Abrasion and Impact Resistance of Concrete under Arctic Conditions

By

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ABSTRACT

This research program aims to investigate the mechanical properties, impact resistance, and abrasion resistance of steel fibers reinforced concrete under cold temperatures. The abrasion and impact resistance of steel fiber reinforced concrete were also evaluated before and after exposure to salt scaling. The studied parameters are the type of concrete (self-consolidated concrete and vibrated concrete), type of steel fibers (SFs) (coated and uncoated), SFs end conditions (needle, single-hooked ends and double-hooked ends), length of SFs (35 mm and 60 mm), volumes of SFs (0%, 0.35%, and 1%), saturation condition, coarse aggregate size (10 mm and 20 mm), coarse to fine aggregate ratio (0.7 and 2), and cement content (300 kg/m^3 and 550 kg/m^3). The mechanical properties of concrete were evaluated by conducting compressive strength, splitting tensile strength (STS) and flexural strength (FS) tests. The impact resistance was assessed by conducting two tests; drop weight test and flexural impact test. Meanwhile, the abrasion resistance of concrete was evaluated by performing rotating cutter test and sand blasting test. The results showed that salt scaled concrete specimens exhibited a considerable reduction in the impact and abrasion resistance compared to non-scaled concrete specimens. However, adding SFs (especially coated SFs) alleviated this reduction and contributed to improve the abrasion and impact resistance of salt scaled concrete surface. The results also revealed that decreasing the temperature below the room temperature (25º C) contributed to enhancing the compressive strength, STS, FS, abrasion resistance, and impact resistance of concrete mixtures. In the meantime, the effect of cold temperatures in enhancing the mechanical properties and abrasion resistance was more pronounced in the saturated samples compared to unsaturated samples. The results also showed that despite the negative effect of cold temperature in increasing the brittleness of concrete, using SFs helped to alleviate the low temperature brittleness of concrete and improved its mechanical properties and impact resistance.

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Co-Authorship Statement

I, Rowyda A. Zaki, hold the principal author status for all the manuscript chapters (Chapters 2 - 4) in this thesis. However, each manuscript is co-authored by my supervisors (Profs. Assem A. A. Hassan, and Bruce Colbourne) and co-researcher (Basem H. AbdelAleem), whose contributions have facilitated the development of this work significantly. Dr. Assem A. A. Hassan and Dr. Bruce Colbourne presented the idea for this project to me and it was my task to carry out the work necessary to complete this manuscript and fulfill the master's requirements.

In the papers presented in Chapters 2, 3 and 4, I performed all experimental work including the preparation of the 11 mixtures and the tests performed. I then collected the data from those tests, analyzed the data and formulated the results and conclusions presented in this thesis.

My co-researcher Dr. Basem H. AbdelAleem was present and offered assistance in the experimental phase and assisted me in finalizing the manuscripts for each paper presented.

Described below is a detailed breakdown of the work facilitated by my team and me.

- Paper 1 in Chapter 2: Rowyda A. Zaki, Basem H. AbdelAleem, Assem A. A. Hassan and Bruce Colbourne, "The interplay of abrasion, impact, and salt scaling damage in fiber reinforced concrete" Published in Magazine of Concrete research.

I was the primary author, with second, third and fourth authors contributing to the idea, its formulation, development, and refinement of the format in which it has been presented.

- Paper 2 in Chapter 3: Rowyda A. Zaki, Basem H. AbdelAleem, Assem A. A. Hassan and Bruce Colbourne, "Mechanical Properties and Impact Resistance of Fiber

Reinforced Concrete under Cold Temperature" submitted in the Journal of Materials in Civil Engineering, ASCE.

I was the primary author, with second, third and fourth authors contributing to the idea, its formulation, development, and refinement of the format in which it has been presented.

- Paper 3 in Chapter 4: Rowyda A. Zaki, Basem H. AbdelAleem, Assem A. A. Hassan and Bruce Colbourne, "Abrasion Resistance of Fiber-Reinforced Concrete under Cold Temperatures" submitted in the ACI Material Journal.

I was the primary author, with second, third and fourth authors contributing to the idea, its formulation, development, and refinement of the format in which it has been presented.

April 20, 2020

Rowyda A. Zaki   Date

Table of Contents

List of Tables

List of Figures

List of Symbols, Nomenclature or Abbreviations

A = the area of abraded cavities, cm^2.

