption capacity in both the batches.

2.4.2.6 Shrinkage

Curing days of concrete influences shrinkage of concrete, regardless of rubber addition. More curing time would mean less shrinkage. One study reported that most of the shrinkage happened in the first 15 days compared to 90 days of curing (Bravo and Brito, 2012). It happened due to higher hydration rate of cement during the initial
curing period. Rubber addition in concrete increased the shrinkage of concrete within a constant curing period due to change in length between rubber-based concrete and regular concrete. It was found that 5% and 20% rubber addition changed the length by 35% and 95%, respectively, thereby causing more shrinkage compared to control specimens (Yung et al., 2013).

Shrinkage depends not only on the amount of rubber content, but also on the size. It was reported that crumb rubber showed less shrinkage compared to rubber powder (Sukontasukkul and Tiamlom, 2012). Rubber acted like a spring because of its flakiness and that might be the reason of this phenomenon. A different study on rubber mortar incorporating two different types showed that rubber shreds (5.5 mm x 1.2 mm and 10.8 mm x 1.8 mm) caused multiple cracks over the width of the samples, whereas rubber granules (2 mm diameter) caused a single crack (Raghavan et al., 1998).

2.4.3 Durability Properties

The following sub-sections cover durability properties of rubber-based cement mortar and concrete covering freezing and thawing resistance, chloride penetration, and sulfate attack. These properties determine the characteristics of concrete over a long period, thereby conversing the effects of waste rubber materials in environmentally exposed conditions.

2.4.3.1 Freezing and thawing resistance

Freeze-thaw resistance of concrete is an essential factor in cold weather. In most of the previous studies, freeze-thaw resistance increased with the addition of crumb rubber in concrete. Moreover, significant mass loss of normal concrete occurred after 300 cycles compared to rubber-based concrete (Gesoglu et al., 2014a and 2014b; Richardson et al., 2012; Richardson et al., 2016). However, the weight loss was minimal up to 240 cycles for both types of concrete. Contradictory results were reported in a separate study and it showed minor freeze-thaw resistance for concrete with 10%, 20% and, 30% ground rubber tire (Fredroff et al., 1996).
Rubber particle size has an influence in freeze thaw-resistance. Crumb rubber was reported to resist the freezing and thawing effect better than coarse rubber aggregate (Raghavan et al., 1998; Zhu et al., 2012; Savas et al., 1996). In this case, the control specimens were discarded even before finishing the full cycles of the testing program. Moreover, surface scaling was found to be minimum in rubber-based concrete. Additionally, expanded rubber aggregates showed better result than compact rubber aggregate, when 30% to 40% rubber by volume of aggregate was used in concrete (Benazzouk and Queneudec, 2002).

Tire rubber ash was also used in mortar and freeze-thaw test results showed better performance compared to specimens without rubber (Al-Akhras and Smadi, 2004). Dynamic modulus of elasticity provides information about internal damages of freeze-thaw exposed concrete samples by utilizing resonance frequencies. Dynamic modulus of elasticity displayed that better durability was achieved with an increment of rubber ash. Five percent and ten percent rubber ash reached 55% and 60% dynamic modulus of elasticity compared to control samples after 150 and 225 cycles, respectively. On the other hand, the control specimens reached 55% dynamic modulus of elasticity within just 50 cycles. A separate study confirmed that crumb rubber could be used as an alternative to air-entraining admixture; hence, improving freezing and thawing resistance (Paine et al., 2002).

2.4.3.2 Chloride penetration

Previous studies confirmed that rubber aggregate substitution resulted in low chloride ion penetration; hence, making rubber concrete less permeable compared to control concrete (Gupta et al., 2014). Rubber mortar was reported to have 14% and 36% reduction in chloride penetration when the mix contained 2.5% and 15% rubber, respectively (Oikonomou and Mavridou, 2009). In a separate study, chloride migration test was performed and the results showed that longer curing period lead to reduced chloride ion penetration for concrete having rubber aggregate (Bravo and Brito, 2012). Moreover, the same study also denoted that rubber size increment would result in higher chloride diffusion coefficient, hence increased chloride penetration.
Rubber aggregate with silica fume also showed superior chloride resistance compared to specimens without silica fume (Onuaguluchi and Panesar, 2014). Silica fume covered micro pores in the cement matrix; thereby, restrained its penetration. In this case, charge transmission through the samples was calculated for determining chloride ion penetration. Since water cannot penetrate rubber particles, similarly chloride ion cannot form a penetration passage. However, opposite trend was also reported in the literature where crumb rubber increment caused higher chloride ion penetration (Thomas et al., 2014; Gesoglu and Guneyisi, 2011). Thomas et al. (2014) reported an increase in chloride penetration when crumb rubber addition was increased from 7.5% to 20%.

2.4.3.3 Sulfate attack

Aggressive chemicals adversely affect the durability of concrete; thereby, causes expensive maintenance costs and deteriorates life cycle performance of concrete structures. As such, it is required to make the concrete samples resistant to harmful chemicals, especially sulfates. Sulfate ions and hydrated cement products react and form expansive products, especially gypsum and ettringite, within cement matrix; hence, distress and cracks occur. Moreover, sulfate attack causes spalling of concrete, softening, shape changing, weight loss, and gypsum corrosion (Neville, 2011).

One of the hydrated cement products is calcium aluminates. This compound reacts with sulfate and forms calcium sulfoaluminate, causing 227% increase in volume of the original compound. In addition, calcium sulfate is formed within the subsequent chemical reactions. Some of the sources of sulfate can be found in the form of Na₂SO₄, MgSO₄ CaSO₄, and (NH₄)₂SO₄, especially in ground water.

Very few studies have been performed considering sulfate attack of rubber-based mortar and concrete. Since the reaction process takes longer time, research is ongoing in making the process faster and reliable. Yung et al. (2013) explored sulfate attack by considering alternate wetting and drying cycles. It was reported that 5%
rubber aggregate addition showed the best performance compared to specimens without rubber aggregate in terms of sulfate resistance.

2.5 Summary

This chapter previewed state-of-the-art knowledge on past and current status of rubber production and scrap tire generation around the world and in Canada. The results showed an upward trend for both production and reuse of waste materials over the years. More to that, some of the applications in key sectors have been explored and stated in this literature. Civil engineering applications of waste rubber materials, however, seemed to be the less explored segment among all other sectors because of its detrimental effects over conventional materials. However, using waste rubber particles in pavement construction was reported to be the most viable and feasible option. Additionally, mechanical (fresh and hard) and durability aspects of rubber-based cement mortar and concrete were explored extensively and mentioned in the literature. In almost every study, rubber aggregate addition caused negative effects on the mechanical properties. Conversely, durability properties were enhanced with the addition of rubber aggregate, especially crumb rubber. Disagreements were also seen in the literature that showed the opposite trends of the previously mentioned characteristics. Since this research focuses on using crumb rubber in cement mortar and concrete in different percentages, the remainder of the thesis is outlined in filling up some of the gaps in the literature; thereby, giving a new outlook on this topic.
Chapter 3

Mechanical Behavior of Mortar with Varying Replacement Levels of Crumb Rubber

3.1 General

Very few studies have been reported on crumb rubber usage in cement mortar; however, different forms of modified rubber were used in some research (Al-Akhras and Smadi, 2004; Pierce and Blackwell, 2003). In other studies, crumb rubber was used directly as a replacement of fine aggregates, i.e. sand, in different percentages (Eldin and Senouci, 1993; Raghavan et al., 1998; Meherier et al., 2015). Even though the mechanical properties of rubber-based mortar decreased, previous studies confirmed positive attributes of the material in terms of durability and thermal properties. Moreover, inconsistency in the obtained results was significant as the sources and quality of recycled crumb rubber varied. Because of this, this sector is yet to explore, as it possesses the possibility of being a sustainable and green solution to the construction industries.

The major objective of this study is to investigate the fresh and mechanical properties of cement mortar made with different replacement levels of crumb rubber in order to observe its behavior and determine the most suitable replacement level. Crumb rubber replaced 10%, 20%, 30%, 40%, and 50% of sand in three different batches (Batch A, Batch B, and Batch C) having different cement to sand ratio (1: 2.5, 1: 2.75, and 1: 3). Volumetric replacement was considered in this study as crumb rubber has a very low specific gravity compared to sand (less than half).
This chapter focuses on the properties of aggregates, including gradation, specific gravity, and water absorption. Chemical analyses using EDS (Energy Dispersive Spectroscopy) and SEM (Scanning Electron Microscopy) images of crumb rubber are incorporated separately in this chapter. Moreover, fresh properties (normal consistency, initial setting time, and final setting time) and mechanical properties (compressive strength, unit weight, and water absorption) of rubber-based cement mortar were investigated and reported with a comparison to conventional cement mortar without crumb rubber.

### 3.2 Properties of Aggregates

#### 3.2.1 Gradation and physical properties of sand and crumb rubber

In this study, the mortar specimens were prepared using cement, sand, crumb rubber, and water. Cement Type GU (general use) was used as a binding material. Moreover, locally available sand was used as fine aggregate. The maximum allowable size utilized for fine aggregates was 4.75 mm. Aggregates bigger than 4.75 mm were discarded from the mix. Crumb rubber was used as aggregates, which is commercially produced by shredding the discarded waste rubber tires without steel fibres. Physical properties of sand and crumb rubber including specific gravity, water absorption capacity, and fineness modulus are summarized in Table 3.1.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Sand</th>
<th>Crumb Rubber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk dry specific gravity</td>
<td>2.56</td>
<td></td>
</tr>
<tr>
<td>Bulk SSD specific gravity</td>
<td>2.60</td>
<td>1.15</td>
</tr>
<tr>
<td>Apparent specific gravity</td>
<td>2.67</td>
<td></td>
</tr>
<tr>
<td>Water absorption capacity (%)</td>
<td>1.52</td>
<td>1.20</td>
</tr>
<tr>
<td>Fineness modulus (FM)</td>
<td>2.24</td>
<td>3.68</td>
</tr>
</tbody>
</table>

Specific gravity and water absorption capacity of sand were examined by following CSA A23.2-6A (2014) standard. However, specific gravity of crumb rubber
was determined according to FM 5-559 (2011). Since crumb rubber has a specific gravity close to water (specific gravity of 1.00), it does not fully submerge in water. As a result, ethyl alcohol was used instead of water by following the standard. Other properties of crumb rubber were determined by following the same standard as that of sand. Fineness modulus of crumb rubber (3.68) is higher than sand (2.24), signifying the existence of more coarse particles in rubber aggregate than sand aggregate. Sieve analysis and gradation of both the aggregates were done by following CSA A23.2-2A (2014) standard. Gradation curves of sand and crumb rubber are presented in Figure 3.1 and Figure 3.2, respectively.

![Figure 3.1: Sieve analysis of sand](image)

It is clear from Figure 3.1 and Figure 3.2 that sand particles and crumb rubber fit within CSA range and they both are well graded. However, it should be mentioned that crumb rubber was fitted within the curve by manual mixing of different sizes, thereby making it well graded. Since crumb rubber was commercially produced and supplied by a company, the original product was gap graded (Figure 3.3).

### 3.2.2 SEM inspection of crumb rubber

In order to fully recognize the combination between crumb rubber and cement paste, morphological understanding of crumb rubber is necessary. As such, Mira3
Tescan Scanning Electron Microscope (SEM) images were used to observe rubber particles in the study. Crumb rubber with four different magnifications are shown in Figure 3.4.

Figure 3.2: Sieve analysis of crumb rubber (well graded)

Figure 3.3: Sieve analysis of crumb rubber (gap graded)
Figure 3.4: SEM images of crumb rubber particles with varying magnification; (a) 28x, (b) 80x, (c) 500x, and (d) 2000x

These SEM images allowed the rubber particles to be analyzed in terms of shape and size; hence, effective conclusions regarding possible air entrainment can be made. The SEM images showed that the recycling process of waste tires fragmented rubber granules into jagged shapes. As such, microscopic rough surfaces were formed (as shown in Figure 3.4). These irregular shapes assisted in entrapping air during the mixing process thereby causing high air entrainment in rubber-based specimens
(Benazzouk et al., 2008). Moreover, another study confirmed the existence of possible pressure release gaps at the interfacial zones between cement paste and crumb rubber (Pelisser et al., 2011). These gaps may weaken the bonding between crumb rubber and cement matrix, causing low compressive strength. Recycled crumb rubber that is being used in this study was supplied by a local company named Dinoflex. The rubber crumb were sourced from KalTire, a Canadian tire manufacturing company, which produces industry standard tires.

3.2.3 Chemical analysis of crumb rubber

Energy Dispersive Spectroscopy (EDS) chemical analysis showed comprehensive idea about the elements present in crumb rubber aggregate as well as the available amount of individual elements based on their peak values (Figure 3.5). Carbon (C) and Oxygen (O) were the most dominant elements, whereas Silicon (Si), Sulfur (S), Iron (Fe), and Zinc (Zn) were also present where each ranged in between 1 to 3% by weight. Entire chemical composition is summarized in Table 3.2. These elements were almost similar to those reported in other studies (Richardson et al., 2012, Milanez and Buhrs, 2009).

![Figure 3.5: EDS (Energy Dispersive Spectroscopy) analysis of crumb rubber](image)
Moreover, the chemical analysis (EDS) identified quite significant level of Silicon (Si) and Zinc (Zn) in crumb rubber samples. Since these two elements are hydrophobic and water resistant, mixing of water and crumb rubber was difficult. Richardson et al. (2012) also confirmed this phenomenon by having high amount of Silicon (Si) in their rubber aggregates.

Table 3.2: Chemical properties of crumb rubber

<table>
<thead>
<tr>
<th>Composition of Elements</th>
<th>Symbol</th>
<th>Weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>C</td>
<td>69.95</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O</td>
<td>20.93</td>
</tr>
<tr>
<td>Sodium</td>
<td>Na</td>
<td>0.38</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Mg</td>
<td>0.23</td>
</tr>
<tr>
<td>Aluminium</td>
<td>Al</td>
<td>0.71</td>
</tr>
<tr>
<td>Silicon</td>
<td>Si</td>
<td>1.53</td>
</tr>
<tr>
<td>Sulfur</td>
<td>S</td>
<td>1.42</td>
</tr>
<tr>
<td>Potassium</td>
<td>K</td>
<td>0.12</td>
</tr>
<tr>
<td>Calcium</td>
<td>Ca</td>
<td>0.22</td>
</tr>
<tr>
<td>Iron</td>
<td>Fe</td>
<td>2.43</td>
</tr>
<tr>
<td>Copper</td>
<td>Cu</td>
<td>0.15</td>
</tr>
<tr>
<td>Zinc</td>
<td>Zn</td>
<td>1.91</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>99.98</strong></td>
</tr>
</tbody>
</table>

### 3.3 Experimental Procedure

#### 3.3.1 Mix design and Sample preparation

Three batches of mortar specimens were prepared and experimented in this study. These batches were named Batch A, Batch B, and Batch C, each having 6 different mixes. These three batches differed in weights of fine aggregate, i.e. sand. Batch A had a cement to sand ratio of 1: 2.5, Batch B and Batch C had cement to sand ratios of 1: 2.75 and 1: 3, respectively. Table 3.3 summarizes the mix proportions of different materials in cement mortar. Cement and water proportions (water-cement ratio) were fixed (0.486) throughout the mix design to eliminate the effect of water in mortar properties. As a result, only the variation in sand and crumb rubber would influence the sample properties. In this study, sand aggregate was replaced by volume
and the different percentages were 10%, 20%, 30%, 40%, and 50%. Since crumb rubber has a very low relative density compared to sand, volume replacement method was considered. Moreover, each mix design was designated with a unique name for ease in referencing within the text. For instance, a C40 sample designation refers to a sample in batch C with 40% crumb rubber replacement.

CSA A3004-B1 (2014) standard was used for mixing hydraulic cement mortar. In the mixing process, cement was first added in the mixing bowl. Half of the mixing water was added afterwards and the mixer was started at slow speed (140 rpm). The cement paste was mixed for 30 seconds at this speed. During the mixing procedure, sand and crumb rubber was added slowly over the next 60 seconds. After 90 seconds of initial mixing at slow speed, the mixer was stopped and the speed was increased to 285 rpm (fast speed). During the next 90 seconds, the remaining water was added to the mix to create a homogenous mix.

Table 3.3: Mix proportions of mortar cubes

<table>
<thead>
<tr>
<th>Batch</th>
<th>Sample Designation</th>
<th>Cement (g)</th>
<th>Water (mL)</th>
<th>Sand (g)</th>
<th>Crumb Rubber (g)</th>
<th>Crumb rubber content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch A (1 : 2.5)</td>
<td>A0</td>
<td>1000</td>
<td>486</td>
<td>2500</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>A10</td>
<td>1000</td>
<td>486</td>
<td>2250</td>
<td>109</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>A20</td>
<td>1000</td>
<td>486</td>
<td>2000</td>
<td>218</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>A30</td>
<td>1000</td>
<td>486</td>
<td>1750</td>
<td>327</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>A40</td>
<td>1000</td>
<td>486</td>
<td>1500</td>
<td>436</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>A50</td>
<td>1000</td>
<td>486</td>
<td>1250</td>
<td>545</td>
<td>50%</td>
</tr>
<tr>
<td>Batch B (1 : 2.75)</td>
<td>B0</td>
<td>1000</td>
<td>486</td>
<td>2750</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>B10</td>
<td>1000</td>
<td>486</td>
<td>2475</td>
<td>120</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>B20</td>
<td>1000</td>
<td>486</td>
<td>2200</td>
<td>240</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>B30</td>
<td>1000</td>
<td>486</td>
<td>1925</td>
<td>359</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>B40</td>
<td>1000</td>
<td>486</td>
<td>1650</td>
<td>479</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>B50</td>
<td>1000</td>
<td>486</td>
<td>1375</td>
<td>599</td>
<td>50%</td>
</tr>
<tr>
<td>Batch C (1 : 3)</td>
<td>C0</td>
<td>1000</td>
<td>486</td>
<td>3000</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>C10</td>
<td>1000</td>
<td>486</td>
<td>2700</td>
<td>131</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>C20</td>
<td>1000</td>
<td>486</td>
<td>2400</td>
<td>261</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>C30</td>
<td>1000</td>
<td>486</td>
<td>2100</td>
<td>392</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>C40</td>
<td>1000</td>
<td>486</td>
<td>1800</td>
<td>523</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>C50</td>
<td>1000</td>
<td>486</td>
<td>1500</td>
<td>653</td>
<td>50%</td>
</tr>
</tbody>
</table>
Freshly prepared mortar mix was then fed into two conical rings. One of them was for penetration test and the other one for setting time test (initial and final). The remaining mix was then fed into brass molds and hand compacted (Figure 3.6). Here, 50 mm standard mortar cubes were prepared for testing. In case of rubber addition, crumb rubber increment decreased the workability of the mix, hence affected mortar compaction. Moreover, rubber content created air bubbles in the mix due to non-conformity with the cement substrate. Afterwards, the molds were kept in a moist cabinet for 24 hours for initial hardening. The samples were then removed carefully from the molds and kept in an ambient condition for moist curing (Figure 3.7). Compressive strength of the prepared samples were examined after 3, 7, 28, and 56 days of continuous moist curing.

![Brass molds for hardened properties of cement mortar; (a) before casting and (b) after casting](image)

Figure 3.6: Brass molds for hardened properties of cement mortar; (a) before casting and (b) after casting

![Hardened mortar specimens are being cured in a moist cabinet](image)

Figure 3.7: Hardened mortar specimens are being cured in a moist cabinet
3.3.2 Penetration Test

Adequate amount of water is needed to prepare hydraulic mortar paste. CSA A3004-B1 (2014) standard was followed for observing the penetration or workability trends of different mortar samples. This test requires a 10 mm flat-end plunger, connected to a Vicat apparatus (Figure 3.8a). Initially, the mixing of all mortar materials, i.e. cement, sand, crumb rubber, and water was done. After that, the freshly prepared mortar mix was placed in a plastic conical ring. The ring was placed on its larger end on a glass plate and excess mortar paste was sliced off using a sharp edged trowel. The sample was then placed under a 10 mm flat-end plunger and the connecting movable rod was lowered until the plunger slightly touched the smoothed mortar surface. The indicator was set at zero and the rod was released for 30 seconds. Thus, the penetration reading was recorded.

3.3.3 Setting time

Setting time of cement mortar consists of two simultaneous tests, i.e. initial setting time and final setting time. The setting time was experimented by following CSA A3004-B2 (2013) standard. Besides, the sample preparation for setting time was similar to that of penetration test (described in section 3.3.2) except that a 1 mm needle was used in this test (Figure 3.8b). For initial setting time, the first reading was taken after 30 minutes of molding. Thereafter, readings were reported every 15 minutes considering a 30-second penetration time. The mortar specimens would be considered initially set when the 1 mm needle penetrated into the mortar paste by 25 mm. Interpolating data in different times gave the exact time required in the process. The data was recorded even after the mortar was initially set to determine its final setting time. Lastly, final penetration time was recorded when the needle could not visibly sink into the mortar paste.

3.3.4 Water absorption and unit weight

Crumb rubber is low in specific gravity and its water absorption capacity is different from natural sand aggregates. As such, water absorption capacity and unit
weight of hardened mortar samples were examined. In this case, the aforementioned tests were done after 28 days of moist curing. The process included visible water removal using a damp cloth immediately after removing the samples from the curing chamber. Saturated surface dry (SSD) weight was measured at this point. A pre-heated oven with a constant temperature of 65 °C was used to dry all the mortar specimens (ASTM C67, 2014). After continuous drying for 48 hours, the samples were removed, cooled at a room temperature and weighed for oven-dry mass. Thus, water absorption was obtained by comparing the weight differences between wet and dry samples.

Figure 3.8: Vicat apparatus for fresh cement mortar properties; (a) penetration test and (b) setting time

For unit weight tests, the volume of each sample is required. As such, length, width, and height were measured to obtain volume of the dried samples. The obtained value was then divided by its dry mass for calculating unit weight. For testing and measuring water absorption and unit weight, ASTM C67 (2014) standard was adopted. An average value of three samples in each mix was taken under consideration for doing both tests. However, only the average data is presented in the results and discussion part of the thesis.
3.3.5 Compressive strength

Compressive strength was tested after curing the samples in different ages (days). In this study, compressive strength was tested after 3, 7, 28, and 56 days of curing. Moreover, CSA A3004-C2 (2014) standard was followed. An INSTRON compressive testing machine was used for conducting the tests with a loading rate of 900 to 1800 N/sec. Figure 3.9 shows a typical testing arrangement for mortar compressive strength test. The machine had a maximum capacity of 250 kN.

![INSTRON compressive testing machine](image)

Figure 3.9: Test setup for compressive strength of mortar samples

Initially, the samples were removed from the curing chamber and the surface water was wiped off with a damp cloth. Afterwards, the samples were placed in the machine and the loading cell was drawn down just before the surface of the tested samples. The samples were loaded in compression until they failed completely. This study examined three samples in each case of the testing parameters. The average value of three samples in each curing date is presented afterwards in the results and discussion section and further compared with the samples having no rubber as aggregate.
3.4 Results and Discussions

3.4.1 Penetration test

The comparative analysis in terms of penetration can be clearly seen in Figure 3.10. It is clear from the graph that within the same batch, increasing crumb rubber in mortar resulted in decreased penetration values. For example, in case of Batch A, control specimens (A0) showed the highest penetration value (36 mm). On the other hand, 50% crumb rubber addition reduced the penetration value by 47.2% and reached 19 mm. Since crumb rubber was low in density, it did not mix properly with the cement matrix thereby increasing inter-particle friction between rubber and cement matrix (Meherier et al., 2015; Fedroff et al., 1996; Khatib and Bayomy, 1999; Dong et al., 2013). Moreover, previous studies reported an increased stiffness of cement matrix (Mavroulidou and Figueiredo, 2010; Thiruppathi, 2013) and high water absorption of rubber particles (Su et al., 2015) could be the pivotal reasons for reduced workability. Reduction in workability of this research aligned with previously reported studies (Raghavan et al., 1998; Del Rio Merino et al., 2007; Turatsinze et al., 2005).

Figure 3.10: Penetration values of fresh mortar samples
On the other hand, increasing cement to sand ratio decreased the overall penetration value, and consequently the workability (Table 3.4). Since the amount of sand increased in Batch B and Batch C (incrementing cement to sand ratio), the resultant cement mortar consisted more fines in the mix that required more water to obtain desired workability. As a result, sample B50 and C50 showed low penetration values of 6 mm and 5 mm, respectively compared to 19 mm of sample A50, irrespective of constant 50% crumb rubber in all these samples. Therefore, rubber addition in the cement matrix reduced the penetration values; hence, workability of cement based rubber mortar.

Table 3.4: Fresh properties of mortar samples

<table>
<thead>
<tr>
<th>Batch</th>
<th>Sample Designation</th>
<th>Crumb Rubber Content</th>
<th>Penetration (mm)</th>
<th>Initial Setting Time (min.)</th>
<th>Final Setting Time (min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch A</td>
<td>A0</td>
<td>0%</td>
<td>36</td>
<td>180</td>
<td>285</td>
</tr>
<tr>
<td></td>
<td>A10</td>
<td>10%</td>
<td>30</td>
<td>210</td>
<td>315</td>
</tr>
<tr>
<td></td>
<td>A20</td>
<td>20%</td>
<td>29</td>
<td>230</td>
<td>360</td>
</tr>
<tr>
<td></td>
<td>A30</td>
<td>30%</td>
<td>25</td>
<td>262</td>
<td>390</td>
</tr>
<tr>
<td></td>
<td>A40</td>
<td>40%</td>
<td>24</td>
<td>270</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>A50</td>
<td>50%</td>
<td>19</td>
<td>345</td>
<td>495</td>
</tr>
<tr>
<td>Batch B</td>
<td>B0</td>
<td>0%</td>
<td>21</td>
<td>150</td>
<td>225</td>
</tr>
<tr>
<td></td>
<td>B10</td>
<td>10%</td>
<td>16</td>
<td>180</td>
<td>285</td>
</tr>
<tr>
<td></td>
<td>B20</td>
<td>20%</td>
<td>15</td>
<td>186</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>B30</td>
<td>30%</td>
<td>10</td>
<td>195</td>
<td>330</td>
</tr>
<tr>
<td></td>
<td>B40</td>
<td>40%</td>
<td>8</td>
<td>210</td>
<td>360</td>
</tr>
<tr>
<td></td>
<td>B50</td>
<td>50%</td>
<td>6</td>
<td>240</td>
<td>405</td>
</tr>
<tr>
<td>Batch C</td>
<td>C0</td>
<td>0%</td>
<td>10</td>
<td>120</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>C10</td>
<td>10%</td>
<td>8</td>
<td>127</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>C20</td>
<td>20%</td>
<td>7</td>
<td>139</td>
<td>275</td>
</tr>
<tr>
<td></td>
<td>C30</td>
<td>30%</td>
<td>6</td>
<td>156</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>C40</td>
<td>40%</td>
<td>6</td>
<td>178</td>
<td>330</td>
</tr>
<tr>
<td></td>
<td>C50</td>
<td>50%</td>
<td>5</td>
<td>182</td>
<td>360</td>
</tr>
</tbody>
</table>
3.4.2 Setting time

Figure 3.11 and Figure 3.12 present initial and final setting time, respectively of three batches (Batch A, Batch B, and Batch C) of samples having different percentage of crumb rubber. The results showed clear indication that incorporating crumb rubber in mortar increased the initial and final setting time. For instance, in Batch A for control specimens A0 (0% crumb rubber), the initial setting time was 180 minutes and became 210, 230, 262, 270, and 345 minutes for mortar samples having 10%, 20%, 30%, 40%, and 50% crumb rubber. However, the increase in final setting time for the same batch (Batch A) was more significant compared to initial setting time having similar replacement levels of crumb rubber. Since incorporating crumb rubber delayed the initial setting time and overall hardening process, final setting time increased. As discussed in section 3.2.3, the chemical analysis (EDS) identified high level of Silicon (Si) and Zinc (Zn) in crumb rubber samples. Silicon and Zinc both are known as hydrophobic and naturally water resistant materials. Thus, rubber and water did not mix properly during batching thereby increasing the initial and final setting time.

![Graph showing initial setting time of fresh mortar samples](image)

Figure 3.11: Initial setting time of fresh mortar samples
Crumb rubber had higher fineness modulus value of 3.68 than sand (2.24). As a result, crumb rubber was coarser with respect to sand and had low surface area compared to its volume. Thus, more water was available for the cement hydration process and therefore rubber-based mortar showed delayed setting time. Previous studies reported an increase in setting time with the incorporation of rubber that aligned with the findings of this research (Al-Akhras and Smadi, 2004; Pierce and Blackwell, 2003; Ray et al., 1994). Besides, in all the three batches the initial setting time of control specimens (A0, B0, and C0) ranged between 120 and 180 minutes, whereas the final setting time ranged between 180 and 285 minutes. Control specimens took less time compared to rubber-based mortar samples irrespective of different cement to sand ratio thereby showing similar trends in all three batches (Table 3.4). However, initial and final setting time of Batch B decreased compared to Batch A. Since crumb rubber and/or sand increased in the mix of Batch B, the setting time decreased with that. Similarly, Batch C showed less time required to set, both initial and final, compared to Batch B. In this case, the mix was almost dry and the rapid evaporation of water initiated quick setting of the mortar samples. However, rubber-based mortar samples (C10, C20, C30, C40, and C50) showed an expected delay in setting time compared to the control specimen (C0).

![Figure 3.12: Final setting time of fresh mortar samples](image-url)
3.4.3 Compressive strength

In terms of compressive strength, control specimens (A₀, B₀, and C₀) showed the best results compared to the mortar samples having crumb rubber as fine aggregate replacement (Table 3.5). Crumb rubber created a weaker bond with cement matrix compared to sand particles and thereby reduced the compressive strength. Figure 3.13 portrays the declining trend of Batch A mortar samples having cement to sand ratio of 1:2.5. The strength reduction was very significant and the more rubber addition even reduced the strength further. After 56 days of curing, compressive strength of A₁₀, A₂₀, A₃₀, A₄₀, and A₅₀ mortar samples reduced by 34.7%, 56.9%, 68.6%, 78.3%, and 85.4%, respectively. Nevertheless, the compressive strength of A₀ sample was 63.5 MPa, which was higher than all other mortar samples in the batch. Therefore, it was observed that 50% crumb rubber replacement (A₅₀) showed the worst results among the specimens. Compressive strength reduction in rubber-based mortar was reported in previous studies (Al-Akhras and Smadi, 2004; Meherier et al., 2015; Turatsinze et al., 2005; Yilmaz and Degirmenci, 2009; Pierce and Blackwell, 2003; Herrero et al., 2013) that complimented the findings of this research.

Figure 3.13: Compressive strength of Batch A mortar samples
One of the reasons for low compressive strength might be lower bulk density of crumb rubber compared to sand. Moreover, crumb rubber and cement matrix caused weak interfacial transition zones between cement matrix and crumb rubber thereby hampering the bonding process (Meherier et al., 2015). Existence of deleterious materials, i.e. Sulfur and Zinc on rubber surface might be one of the reasons for poor bonding capabilities of crumb rubber. Compressive strength for non-load-bearing concrete masonry unit is, however, minimum 3.50 MPa according to ASTM C129 (2014). According to this reference, all mortar samples of Batch A fulfilled this criterion.

Table 3.5: Compressive strength of mortar samples in different days

<table>
<thead>
<tr>
<th>Batch</th>
<th>Sample Designation</th>
<th>Crumb Rubber Content</th>
<th>Compressive Strength (MPa)</th>
<th>3 Days</th>
<th>7 Days</th>
<th>28 Days</th>
<th>56 Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch A</td>
<td>A1 0%</td>
<td>24.90</td>
<td>34.01</td>
<td>49.18</td>
<td>63.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A2 10%</td>
<td>18.10</td>
<td>23.50</td>
<td>30.59</td>
<td>41.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1 : 2.5)</td>
<td>A3 20%</td>
<td>14.84</td>
<td>16.96</td>
<td>23.76</td>
<td>27.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A4 30%</td>
<td>11.58</td>
<td>14.27</td>
<td>19.43</td>
<td>19.98</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A5 40%</td>
<td>5.81</td>
<td>8.39</td>
<td>11.49</td>
<td>13.77</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A6 50%</td>
<td>5.56</td>
<td>7.21</td>
<td>9.03</td>
<td>9.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Batch B</td>
<td>B1 0%</td>
<td>30.91</td>
<td>41.37</td>
<td>51.10</td>
<td>55.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1 : 2.75)</td>
<td>B2 10%</td>
<td>22.10</td>
<td>25.37</td>
<td>33.67</td>
<td>37.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B3 20%</td>
<td>16.52</td>
<td>20.03</td>
<td>23.83</td>
<td>25.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B4 30%</td>
<td>10.60</td>
<td>11.90</td>
<td>15.04</td>
<td>17.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B5 40%</td>
<td>7.17</td>
<td>9.25</td>
<td>11.09</td>
<td>12.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B6 50%</td>
<td>3.57</td>
<td>5.45</td>
<td>6.93</td>
<td>7.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Batch C</td>
<td>C1 0%</td>
<td>25.14</td>
<td>30.34</td>
<td>42.37</td>
<td>54.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1 : 3)</td>
<td>C2 10%</td>
<td>18.09</td>
<td>22.71</td>
<td>30.86</td>
<td>36.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C3 20%</td>
<td>14.03</td>
<td>16.36</td>
<td>21.30</td>
<td>24.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C4 30%</td>
<td>9.69</td>
<td>11.61</td>
<td>13.15</td>
<td>15.73</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C5 40%</td>
<td>6.88</td>
<td>7.17</td>
<td>9.77</td>
<td>10.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C6 50%</td>
<td>4.61</td>
<td>5.03</td>
<td>6.60</td>
<td>7.13</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.14 and Figure 3.15 represent the compressive strength of Batch B and Batch C mortar cubes, respectively. Both of these batches showed decreasing trends with the increased amount of crumb rubber, which was identical to Batch A results.
For Batch B and Batch C, 56 days compressive strength of control specimens (B0 and C0) reached 55.1 MPa and 54.2 MPa, respectively. These values started decreasing drastically with the incorporation of crumb rubber in the matrix. For Batch B, after 56 days of curing, compressive strength of mortar samples B10, B20, B30, B40, and B50 reduced by 31.8%, 54.5%, 68.7%, 78.0%, and 86.7%, respectively (Table 3.5).

In case of Batch C, 32.0%, 55.3%, 71.0%, 81.1%, and 86.9% compressive strength reduction was reported for C10, C20, C30, C40, and C50 samples, respectively (Table 3.5). Since crumb rubber created weak bonding with the cement paste, compressive strength reduction was obvious. However, the minimum requirement for non-load-bearing masonry unit was fulfilled (ASTM C129, 2014).

It is also of note that Batch A showed maximum compressive strength values compared to both Batch B and Batch C. Batch B and Batch C had cement to sand ratio of 1: 2.75 and 1: 3, respectively. Since Batch B and Batch C had higher crumb rubber content in the matrix, the bonding between cement paste and crumb rubber deteriorated as such. Subsequently, the results confirmed that cement to sand ratio was also a significant parameter along with different levels of crumb rubber in determining the compressive strength of mortar samples.
3.4.4 Unit weight and water absorption capacity

Unit weights of mortar cubes are linked in reverse to the growing amount of crumb rubber. Figure 3.16 shows the declining trend of Batch A, Batch B, and Batch C samples, irrespective of the change in cement to sand ratio. For control specimens A₀, B₀, and C₀ (0% crumb rubber), the unit weight was 2146 kg/m³, 2110 kg/m³, and 2062 kg/m³, respectively (Table 3.6).

In case of Batch A, unit weight was decreased by 8%, 12%, 17%, 22%, and 28% for samples A₁₀, A₂₀, A₃₀, A₄₀, and A₅₀, respectively compared to A₀. Approximately, 7%, 12%, 18%, 22%, and 27% unit weight reductions were reported for rubber-based B₁₀, B₂₀, B₃₀, B₄₀, and B₅₀ samples compared to B₀, respectively. Similar to Batch A and Batch B, unit weight reduction for Batch C was also reported. In this case, compared to C₀, C₁₀, C₂₀, C₃₀, C₄₀, and C₅₀ samples decreased by 7%, 12%, 17%, 23%, and 26%, respectively. The increased amount of crumb rubber reduced the unit weight of different mixes as crumb rubber had a specific gravity less than half of sand.
Table 3.6: Unit weight and absorption capacity of mortar specimens

<table>
<thead>
<tr>
<th>Batch</th>
<th>Sample Designation</th>
<th>Crumb Rubber Content</th>
<th>Unit Weight (kg/m³)</th>
<th>Absorption Capacity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch A</td>
<td>A0</td>
<td>0%</td>
<td>2146.0</td>
<td>3.5%</td>
</tr>
<tr>
<td></td>
<td>A10</td>
<td>10%</td>
<td>1974.9</td>
<td>4.1%</td>
</tr>
<tr>
<td></td>
<td>A20</td>
<td>20%</td>
<td>1879.8</td>
<td>4.2%</td>
</tr>
<tr>
<td>Batch A</td>
<td>A30</td>
<td>30%</td>
<td>1775.3</td>
<td>4.3%</td>
</tr>
<tr>
<td></td>
<td>A40</td>
<td>40%</td>
<td>1677.0</td>
<td>4.8%</td>
</tr>
<tr>
<td></td>
<td>A50</td>
<td>50%</td>
<td>1547.4</td>
<td>4.9%</td>
</tr>
<tr>
<td>Batch B</td>
<td>B0</td>
<td>0%</td>
<td>2110.1</td>
<td>3.7%</td>
</tr>
<tr>
<td>Batch B</td>
<td>B10</td>
<td>10%</td>
<td>1954.5</td>
<td>4.1%</td>
</tr>
<tr>
<td></td>
<td>B20</td>
<td>20%</td>
<td>1854.3</td>
<td>4.4%</td>
</tr>
<tr>
<td></td>
<td>B30</td>
<td>30%</td>
<td>1723.4</td>
<td>4.8%</td>
</tr>
<tr>
<td></td>
<td>B40</td>
<td>40%</td>
<td>1644.8</td>
<td>4.9%</td>
</tr>
<tr>
<td></td>
<td>B50</td>
<td>50%</td>
<td>1534.9</td>
<td>5.0%</td>
</tr>
<tr>
<td>Batch C</td>
<td>C0</td>
<td>0%</td>
<td>2061.6</td>
<td>4.1%</td>
</tr>
<tr>
<td>Batch C</td>
<td>C10</td>
<td>10%</td>
<td>1910.8</td>
<td>4.3%</td>
</tr>
<tr>
<td></td>
<td>C20</td>
<td>20%</td>
<td>1819.7</td>
<td>4.6%</td>
</tr>
<tr>
<td></td>
<td>C30</td>
<td>30%</td>
<td>1705.2</td>
<td>4.8%</td>
</tr>
<tr>
<td></td>
<td>C40</td>
<td>40%</td>
<td>1581.2</td>
<td>5.0%</td>
</tr>
<tr>
<td></td>
<td>C50</td>
<td>50%</td>
<td>1517.7</td>
<td>5.1%</td>
</tr>
</tbody>
</table>
Among the three batches of specimens (Batch A, Batch B, and Batch C), the ratio of cement to sand also played an important role in changing their unit weights as these samples followed a decreasing pattern with an increase in the ratio. As it can be well understood that more crumb rubber in the matrix would reduce its unit weight. For instance, Batch C showed less unit weight than Batch B and likewise, Batch B showed less unit weight compared to Batch A.

Water absorption capacity of mortar cubes increased with the increased amount of crumb rubber. Figure 3.17 shows the rising trend of sample specimens for Batch A, Batch B, and Batch C, irrespective of the change in cement to sand ratio. In case of Batch A, water absorption capacity was increased by 15%, 18%, 23%, 35%, and 40% for samples A10, A20, A30, A40, and A50, respectively compared to A0. Approximately, 12%, 18%, 29%, 34%, and 34% water absorption capacity was reported to increase for rubber-based B10, B20, B30, B40, and B50 samples compared to B0, respectively. Similar to Batch A and Batch B, unit weight reduction for Batch C was also reported. In this case, C10, C20, C30, C40, and C50 samples were increased by 3%, 11%, 16%, 22%, and 23%, respectively. The increased amount of crumb rubber increased the water absorption capacity of different mixes as crumb rubber created porous mortar by creating air voids and thereby trapped water in those voids.

The change in cement to sand ratio also played an important role in changing water absorption capacity in all three batches. However, the results followed an increasing pattern with an increase in the ratio. For instance, A0, B0, and Co control specimens were reported to have 3.5%, 3.7%, and 4.1% water absorption capacity, respectively (Table 3.6). Likewise, all other samples in Batch B showed higher water absorption capacity than Batch A because of higher cement to sand ratio of 1: 2.75 compared to 1: 2.5. Increased cement to sand ratio means more sand and crumb rubber particles in the mix, which helped in consisting more water in its voids because of entrapped air being filled with water. Similar conclusion can also be drawn in case of Batch C mortar samples compared to Batch B. In this case, however, Batch C had a higher cement to sand ratio (1: 3) compared to Batch B (1: 2.75).
3.4.5 Failure pattern

Failure pattern of mortar mixes with different crumb rubber replacement is presented in Figure 3.18. Failure patterns were examined after the mortar specimens failed in compression. The control specimens (0% crumb rubber) showed an explosive and abrupt failure with full disintegration of the specimens (Figure 3.18a). It is because the mortar samples were brittle in nature and the failure occurred immediately after reaching the peak compressive load. On the other hand, cement mortar with 10% (Figure 3.18b) and 20% (Figure 3.18c) crumb rubber content experienced significant damage even though the failure mechanisms were comparatively gradual compared to brittle failure in control specimens. Rubber inclusion in the matrix showed gradual and slow failure patterns due to high deformability of soft crumb rubber. This phenomenon was more pronounced in cement mortar with higher crumb rubber replacement (Figure 3.18d-f). Besides, the failure patterns were uniform and almost identical throughout the last three batches.
Figure 3.18: Failure pattern of different mortar mixes; (a) control or 0% crumb rubber, (b) 10% crumb rubber, (c) 20% crumb rubber, (d) 30% crumb rubber, (e) 40% crumb rubber, and (f) 50% crumb rubber
Chapter 4

Mechanical Behavior of Concrete with Varying Replacement Levels of Crumb Rubber

4.1 General

Concrete has emerged as the most extensively used construction material due to its global availability, low cost, and flexibility in forming different shapes. Globally more than 15 billion tons of concrete is produced annually and the number is rising every year (CAC, 2010). In general, concrete contains 12% cement and 80% aggregate by mass (Mehta, 2001). One metric ton of cement emits 0.13 metric ton of CO$_2$ that accounts for about 5% of global greenhouse gas (GHG) emission (CAC, 2016). Moreover, mining large quantities of aggregate (gravel and sand) adversely affects the environment, mostly forest areas and riverbeds (Mehta, 2001). Globally, the demand for aggregate in construction industry is ten to eleven billion metric tons per year (Huda and Alam, 2014). As such, researchers are constantly striving to explore new ways of producing concrete with less environmental impact. Recycled rubber tire, especially crumb rubber, has the potential of reducing the GHG emission and may contribute in paving the way for a sustainable design of concrete production.

The concrete industry can become one of the viable options for using waste rubber materials as aggregates. Researchers experimented on using tire derived aggregates (TDA) and crumb rubber as partial or full replacement of coarse aggregates and fine aggregates, respectively (Ling et al., 2009 and 2010; Meherier et al., 2015; El-Gammal et al., 2010; Pierre, 2013). However, poor mechanical properties reduced its structural applications (Al Bakri et al., 2007; IRSG, 2014; Ling et al., 2009). Nevertheless, concrete made with rubber materials showed better performance in
terms of energy absorption capacity, thermal, acoustic, and durability aspects (Li et al., 1998; Kaloush et al., 2005; Tantala et al., 1996; Richardson et al., 2012; Fedroff et al., 1996; Gupta et al., 2014; Yung et al., 2013). Since the sources of crumb rubber differ depending on its original chemical composition, it will be difficult to get consistent results on rubber-based concrete, thus making it difficult in predicting its performance.

The major objective of this study is to investigate the fresh, mechanical, and durability properties of cement concrete made with different replacement levels of crumb rubber as a fine aggregate. Crumb rubber is being replaced by 10%, 20%, 30%, 40%, and 50% of sand particles in a concrete mix with a fixed water to cement ratio. Since crumb rubber had very low specific gravity compared to sand, volumetric replacement was considered in this study. However, this chapter focuses only on the fresh and mechanical properties of rubber-based cement concrete. Chapter 5 extensively focuses on the durability characteristics (freeze-thaw resistance and chloride permeability) of these specimens.

This chapter is divided into different sections, focusing on the properties of coarse aggregates including gradation, specific gravity, and water absorption. Moreover, chemical analysis using EDS (Energy Dispersive Spectroscopy) and SEM (Scanning Electron Microscopy) images of crumb rubber are incorporated separately in sections 4.2.2 and 4.2.3 of chapter 4.

In terms of examining fresh concrete properties, slump, air content, and fresh density were measured and reported. Mechanical properties of hardened samples including compressive strength, splitting tensile strength, and flexural strength were examined. Moreover, stress-strain behavior of the specimens in different batches was observed in order to have a comprehensive material properties combining crumb rubber. All these observations were reported with a comparison to conventional concrete without crumb rubber.
4.2 Properties of Aggregates

In this study, concrete specimens were prepared using cement (as binder), gravel (as coarse aggregate), sand and crumb rubber (as fine aggregate), water, water reducer, and air entraining admixture. Locally available sand and gravel were used in this study with maximum nominal size of 4.75 mm and 20 mm, respectively. Bigger sized materials were discarded from the mix in order to maintain consistency. Discarded and recycled waste tire rubber was the source of crumb rubber and commercially available products were used in this study. Physical properties (specific gravity, water absorption capacity, fineness modulus, and bulk density) are summarized in Table 4.1.

Specific gravity and water absorption capacity of gravel was measured by utilizing CSA A23.2-10A (2014) whereas bulk density was measured by following CSA A23.2-12A (2014). Moreover, sieve analysis and gradation of gravel were done using CSA A23.2-2A (2014) standard. The gradation of gravel (Figure 4.1) showed a perfectly fitting curve within the CSA range thereby ensuring well-graded aggregate. Gradation curves of sand and crumb rubber were previously presented in section 3.2.1 (Figure 3.1 and Figure 3.2).

![Figure 4.1: Sieve analysis of gravel](image-url)
4.3 Experimental Procedure

4.3.1 Mix design and Sample preparation

Six different mix designs were prepared and tested for this study in order to have a comparative analysis of the results. Water-cement ratio was fixed (0.31) throughout the mix design to eliminate the effects of water on concrete properties. As a result, only the variation in sand and crumb rubber would influence the samples. The coarse aggregates used in concrete had saturated surface dry condition. The target compressive strength of this mix design was 35 MPa. Sand aggregate was replaced by volume where the different replacement levels were 10%, 20%, 30%, 40%, and 50%. Since crumb rubber had a very low relative density compared to sand, volume replacement method was considered. Table 4.2 summarizes the mix proportions of different materials in the concrete samples. Moreover, each mix design is designated with a unique name for ease in referencing within the text. Batch code S70-CR30 indicates that this mix consists 70% sand (S) and 30% crumb rubber (CR). So, 30% sand was replaced by crumb rubber in this mix. Similarly, all other samples were named.

Table 4.1: Physical properties of aggregates

<table>
<thead>
<tr>
<th>Variables</th>
<th>Gravel</th>
<th>Sand</th>
<th>Crumb Rubber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk dry specific gravity</td>
<td>2.64</td>
<td>2.56</td>
<td></td>
</tr>
<tr>
<td>Bulk SSD specific gravity</td>
<td>2.66</td>
<td>2.60</td>
<td>1.15</td>
</tr>
<tr>
<td>Apparent specific gravity</td>
<td>2.71</td>
<td>2.67</td>
<td></td>
</tr>
<tr>
<td>Water absorption capacity (%)</td>
<td>0.98</td>
<td>1.52</td>
<td>1.20</td>
</tr>
<tr>
<td>Fineness modulus</td>
<td>-</td>
<td>2.24</td>
<td>3.68</td>
</tr>
<tr>
<td>Bulk density (kg/m³)</td>
<td>1563.37</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

GU (General Use) cement was utilized in the concrete mix as a binding material. Moreover, Glenium 3030 NS and Micro-Air were used as water reducer and air entraining admixture, respectively. Control specimens were made without having any crumb rubber in the mix and further compared with the specimens having rubber particles. During the mixing process, the ingredients were added in the automated
mixing machine in order to have a homogenous mixture. For this purpose, CSA A23.2-2C (2014) standard was utilized. Initially, gravel and sand were added in the mixing drum. Crumb rubber was added to the mix following the natural aggregates. Cement and water were added simultaneously after the previous ingredients. Water reducer and air entraining admixture were both added to the water before pouring it to the mixing drum. The mixing was continued for 3 minutes with a resting time of 3 minutes. The mixing was restarted for additional 2 minutes before casting the cylinders.

Table 4.2: Mix proportions of concrete cylinders (per cubic meter)

<table>
<thead>
<tr>
<th>Batch Code</th>
<th>Crumb Rubber Content</th>
<th>Water (kg)</th>
<th>Cement (kg)</th>
<th>Gravel (kg)</th>
<th>Sand (kg)</th>
<th>Crumb Rubber (kg)</th>
<th>Entraining Admixture (ml)</th>
<th>Water Reducer (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S100-CR0</td>
<td>0%</td>
<td>119</td>
<td>385</td>
<td>1142</td>
<td>633</td>
<td>0</td>
<td>192</td>
<td>3140</td>
</tr>
<tr>
<td>S90-CR10</td>
<td>10%</td>
<td>119</td>
<td>385</td>
<td>1142</td>
<td>570</td>
<td>29</td>
<td>192</td>
<td>3140</td>
</tr>
<tr>
<td>S80-CR20</td>
<td>20%</td>
<td>119</td>
<td>385</td>
<td>1142</td>
<td>507</td>
<td>57</td>
<td>192</td>
<td>3140</td>
</tr>
<tr>
<td>S70-CR30</td>
<td>30%</td>
<td>119</td>
<td>385</td>
<td>1142</td>
<td>443</td>
<td>86</td>
<td>192</td>
<td>3140</td>
</tr>
<tr>
<td>S60-CR40</td>
<td>40%</td>
<td>119</td>
<td>385</td>
<td>1142</td>
<td>380</td>
<td>115</td>
<td>192</td>
<td>3140</td>
</tr>
<tr>
<td>S50-CR50</td>
<td>50%</td>
<td>119</td>
<td>385</td>
<td>1142</td>
<td>317</td>
<td>143</td>
<td>192</td>
<td>3140</td>
</tr>
</tbody>
</table>

Freshly prepared concrete was then fed into a conical ring for slump test and into a cylinder for air content test. The remaining mix was fed into cylindrical molds for compressive strength and splitting tensile strength tests (Figure 4.2a). In addition, beams were fed with concrete for flexural strength testing (Figure 4.2b). For ensuring uniform compaction, a vibrator was used in all of the molds. Afterwards, all the molds were kept in a moist cabinet for 24 hours of initial hardening. The samples were then removed carefully from the molds and kept in a curing room with controlled temperature and moisture.

4.3.2 Slump value and air content

CSA A23.2–5C (2014) standard was used for measuring slump value of concrete samples (Figure 4.3a). Slump value provides an indication of the workability
of concrete. On the other hand, CSA A23.2—4C (2014) was utilized for air content measurement of fresh concrete samples (Figure 4.3b). In both of these tests, hand compaction was done using a tamping rod. Air content was ensured for better durability of concrete. Moreover, it also influences the workability and strength of hardened concrete.

![Molds for (a) compressive strength, splitting tensile strength, and stress-strain tests and (b) flexural strength test](image)

**Figure 4.2:** Molds for (a) compressive strength, splitting tensile strength, and stress-strain tests and (b) flexural strength test

### 4.3.3 Compressive strength

Compressive strength was measured after curing the concrete cylinders for different ages (days). In this study, the sample specimens were tested in compression after 7, 28, 56, and 168 days of moist curing. In order to understand long-term performance in compression, the concrete cylinders were tested after 56 and 168 days of curing. CSA A23.2-9C (2014) standard was used for performing the test. Figure 4.4 shows a typical arrangement of the test setup. Moreover, an INSTRON machine was used with a loading rate of 0.15 MPa/sec. to 0.35 MPa/sec. The loading rate was kept constant throughout the ultimate failure of the specimens. The same instrument was also used for stress – strain analysis with an additional National Instrument (NI) data acquisition system (Figure 4.5b). Three samples were tested in each mix and the average values were reported afterwards.
4.3.4 Splitting tensile strength

In order to observe the tensile behavior of sample specimens, splitting tensile strength test was adopted. For experimenting the concrete cylinders, the loading rate was maintained between 0.7 MPa/min and 1.4 MPa/min using the INSTRON machine. CSA A23.2-13C (2014) standard was used for this purpose. Equation 4.1 is adopted for obtaining the results after testing the samples.

\[
 f'_{t} = \frac{(2P)}{(\pi LD)} \quad --- (4.1)
\]

Here, \( P \) = maximum load at failure (MPa), \( L \) = length (mm), \( D \) = diameter (mm) and \( f'_{t} \) = splitting tensile strength of concrete cylinders.

Initially, the cylinders were removed from the curing chamber and the surface water was wiped off. Three samples of each mix were considered in each set of tests for better reliability; however, only the average value is presented in the results section. For this study, standard dimensions of φ100 mm x 200 mm concrete cylinders were used. The cylinders were tested after 28 days of moist curing.
Concrete beams were cast in order to test flexural strength. This test was also done in order to have an overview of samples’ tensile behavior; however, the method is indirect similar to splitting tensile strength. The fracture (rupture) is meant to occur in the tension surface (the bottom surface) of the concrete beams. A HUMBOLDT machine was used with a loading rate of 0.85 MPa/min. to 1.20 MPa/min (Figure 4.5a). The standard followed for this test was CSA A23.2-8C (2014). For obtaining the flexural strength of beam samples, Equation 4.2 was used. The concrete beam samples had dimensions of 530 mm (L) x 150 mm (b) x 150 mm (d). The beam samples were cured for 28 days before testing for flexural strength.

\[ f_r = \frac{PL}{bd^2} \]  

--- (4.2)
Here, $P = \text{maximum load at failure (MPa)}$, $L = \text{span length (mm)}$, $b = \text{width of the beam (mm)}$, $d = \text{depth of the beam (mm)}$ and $f_r = \text{flexural strength of concrete beams}$.

![Figure 4.5: Test setup for (a) flexural strength test and (b) stress-strain test](image)

### 4.3.6 Unit weight and water absorption capacity

Crumb rubber is low in relative density and shows reduced water absorption capacity compared to sand. In order to observe these two properties of rubber-based concrete cylinders, unit weight and water absorption capacity was tested after 28 days of continuous moist curing. A pre-heated oven with 65 °C was used to dry all the cylinders before measuring their oven-dry weight. The difference in weights between saturated surface dry and oven dry samples was recorded as water absorption capacity. Moreover, unit weight was obtained throughout the process by dividing the sample’s volume by its oven dry mass. ASTM C67 (2014) standard was adopted in doing these tests.
4.4 Results and Discussions

4.4.1 Slump value

Figure 4.6 presents the comparative analysis of workability in terms of slump value. It was observed that increasing crumb rubber in concrete resulted in decreased slump value. For example, control samples (Batch S100-CR0) showed the highest slump value (95 mm), whereas the slump value was reduced by 5.3%, 15.8%, 21.0%, 21.1%, and 36.8% for Batch S90-CR10, S80-CR20, S70-CR30, S60-CR40, and S50-CR50, respectively.

![Slump value graph](image)

Figure 4.6: Slump value of fresh concrete samples

Crumb rubber was porous and did not mix properly with the cement matrix thereby requiring more water to overcome inter-particle friction (Meherier et al., 2015; Fedroff et al., 1996; Khatib and Bayomy, 1999; Dong et al., 2013). In addition, crumb rubber increased stiffness of the cement matrix. Thus, slump value or workability was reduced with the increment of rubber particles in the matrix. This phenomenon aligned with previous studies (Holmes et al., 2014; Khatib and Bayomy, 1999; Khaloo et al., 2008). Moreover, the design slump value was 75 mm ± 20 mm.
and all the batches showed the slump value within that range. Slump values of all the batches are summarized in Table 4.3.

4.4.2 Air content

The air content of fresh concrete samples is presented in Figure 4.7 and Table 4.3. S100-CR0 (control batch) showed 5% air content in the mix, whereas rubber-based concrete showed higher values than the control batch. In the case of 50% crumb rubber content (Batch S50-CR50), air content in concrete increased by 60% compared to control sample. Crumb rubber entrapped air in their rough surface and created air bubbles in the mix. As a result, rubber-based batches showed higher air content. Similar trends having high air content with rubber as fine aggregate were reported in previous studies (Fedroff et al., 1996; Khatib and Bayomy, 1999; Dong et al., 2013).

![Figure 4.7: Air content in fresh concrete samples](image)

4.4.3 Fresh density

Fresh density or unit weight of fresh concrete samples are showed in Table 4.3. Moreover, comparative between batches of concrete samples are presented in Figure 4.8. It can be seen from the graph that rubber content in the mix reduced the fresh density of the samples. Since crumb rubber was low in specific gravity (compared to
sand), addition of this material in the mix significantly reduced the overall weight. Fresh density of fresh concrete was reduced by approximately 6%, 7%, 11%, 12%, and 14% by adding 10%, 20%, 30%, 40%, and 50% crumb rubber, respectively.

Table 4.3: Fresh properties of concrete cylinders

<table>
<thead>
<tr>
<th>Batch Code</th>
<th>Crumb rubber content</th>
<th>Slump value (mm)</th>
<th>Air content (%)</th>
<th>Fresh density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S100-CR0</td>
<td>0%</td>
<td>95</td>
<td>5.0%</td>
<td>2474.0</td>
</tr>
<tr>
<td>S90-CR10</td>
<td>10%</td>
<td>90</td>
<td>5.5%</td>
<td>2320.7</td>
</tr>
<tr>
<td>S80-CR20</td>
<td>20%</td>
<td>80</td>
<td>6.0%</td>
<td>2289.8</td>
</tr>
<tr>
<td>S70-CR30</td>
<td>30%</td>
<td>75</td>
<td>6.0%</td>
<td>2179.8</td>
</tr>
<tr>
<td>S60-CR40</td>
<td>40%</td>
<td>75</td>
<td>7.0%</td>
<td>2173.0</td>
</tr>
<tr>
<td>S50-CR50</td>
<td>50%</td>
<td>60</td>
<td>8.0%</td>
<td>2132.2</td>
</tr>
</tbody>
</table>

Figure 4.8: Fresh density of concrete samples

4.4.4 Compressive Strength

Compressive strength of concrete samples in each batch was determined after 7, 28, 56, and 168 days of moist curing. S100-CR0 (control specimens) showed the best results compared to concrete cylinders having crumb rubber as fine aggregate.
Figure 4.9 and Table 4.4 portray the declining trend of concrete samples having crumb rubber in increased percentages. In the case of crumb rubber concrete, rate of strength gain gradually decreased with the increase in crumb rubber content as shown in Figure 4.9. Moreover, the strength reduction was significant and the more rubber addition even reduced the strength further. After 168 days of curing period, compressive strength of Batch S90-CR10, S80-CR20, S70-CR30, S60-CR40, and S50-CR50 reduced by 7.5%, 25.5%, 46.4%, 49.2%, and 63.1%, respectively. Compressive strength reduction of rubber-based concrete with the increment of crumb rubber was also reported in previous studies (Khatib and Bayomy, 1999; Fedroff et al., 1996; Eldin and Senouci, 1993; Dong et al., 2013; Holmes et al., 2014; Khaloo et al., 2008; Fattuhi and Clark, 1996).

Crumb rubber created a weaker bond within the cement matrix compared to sand particles thereby reducing the compressive strength. Transition zones between crumb rubber and cement matrix are presented in Figure 4.10a. The SEM images showed that cement matrix failed all around the crumb rubber particles. It was
because crumb rubber created weaker transition zones, as it did not react uniformly with the matrix thereby weakening the bonding process. A significantly magnified (500x) image in Figure 4.10b also confirmed this phenomenon. Moreover, lower bulk density and existence of deleterious materials, i.e. Sulfur and Zinc on rubber surface might be one of the reasons for poor bonding capabilities of crumb rubber.

Figure 4.10: Microstructure of concrete with crumb rubber; (a) cement matrix with rubber particle (300x) and (b) interface crumb rubber/concrete (500x)

It was also observed that Batch S100-CR0 (control) kept gaining strength after 56 days due to continuous hydration process, although the rate of strength gain was slower compared to 7 days and 28 days curing period. Batch S90-CR10 and S80-CR20 kept gaining strength after 56 days of curing. However, other batches showed almost constant compressive strength after 56 days of curing. Up to 20% crumb rubber replacement showed compressive strength higher than the design strength of 35 MPa.
### Table 4.4: Compressive strength of concrete cylinders

<table>
<thead>
<tr>
<th>Batch Code</th>
<th>Crumb Rubber Content</th>
<th>Compressive Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>7 Days</td>
</tr>
<tr>
<td>S100-CR0</td>
<td>0%</td>
<td>34.88</td>
</tr>
<tr>
<td>S90-CR10</td>
<td>10%</td>
<td>32.99</td>
</tr>
<tr>
<td>S80-CR20</td>
<td>20%</td>
<td>26.61</td>
</tr>
<tr>
<td>S70-CR30</td>
<td>30%</td>
<td>20.29</td>
</tr>
<tr>
<td>S60-CR40</td>
<td>40%</td>
<td>17.18</td>
</tr>
<tr>
<td>S50-CR50</td>
<td>50%</td>
<td>14.70</td>
</tr>
</tbody>
</table>

### 4.4.5 Splitting tensile strength

Splitting tensile strength of six batches of concrete are presented in Figure 4.11 and Table 4.5. Moreover, failure patterns and crack propagation of concrete cylinders after splitting tensile strength test are presented in Figure 4.12. Crumb rubber increment decreased the splitting tensile strength of concrete samples; however, an increase in strength was observed for Batch S90-CR10. Crumb rubber withstood large tensile deformations thereby delaying the crack growth of the concrete matrix. Moreover, rubber created high internal stress due to its low modulus of elasticity. As such, cement paste failed before rubber aggregates due to its weakness against tension. However, only 10% crumb rubber in concrete matrix (Batch S90-CR10) could not restrict from sudden fracturing of concrete specimens thereby showing high splitting tensile strength. Splitting tensile strength of Batch S90-CR10 increased by 6.7% compared to control samples without any crumb rubber (S100-CR0). Similar trends were also observed in a previous study (Ganesan et al. 2013).
In all other batches apart from S90-CR10, splitting tensile strength decreased. Due to poor bonding between cement paste and crumb rubber, weakened interfacial zones facilitated low splitting tensile strength of rubber-based concrete. However, the decrease in splitting tensile strength was not significant compared to compressive strength reduction. For instance, splitting tensile strength decreased by 5.9%, 13.1%, 18.4%, and 20.8% for concrete Batch S80-CR20, S70-CR30, S60-CR40, and S50-CR50, respectively. The trends aligned with previously reported findings (Ganjian et
al., 2009; Fedroff et al., 1996; Eldin and Senouci, 1993; Dong et al., 2013; Su et al., 2015).

Figure 4.12: Crack propagation of concrete cylinders after splitting tensile strength test; (a) S100-CR0 (10% CR), (b) S90-CR10 (10% CR), (c) S80-CR20 (20% CR), (d) S70-CR30 (30% CR), (e) S60-CR40 (40% CR) and (f) S50-CR50 (50% CR)

While doing the tests, it was observed from Figure 4.12 that concrete cylinders with crumb rubber showed gradual failure compared to brittle failure in the case of control specimens (S100-CR0). It can be seen from Figure 4.12b and Figure 4.12c that Batches S100-CR0 and S90-CR10 showed almost identical crack propagation,
respectively. However, other batches with higher rubber content showed less crack width (Figure 4.12.d-f). Batch S50-CR50 showed the best result with minimum crack width. Since crumb rubber helped in absorbing more energy due to its low modulus of elasticity, the concrete cylinders showed slow and gradual failure pattern with minimum crack width. Moreover, rubber concrete withstood additional loads after the specimens cracked. The specimens did not separate or disintegrate completely due to bridging of cracks by rubber. Thus, rubber in concrete prevented catastrophic failure.

4.4.6 Flexural strength

Flexural strength of concrete beams were tested after 28 days of moist curing. The results are presented in Table 4.5 and a comparative graph is illustrated in Figure 4.13. In this case, the behavior was similar to splitting tensile strength. Flexural strength of Batch S90-CR10 increased by 12.9% compared to the control (S100-CR0) beam sample. Since crumb rubber was a soft material, it acted as a barrier against crack propagation. However, only 10% crumb rubber was present in concrete matrix in the case of Batch S90-CR10. As a result, the bonding between cement paste and rubber aggregate broke suddenly and a peak value was recorded. Flexural strength decreased due to increasing replacement level of crumb rubber in concrete. Flexural strength declined by 8.8%, 17.5%, 18.7%, and 26.3% for Batch S80-CR20, S70-CR30, S60-CR40, and S50-CR50, respectively. Since crumb rubber created weak interfacial transition zones with the cement paste, it withstood less flexural stress compared to control (0% crumb rubber) concrete samples. Decrease in flexural strength with the increase in rubber content was reported in previous studies (Khatib and Bayomy, 1999; Topcu, 1995; Ganjian et al., 2009; Fedroff et al. 1996; Su et al., 2015; Aiello and Leuzzi, 2010).
Figure 4.14 shows a typical failure pattern of a concrete beam after flexural strength test. In all the samples, the beam showed identical failure pattern where one major crack appeared within the middle third of its length. Concrete beams with crumb rubber showed slow and gradual failure compared to brittle failure in the case of control specimens. This phenomenon was identical to the concrete cylinders of splitting tensile strength test.

### 4.4.7 Stress – strain behavior

Uniaxial stress-strain behavior of control concrete and concrete with crumb rubber of different mixes are illustrated in Figure 4.15a. The test was done after 168 days of curing. Crumb rubber replacement in different percentages showed significant change in stress-strain curves of all the samples compared to control (S100-CR0) specimens. The control specimens showed a peak stress of 62.58 MPa and its corresponding strain of 0.002. Transverse strain at peak stress are also presented in Table 4.6. Crumb rubber based concrete showed better performance in terms of strain gain compared to control specimens because of its soft material property and high-energy absorption capacity before failure.
Figure 4.14: Typical failure pattern of a concrete beam after flexural strength test

Axial strain value at peak stress was significantly higher for crumb rubber based concrete. For instance, peak axial strain of Batches S90-10 and S80-CR20 were 0.00257 and 0.00322, respectively. On the other hand, peak axial strain of 0.00393, 0.00522, and 0.00549 were recorded in Batches S70-CR30, S60-CR40, and S50-CR50, respectively. This is due to the lower modulus of elasticity of rubber-based concrete compared to control specimens as shown in Table 4.6 and Figure 4.15b. The table shows rapid decrease in modulus of elasticity of concrete cylinders with increased crumb rubber in the matrix. Modulus of elasticity decreased by 36.2%, 52.4%, 67.8%, 74.8%, and 85.7% when replacing sand with 10%, 20%, 30%, 40%, and 50% crumb rubber, respectively. Lower modulus of elasticity was one of the primary causes of decreased compressive strength in rubber-based concrete.

However, control specimens showed the highest modulus of elasticity (33.41 GPa) among all the batches. Since modulus of elasticity decreased, the failure mechanism of rubber-based concrete was slow and gradual. Increased rubber particles in the mix made the concrete more deformable thereby ensuring gradual failure instead of brittle failure. Reduced modulus of elasticity also indicated the soft morphological characteristics of crumb rubber compared to sand aggregate. Moreover, Poisson’s ratio changed with the incorporation of crumb rubber in the mix. The values of Poisson’s ratio increased with the increment of rubber (Table 4.6). It was reported that Poisson’s ratio increased by 15.6%, 26.2%, 30.3%, 42.2%, and 41.8% for
Batches S90-CR10, S80-CR20, S70-CR30, S60-CR40, S50-CR50, respectively. Since crumb rubber increment in the matrix showed more deflections in both axial and transverse directions, the Poisson’s ratio increased as such. This behavior of the material signified better deformability or energy absorption capacity by the action of compressive force in one of its perpendicular directions.

Figure 4.15: (a) Uniaxial stress-strain curve of concrete cylinders and (b) Co-relation of peak stress and modulus of elasticity with varying crumb rubber content; [S100-CR0 (0% CR), S90-CR10 (10% CR), S80-CR20 (20% CR), S70-CR30 (30% CR), S60-CR40 (40% CR) and S50-CR50 (50% CR)]
Table 4.6: Mechanical properties of different concrete mixes

<table>
<thead>
<tr>
<th>Batch Designation</th>
<th>Crumb Rubber Content</th>
<th>Modulus of Elasticity (GPa)</th>
<th>Peak Stress (MPa)</th>
<th>Axial Strain at Peak Stress</th>
<th>Transverse Strain at Peak Stress</th>
<th>Poisson's Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>S100-CR0</td>
<td>0%</td>
<td>33.42</td>
<td>62.58</td>
<td>0.00200</td>
<td>-0.00038</td>
<td>0.19</td>
</tr>
<tr>
<td>S90-CR10</td>
<td>10%</td>
<td>21.31</td>
<td>53.62</td>
<td>0.00257</td>
<td>-0.00059</td>
<td>0.22</td>
</tr>
<tr>
<td>S80-CR20</td>
<td>20%</td>
<td>15.91</td>
<td>39.88</td>
<td>0.00322</td>
<td>-0.00078</td>
<td>0.24</td>
</tr>
<tr>
<td>S70-CR30</td>
<td>30%</td>
<td>10.75</td>
<td>30.68</td>
<td>0.00393</td>
<td>-0.00098</td>
<td>0.25</td>
</tr>
<tr>
<td>S60-CR40</td>
<td>40%</td>
<td>8.42</td>
<td>29.77</td>
<td>0.00522</td>
<td>-0.00133</td>
<td>0.27</td>
</tr>
<tr>
<td>S50-CR50</td>
<td>50%</td>
<td>4.79</td>
<td>21.56</td>
<td>0.00549</td>
<td>-0.00144</td>
<td>0.27</td>
</tr>
</tbody>
</table>

4.4.8 Unit weight and water absorption capacity

Unit weights of hardened concrete cylinders were inversely related to the increasing amount of crumb rubber content. The declining trend of unit weight of rubber-based concrete Batches S90-CR10, S80-CR20, S70-CR30, S60-CR40, and S50-CR50 are presented in Figure 4.16 and Table 4.7. For control Batch S100-CR0, 2361 kg/m³ unit weight was recorded. However, unit weight decreased by approximately 1%, 4%, 7%, 11%, and 14% for concrete cylinders with 10%, 20%, 30%, 40%, and 50% crumb rubber, respectively. Since crumb rubber had a low specific gravity (less than half of sand), increasing rubber percentage in the matrix significantly reduced the unit weight of concrete thereby making the concrete lightweight. This property of concrete would eventually help in designing and constructing lightweight structural members.
Figure 4.16: Unit weight of concrete cylinders

Crumb rubber incorporation in concrete increased water absorption capacity of concrete cylinders (Table 4.7). It was observed from Figure 4.17 that 10% and 20% crumb rubber replacement increased the water absorption capacity by 5% and 8%, respectively compared to Batch S100-CR0 (control) without any rubber in the mix. Crumb rubber created air voids within the mix as it repelled water thereby trapping water in those voids during the curing period.

Table 4.7: Water absorption capacity and unit weight of concrete cylinders

<table>
<thead>
<tr>
<th>Batch Designation</th>
<th>Crumb Rubber Content</th>
<th>Water Absorption Capacity (%)</th>
<th>Unit Weight (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S100-CR0</td>
<td>0%</td>
<td>0.88%</td>
<td>2360.5</td>
</tr>
<tr>
<td>S90-CR10</td>
<td>10%</td>
<td>0.93%</td>
<td>2340.0</td>
</tr>
<tr>
<td>S80-CR20</td>
<td>20%</td>
<td>0.95%</td>
<td>2269.0</td>
</tr>
<tr>
<td>S70-CR30</td>
<td>30%</td>
<td>1.16%</td>
<td>2202.3</td>
</tr>
<tr>
<td>S60-CR40</td>
<td>40%</td>
<td>1.36%</td>
<td>2110.4</td>
</tr>
<tr>
<td>S50-CR50</td>
<td>50%</td>
<td>1.99%</td>
<td>2036.2</td>
</tr>
</tbody>
</table>
The microstructure of concrete cylinders with and without crumb rubber are illustrated in Figure 4.18. The images conferred well with a good distribution of crumb rubber throughout the cross-section of concrete cylinders. Figure 4.18a shows the microstructure of control specimens (0% CR) without any crumb rubber. Crumb rubber distribution (small black particles in Figure 4.18b-f) confirmed high quality batching process without any segregation. In order to ensure high standard mechanical properties, there should be proper aggregates distribution in the mix. It was also observed that crumb rubber filled up the gaps between coarse aggregates and cement paste thereby showing uniformity in behavior similar to that of sand as fine aggregates.
Figure 4.18: Microstructure of concrete cylinders revealing rubber particle distribution (in black dots); (a) C100-CR0 (0% CR), (b) S90-CR10 (10% CR), (c) S80-CR20 (20% CR), (d) S70-CR30 (30% CR), (e) S60-CR40 (40% CR), and (f) S50-CR50 (50% CR)

4.4.10 Failure pattern of concrete

Failure pattern of various batches of concrete with and without crumb rubber is presented in Figure 4.19. Compressive strength test revealed the failure pattern of these concrete cylinders. Batch S100-CR0 (control) showed combined cone and shear failure (Figure 4.19a). However, concrete cylinders with crumb rubber showed slow and gradual failure compared to brittle failure of control batch (Figure 4.19b-f). Crumb rubber facilitated high deformation while exposed to compressive stress, as it was a soft material compared to sand. Moreover, the failure patterns were mostly cone on both ends and cone on one end with vertical cracks running through the end that were comparable to ASTM C39 (2015) Type 1 and Type 2 failure patterns.
Figure 4.19: Failure pattern of various concrete batches; (a) C100-CRO (0\% CR), (b) S90-CR10 (10\% CR), (c) S80-CR20 (20\% CR), (d) S70-CR30 (30\% CR), (e) S60-CR40 (40\% CR), and (f) S50-CR50 (50\% CR)
Chapter 5

Durability Properties of Rubber Concrete Using Crumb Rubber as Fine Aggregate Replacement

5.1 General

In order to perform better in cold weather and in deleterious chemical exposures, concrete needs to be resistant and durable enough to withstand harsh environments. Moreover, rehabilitation due to durability of concrete causes high maintenance cost and enhances life cycle performance of concrete structures. Consequently, it is a requirement for concrete samples to be resistant to harmful environmental conditions.

The production of rubber-based cement mortar and concrete would obviously offer a green and sustainable product to the construction industry; however, their durability performance needs to be verified before any practical applications. Very few studies were reported on the durability performance of rubber-based concrete. However, inconsistency in the results was found since the quality of rubber products and its associated chemical elements varied enormously.

This chapter primarily focuses on freezing and thawing resistance and chloride permeability of rubber-based concrete with 10%, 20%, 30%, 40%, and 50% crumb rubber replacement. Compressive strength of concrete samples was fixed at 35 MPa with identical mix design, fresh properties, and hardened properties that have been already discussed in Chapter 4. All the test samples for durability, fresh, and hardened are cast simultaneously for maintaining consistency. Moreover, for relative analysis,
rubber-based specimens are compared with control specimens (without crumb rubber as fine aggregate).

5.2 Test Method for Rapid Freeze-Thaw Durability Test

Procedure ‘A’ of ASTM C666 (2015) standard, rapid freezing and thawing in water, was adopted to examine the durability of rubber-based concrete prisms (Figure 5.1). The molds that were used for casting concrete had standard dimensions of 76 mm x 102 mm x 406 mm. Besides, two prisms were cast in each batch of specimens and the average of the two were considered for interpreting durability behavior. Two control specimens were also cast as reference samples and the results were further compared with the samples having crumb rubber as fine aggregate replacement.

Figure 5.1: Freeze-thaw test setup; (a) HUMBOLDT freezing and thawing cabinet, (b) samples after thawing temperature, and (c) samples after freezing temperature

The specimens were moist cured for 14 days before starting the freeze-thaw test. Besides, the specimens were thawed to a target temperature of 2 °C for measuring initial weight, transverse frequency, and dimensions. These parameters were measured in every 36 cycles of continuous freezing and thawing. After measuring the initial values, the samples were submerged in containers filled with clean water. The repeated freeze-thaw test was continued up to 300 cycles and the measurements were
taken in regular intervals of 36 cycles. In general, almost 6 days were required for finishing a complete cycle of 36. Moreover, ASTM C666 (2015) mentioned failure criteria for discarding the samples.

Figure 5.2: Test setup for measuring fundamental transverse frequency

Relative dynamic modulus of elasticity and weight change were the two considered parameters for determining the effects of repeated rapid freezing and thawing test. Figure 5.2 shows a HUMBOLDT Sonometer for measuring fundamental transverse frequency of tested concrete samples. The setup consists of a driver and a pickup. The driver converts electrical power into mechanical vibrations that are transmitted through the specimen. The pickup helps in detecting the resonant frequency. Moreover, durability factor (DF) of the tested specimens were also recorded as one of the primary investigations of the testing process. The numerical values of relative dynamic modulus of elasticity, weight change, and durability factor were calculated by using Equations 5.1, 5.2, and 5.3, respectively that are presented as follows:

\[ P_n = \frac{n_n^2}{n^2} \times 100 \]  

--- (5.1)

Here, \( n = \) fundamental transverse frequency at 0 cycle of freezing and thawing (Hz), \( n_n = \) fundamental transverse frequency after \( n \) cycles of freezing and thawing (Hz), and \( Pn = \) relative dynamic modulus of elasticity after \( n \) cycles of freezing and thawing (in percent).
Here, $W_n = \frac{w_2 - w_1}{w_1} \times 100$ \(---\) (5.2)

Here, $W_n = \text{weight change of the test specimens after } n \text{ cycles of freezing and thawing (in percent)}, w_1 = \text{weight at 0 cycle}, \text{ and } w_2 = \text{weight after } n \text{ cycles.}$

$$DF = \frac{PN}{M} \quad --- \ (5.3)$$

Here, $DF = \text{durability factor of test specimens (in percent)}, P = \text{relative dynamic modulus of elasticity at } N \text{ cycles}, N = \text{number of cycles at which } P \text{ reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated or whichever is less, and } M = \text{specified number of cycles at which the exposure is to be terminated.}$

### 5.3 Test Method for Rapid Chloride Penetration Test

Chloride penetration affects the durability of concrete structures significantly; thereby, resistance to chloride penetration is of immense importance. However, the process for determining chloride penetration is a long-term process. As a result, rapid chloride penetration test (RCPT) was adopted conforming ASTM C1202 (2015). This method determines the electrical conductance of concrete; hence, a rapid indication of concrete’s resistance to chloride ion penetration can be obtained.

The test cell of RCPT is illustrated in Figure 5.3. Concrete specimen (Figure 5.3c) was positioned between two fluid chambers (Figure 5.3a, b) with an electrical potential of 60 V. Electrodes located in NaCl and NaOH were charged with negative and positive charges, respectively. Current was passed through the specimen as the negatively charged chloride ions migrate towards the positive terminal. Since the rate of chloride ion migration depends on the permeability of tested samples, the more permeable the concrete the more current would pass. RCPT apparatus can measure the current during 6 hours that is required for completing the test. A data acquisition system plots the current passed through the samples over time and the area under curve represents the total charge or Coulombs passed. As a result, RCPT test is also
known as Coulomb test. Table 5.1 shows the classification of concrete samples according to the Coulomb value.

Table 5.1: Permeability class of concrete samples based on Coulomb’s value

<table>
<thead>
<tr>
<th>Charge Passed (Coulomb)</th>
<th>Permeability Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>More than 4,000</td>
<td>High</td>
</tr>
<tr>
<td>2,000 – 4,000</td>
<td>Moderate</td>
</tr>
<tr>
<td>1,000 – 2,000</td>
<td>Low</td>
</tr>
<tr>
<td>100 – 1,000</td>
<td>Very low</td>
</tr>
<tr>
<td>Less than 100</td>
<td>Negligible</td>
</tr>
</tbody>
</table>

Figure 5.3: Schematic diagram of a test cell; (a) reservoir for 3% NaCl solution, (b) 50 mm thick test specimen, and (c) reservoir for 0.3N NaOH solution

RCPT test required 100 mm diameter and 50 mm thick concrete specimens after 28 days of moist curing (see Figure 5.4c). Initially, the specimens were cast as standard 100 mm diameter and 200 mm height. Afterwards, the samples were cut using a diamond saw concrete cutter (Figure 5.4a) and thus 50 mm thick samples were obtained (Figure 5.4b). The samples were pre-treated before running the test. First, a vacuum desiccator was used to remove air from concrete voids by using a vacuum pump. Then the samples were soaked in water for 20 hours. This process ensured
maximum permeability while exposed to chloride ions. Besides, three identical specimens were tested within a single batch and the average of the three values are presented. Similar specifications were chosen for control specimens as well and further compared with the rubber-based concrete samples.

5.4 Results and Discussions

5.4.1 Rapid freeze-thaw durability test

Relative dynamic modulus of elasticity helped in determining the quality of concrete samples. In case of repeated freeze-thaw durability test, concrete samples underwent rapid deformation and thereby formed internal cracks and degradation. As such, change in relative dynamic modulus of elasticity was evident during the period of 300 cycles. Figure 5.5 illustrates the test results of relative dynamic modulus of elasticity of rubber-based concrete samples. All the samples showed declining trends as the number of freeze-thaw cycles increased over time.

As indicated in Figure 5.5, relative dynamic modulus of elasticity of all the samples, including the control samples without crumb rubber, declined at 72\textsuperscript{nd} cycles;
however, the drop was significantly lower for specimens with 40% and 50% crumb rubber (S60-CR40 and S50-CR50) compared to the control concrete. For both of these samples, the drop was 3%. On the contrary, the control specimens showed the lowest value (91%) for relative dynamic modulus of elasticity at 72\(^{nd}\) freeze-thaw cycle among all other samples.

![Graph showing relative dynamic modulus of elasticity over freeze-thaw cycles for different rubber-based concrete samples.](image.png)

Figure 5.5: Relative dynamic modulus of elasticity of concrete

Since the declining trend was continuing, the values of relative dynamic modulus of elasticity decreased simultaneously. However, the declining trend was higher for control specimens (S100-CR0) compared to rubber-based concrete samples at 300\(^{th}\) freeze-thaw cycle. Lowest dynamic modulus of elasticity was reported for Batch S100-CR0 (control), which was 66.4%. However, the maximum result (80.3\%) was observed for Batch S50-CR50 (50% crumb rubber replacement). Crumb rubber created porous concrete and thereby entrapped water in the voids. After freezing, water created internal stress. Moreover, micro cracks generated inside the concrete.
due to internal stress of aggregates. Thus, crumb rubber influenced the relative dynamic modulus of elasticity of concrete samples (Salem et al., 2003). Besides, crumb rubber had better tensile and energy absorption capability than natural sand aggregate as it had high deformation capability. As such, rubber-based concrete facilitated contraction and expansion during freezing and thawing environment, respectively. Therefore, crumb rubber in concrete showed better response compared to specimens without it. Decrease in relative dynamic modulus of elasticity was reported in previous studies (Al-Akhras and Smadi, 2004; Zhang et al., 2005; Richardson et al., 2012; Gesoglu et al., 2014a; 2014b; Richardson et al., 2016). Moreover, after 300th freeze-thaw cycles, 10%, 20%, 30%, and 40% crumb rubber replacement showed 70.0%, 71.5%, 73.5%, and 78.0% relative modulus of elasticity, respectively. Therefore, increasing rubber content in the matrix increased the freeze-thaw resistance of the concrete samples. It was also observed that all the samples survived up to the maximum number of cycles (300) and the relative modulus of elasticity was above 60%. According to ASTM C666 (2015), the criteria for terminating the testing samples is 60% of the initial values.

The change in weights over the period of cycles are illustrated in Figure 5.6. For all mixes of concrete, increasing trend was observed at 36th freeze-thaw cycles. The weight gain signified propagation of water filled internal voids (Richardson et al., 2012). Control samples (S100-CR0) underwent the maximum weight change (2.9%) at this stage. However, the control samples gained weight up to 72nd cycles and thereafter it showed a decreasing trend in terms of weight change. Visual observations also confirmed slight spalling of concrete at this point, however, the spalling of concrete continued aggressively afterwards. For freeze-thaw test, weight gain represented the presence of micro cracks and weight loss signified spalling of concrete (Kriesel et al., 1998). Both of these changes, weight gain and loss indicated the ongoing damaging process.

After 300 freeze-thaw cycles, the highest (2.7%) and lowest (1.9%) weight change was observed for Batch S100-CR0 and S50-CR50, respectively. In other words, rubber-based concrete samples exhibited better performance than the control
samples. Crumb rubber hindered the formation of micro cracks within the concrete because of its low modulus of elasticity thereby making the concrete more deformable compared to the control specimens. As a result, weight gain and weight loss (weight change) of rubber-based concrete remained almost constant throughout the freeze-thaw cycles. The findings aligned with previous results having crumb rubber as a replacement of fine aggregate (Savas et al., 1997; Zhang et al., 2005; Zhu et al., 2012; Raghavan et al., 1998).

Figure 5.6: Weight change of concrete after different cycles of freezing and thawing

The durability factor was calculated after finishing the freeze-thaw test at 300 cycles and the results are presented in Figure 5.7. Higher durability factor signified better resistance to freeze-thaw exposure condition. It was observed that crumb rubber-based concrete samples outperformed control samples (concrete without crumb rubber as fine aggregate). Batch S100-CR0 (control) had a durability factor of 66.4%, which is 3.7%, 5.3%, 7.1%, 11.7%, and 13.9% lower than concrete samples having 10%, 20%, 30%, 40%, and 50% crumb rubber, respectively. Moreover, out of
all the rubber-based samples, 50% crumb rubber replacement showed the best result (80.3%).

Figure 5.7: Durability factor of concrete with 0%, 10%, 20%, 30%, 40%, and 50% replacement level of crumb rubber as fine aggregate

Meanwhile visual inspections were done to investigate the extent of damage occurred within the concrete samples. The initial conditions of concrete samples before being placed in the freeze-thaw cabinet are illustrated in Figure 5.8. On the other hand, Figure 5.9 demonstrates the degraded concrete samples after being exposed to 300 freezing and thawing cycles. It can be well observed that all the samples underwent quite significant surface scaling; however, Batch S100-CR0 (control) showed the worst result with significant spalling of concrete as well as pop out of aggregates (circled in black color). Crumb rubber based concrete samples showed remarkably good results with minimal surface scaling. Batch S50-CR50 showed the best results among all other rubber-based concrete samples due to higher content of rubber in the matrix compared to other specimens.
Figure 5.8: Visual inspection of concrete samples before being placed in freeze-thaw cabinet; (a) S100-CR0 (control or 0% crumb rubber), (b) S90-CR10 (10% crumb rubber), (c) S80-CR20 (20% crumb rubber), (d) S70-CR30 (30% crumb rubber), (e) S60-CR40 (40% crumb rubber), and (f) S50-CR50 (50% crumb rubber)

Figure 5.9: Visual inspection of concrete samples after before exposed to 300 freeze-thaw cycles; (a) S100-CR0 (control or 0% crumb rubber), (b) S90-CR10 (10% crumb rubber), (c) S80-CR20 (20% crumb rubber), (d) S70-CR30 (30% crumb rubber), (e) S60-CR40 (40% crumb rubber), and (f) S50-CR50 (50% crumb rubber)
5.4.2 Rapid chloride penetration test

The results of rapid chloride penetration test is presented in Table 5.2 and Figure 5.10. It was observed that crumb rubber incorporation significantly decreased the chloride penetration of concrete samples compared to control specimens (Batch S100-CR0). Moreover, 41%, 55%, 56%, 40%, and 39% reduction in Coulomb’s value was recorded for concrete samples with 10%, 20%, 30%, 40%, and 50% crumb rubber as a replacement of sand. Crumb rubber restricted chloride ions from creating penetration passages. As the voids developed in rubber-based concrete were individual air bubbles due to hydrophobic nature of rubber aggregate. On the other hand, sand exhibited more chloride ions penetration by forming penetration passages. Batch S70-CR30 showed the best performance in terms of low Coulomb’s value (1194.0) among all other samples. Previous studies reported that rubber-concrete performed better while exposed to chloride environment (Al-Akhras and Smadi, 2004; Gupta et al., 2014; Bravo and Brito, 2012; Oikonomou and Mavridou, 2009) that aligned with the findings of this research.

Table 5.2: Charge passed (Coulomb) and permeability class of concrete samples

<table>
<thead>
<tr>
<th>Batch Designation</th>
<th>Crumb Rubber Content</th>
<th>Charge Passed (Coulomb)</th>
<th>Permeability Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>S100-CR0</td>
<td>0%</td>
<td>2686.5</td>
<td>Moderate</td>
</tr>
<tr>
<td>S90-CR10</td>
<td>10%</td>
<td>1574.5</td>
<td>Low</td>
</tr>
<tr>
<td>S80-CR20</td>
<td>20%</td>
<td>1204.0</td>
<td>Low</td>
</tr>
<tr>
<td>S70-CR30</td>
<td>30%</td>
<td>1194.0</td>
<td>Low</td>
</tr>
<tr>
<td>S60-CR40</td>
<td>40%</td>
<td>1612.0</td>
<td>Low</td>
</tr>
<tr>
<td>S50-CR50</td>
<td>50%</td>
<td>1632.5</td>
<td>Low</td>
</tr>
</tbody>
</table>

Moreover, it was observed that crumb rubber increment up to 30% lowered the Coulomb’s value; however, 40% (Batch S60-CR40) and 50% (S50-CR50) crumb rubber replacement showed higher values. Higher crumb rubber incorporation increased the voids in the concrete samples. As a result, crumb rubber assisted in higher chloride ions penetration; hence, Coulomb’s value increased. Besides, all crumb rubber based concrete fall under low permeability class compared to moderate...
permeability of control (Batch S100-CR0) concrete. Lower value of chloride ion penetration reduces the corrosion potential of embedded reinforcement in rubber-based concrete, ensuring great practical importance in case of highly corroded environment.

Figure 5.10: Charge passed (Coulomb) of concrete with 0%, 10%, 20%, 30%, 40%, and 50% replacement level of crumb rubber as fine aggregate
Chapter 6

Conclusions and Recommendations

6.1 Summary

Waste products are rising globally and waste rubber materials are increasing simultaneously, causing environmental degradation. Various avenues are explored in using waste rubber materials effectively; however, civil engineering applications have been less explored. Moreover, rapid urbanization creates substantial demand for readily available concrete as construction material. Crumb rubber has the potential in becoming a reused source of aggregates for producing concrete thereby reducing the carbon footprint.

This study looked into the behavior and characteristics of cement mortar and concrete specimens with different percentage of crumb rubber, replacing sand as fine aggregates. Fresh and hardened properties of cement mortar were the major areas of investigation; however, durability aspects were also examined for concrete samples. Three batches of mortar samples, each involving six different mixes (total 18 mixes) were examined. For concrete, six different mixes were examined. Afterwards, the performance of rubber-based mortar and concrete was compared with the control mix. This chapter summarizes the conclusions of this study in sections. Moreover, limitations and recommendations for future study are also presented.

6.2 Conclusions

Fresh, mechanical, and durability properties of crumb rubber based cement mortar and concrete were investigated with varying crumb rubber replacement levels. The conclusions of this research are briefly summarized as follows.
6.2.1 Mechanical properties of cement mortar with varying crumb rubber replacement levels

•Penetration values decreased with the increased amount of crumb rubber level, irrespective of cement to sand ratio. Thus, confirmed the adverse effect of rubber-based mortar by reducing its workability. Besides, increase in cement to sand ratio decreased the penetration values and workability. Since more sand and crumb rubber was added, the matrix became less workable with a constant water to cement ratio. As a result, Batch A showed higher penetration values compared to Batch B and Batch C mortar samples.

•In case of both initial and final setting time test, the time required to set increased with the increase in crumb rubber content in the mix. All three batches followed the same trend compared to their respective control specimens. Since crumb rubber consisted high amount of hydrophobic Silicon and Zinc on its surface, rubber and water did not mix properly and thereby delayed the setting time of rubber-based mortar.

•Compressive strength tests showed a sharp decline in strength when crumb rubber was used as a replacement of sand in all three batches. The strength reduction, however, was comparable up to 10% of crumb rubber replacement. Since crumb rubber made weak bonds within the cement matrix, compressive strength reduced rapidly. Among all three batches, Batch A showed the highest value; Batch B and Batch C followed simultaneous reduction in their strength. Therefore, increase in cement to sand ratio adversely affected the samples specimens.

•Crumb rubber was low in specific weight compared to natural sand aggregate thereby reducing the overall unit weight of rubber-based mortar samples. Although unit weight reduction followed similar trend in all three batches, Batch C showed the lowest unit weight compared to Batch A and Batch B. Since cement to sand ratio was the most in Batch C, it contained more crumb rubber than other two batches.
• Crumb rubber in mortar also influenced the water absorption capacity of sample specimens. Since crumb rubber entrapped air within the matrix during the batching process, these voids facilitated high water absorption during the curing process. As a result, increasing crumb rubber content increased the water absorption capacity in a similar trend, irrespective of change in cement to sand ratio. However, increase in cement to sand ratio increased the absorption capacity as the matrix contained more crumb rubber. Batch C showed the highest water absorption capacity followed by Batch B and Batch A, respectively.

• As a lightweight material, rubber-based mortar has the immense potential of using it in non-structural applications. Moreover, gradual and non-brittle failure confirms its high-energy absorption capacity; thereby, creating scopes in low strength structural applications.

6.2.2 Mechanical properties of concrete with varying crumb rubber replacement levels

• Slump values of rubber-based concrete decreased with the increased amount of crumb rubber in the mix. However, air content increased with the increased amount of rubber particle. Crumb rubber repelled water and entrapped air within the voids thereby causing these phenomena.

• Compressive strength showed a significant decline when crumb rubber was used more than 20%. An increased amount of rubber in the matrix caused weak interfacial bonds between the cement matrix and the rubber particles. However, both 10% and 20% crumb rubber showed comparable results with the control batch surpassing the design strength of 35 MPa. Even though the strength reduction was significant, up to 20% crumb rubber replacement fulfilled the expected design standard. In order to encourage massive usages of environment friendly rubber-concrete, federal and provincial government could provide incentives to the concrete industry and consumers.
• Crumb rubber based concrete, however, showed better strain capability compared to cylinders without any rubber. Thus, rubber-based concrete deformed more compared to regular aggregate based concrete before coming to a complete failure. This phenomenon caused slow and gradual failure of concrete cylinders thereby implying a good material property.

• Splitting tensile strength and flexural strength of rubber-based concrete samples reduced with an increase in replacement of crumb rubber. However, 10% crumb rubber replacement showed a superior behavior compared to control batch (S100-CR0) showing enhanced tensile strength capacity. Moreover, the strength reduction was comparatively lower compared to compressive strength reduction.

• Unit weight of crumb rubber based concrete decreased with the increase in crumb rubber, whereas water absorption capacity showed the opposite trend. Low relative density of crumb rubber reduced the unit weight of concrete significantly whereas entrapped air voids caused higher water absorption capacity.

6.2.3 Durability of concrete with varying crumb rubber replacement levels

• Crumb rubber significantly enhanced the freeze-thaw resistance freeze-thaw capability and chloride resistance of concrete samples. Increasing rubber content in the mix enhanced the concrete’s freezing and thawing capability; however, up to 30% crumb rubber replacement showed the best resistance to chloride exposure.

• While exposed to rapid freezing and thawing cycles, control samples (Batch S100-CR0) underwent significant surface scaling and concrete spalling. Moreover, relative dynamic modulus of elasticity and weight loss was significant compared to concrete with crumb rubber. High-energy absorption capability of crumb rubber enhanced the freeze-thaw capacity.
• Crumb rubber formed a barrier to chloride penetration thereby creating low permeable concrete. It helped in lowering the Coulomb value up to 56% for 30% crumb rubber replacement. High chloride resistance can make rubber concrete an alternative construction material where corrosion is an issue.

6.3 Research Contributions

This research investigated the feasibility of using crumb rubber as fine aggregates in both cement mortar and concrete. The experimental results and analyses revealed that crumb rubber could be used efficiently in cement mortar with a replacement level of 10%. On the other hand, up to 20% crumb rubber in concrete showed comparable results with the control specimens having no crumb rubber in the matrix. In case of freeze-thaw resistance and chloride penetration, rubber-based concrete showed superior qualities over conventional aggregate based concrete. Consequently, crumb rubber can become a suitable alternative to conventional fine aggregates up to a certain replacement level, thereby conserving the environment and utilizing rubber waste as a sustainable construction material.

6.4 Limitations of This Study

Because of unavailability of proper equipment, materials, and time restriction, this study has the following limitations.

• The mixing of a single batch of concrete was done in multiple times due to low concrete mixer’s capacity. This led to variable and inconsistent results within the same batch of samples.

• Due to time limitation, sample size had to be reduced in this research. Instead of having 10% interval, it could be reduced to 5% for better comprehensive ideas about the material. Moreover, the investigated parameters were reduced due to time constraint.
• The supplied crumb rubber had almost identical size, thereby making the materials gap-graded. As such, manual mixing of different sizes of crumb rubber was done to fit the materials within CSA acceptable well-graded range.

### 6.5 Recommendations for Future Research

Crumb rubber based concrete is definitely a green solution to the sustainable development of construction materials. The results in this study would grow interest among researchers towards a waste-free era. Crumb rubber has the potential to decrease the demand for naturally sourced aggregates. Globally the natural sources of aggregates are becoming scarce due to high-demand in concrete industry. Since rubber in concrete is considerably a new concept, more research is required before recommending the product as an alternative solution to natural aggregate based concrete. Some future investigations may include:

- Different sources and sizes of crumb rubber might alter the properties of rubber-based concrete. Moreover, replacement levels can be reduced up to 20% with more intervals, thereby giving a comprehensive idea about its behavior.

- Compressive strength reduction hinders structural applications of crumb rubber based concrete. Modifications of crumb rubber surface using chemical treatment, plasma treatment, and ozone treatment can become a significant research area to work on. These methods might increase the contact angles between rubber and cement paste thereby ensuring good bonding.

- Instead of using cement as a binder, fly ash and cement both can be used in different percentage as an alternative to increase the concrete’s mechanical strength.

- This research focused only on freeze-thaw and chloride penetration of crumb rubber based concrete. Sulfate attack and carbonation can be researched as a long-term examination of concrete’s durability properties.
• Crumb rubber has superior energy absorption capabilities over natural aggregates. Therefore, dynamic loading test and impact test may incorporate vital properties towards the development of this material.

• Reusing rubber-based concrete as recycled coarse aggregates (RCA) can become a new avenue to research.
Bibliography