A_c = the abrasion coefficient, cm^3/cm^2

ASTM = American Society for Testing and Materials

C/F= Coarse-to-Fine Aggregate

DH= single-hooked ends

FA= Fly Ash

f_c' = Characteristic Compressive Strength of Concrete (MPa)

FS= Flexural Strength (MPa)

G = acceleration due to gravity (9·81 m/s^2)

h = drop height

HRWRA= High-Range Water-Reducer Admixture

I_{Ea} = absorbed impact energy after exposure to salt scaling

I_{Eb} = absorbed impact energy before exposure to salt scaling.

IE= Impact energy

ITZ= Interfacial Transition Zone

m = mass of drop hammer

M_{La} = abrasion mass loss after exposure to salt scaling

M_{Lb}= abrasion mass loss before exposure to salt scaling

MK= Metakaolin

N = number of drops

N_1 = number of drops required to cause the first crack

N_2 = number of drops required to cause the failure crack

S_{AR}= scaling factor related to the abrasion resistance

S_{IE}= scaling factor associated with absorbed impact energy

SCC= Self-Consolidating Concrete

SCMs= Supplementary Cementing Materials

SFVC= Steel fiber vibrated concrete

*SFSC*C= Steel fiber self-consolidating concrete mixtures

SH= single-hooked ends

SR= Segregation Resistance Factor (%)

STS = Splitting Tensile Strength of Concrete (MPa)

V = the abraded volume, cm^3

V_C= Vibrated Concrete

V_f = volume fraction of fibres

w/b= Water-to-Binder Ratio

1 Introduction and Overview

Concrete structures in arctic regions such as offshore structures and bridge piers are significantly affected by the cold temperature, freezing and thawing cycles with penetration of salt into the concrete, and tidal cycles with different water levels. This research aims to improve the concrete properties in cold temperature and enhance its behavior under the effect of salt scaling.

1.1 Background

Self-consolidating concrete (SCC) is a highly flowable concrete that can spread under its own weight with no need of vibration. SCC is designed to maintain high workability and passing ability (Daczko, 2002; Skarendahl and Petersson, 2001) that could fill the structures with congested reinforcement without segregation. These advantages allow SCC to be widely used in sections where it is difficult to access vibration during casting. In addition, it is also used to accelerate the construction process in non-congested sections.

Steel fibers (SFs) are used to enhance the concrete ductility, tensile strength, flexural strength, energy absorption, flexural toughness, and impact resistance of concrete under normal temperatures (Altun and Aktas, 2013; Nia et al. 2012; Khaloo et al. 2014; Ismail and Hassan, 2016a). Using different SFs types, lengths, and volumes has proven to enhance concrete performance in small scale and large-scale testing. Murali et al. (2016) found that using up to 1.5% crimped SFs enhanced the flexural strength and impact resistance of concrete by 50.7% and 63%, respectively. Meanwhile, using the hooked-end SFs improved the flexural strength and impact resistance by 55% and 72%, respectively. On the other hand, despite the advantages of adding SFs to the concrete, it was found that using SFs showed a negative effect on the fresh properties of concrete mixtures.

Supplementary cementitious materials (SCMs) with high pozzolanic reactivity appeared to have a significant role in enhancing concrete microstructure, which in turn improves the overall mechanical properties. SCMs also proved to enhance the salt scaling resistance, abrasion resistance, and impact resistance of concrete (Hassan et al. 2000; Blomberg, 2003; Bouzoubaâ et al. 2008). Metakaolin (MK) is considered one of the most effective SCMs that can be used to significantly improve concrete strengths. Madandoust and Mousavi, (2012) observed that adding 15% MK increased the compressive strength and splitting tensile strength (STS) by 27% and 11.1%, respectively, while this increase reached up to 49.2% and 17%, respectively, when 20% MK was used. MK also has an advantage of enhancing mixture viscosity, which in turn improves particle suspension and reduce the risk of segregation. On the other hand, in order to develop a successful SCC mixture, a balanced viscosity with sufficient flowability should be obtained. Using fly Ash as a SCMs has proven to enhance the mixture flowability.

The durability of concrete structures in cold regions is affected by the exposure to freezing and thawing in the presence of salt. Exposing concrete to freezing and thawing in the presence of salt can result in damage to the bond between aggregate and cement paste, which leads to cracking and surface crumbling. The deterioration of the concrete surface also increases the probability of saline water penetration, which can induce corrosion of the steel reinforcement. Concrete surfaces can also be subjected to abrasion loading. Continuous abrasion of concrete surfaces eventually causes the complete wearing of concrete cover and disintegration of aggregate particles at the surface, which leads to a severe decay in concrete strength (Ridgley et al., 2018; Sonebi and Khayat, 2001). In addition to abrasion and salt scaling, concrete may also be subjected to impact loading. For example, offshore structures, bridge piers, and harbor platforms in cold regions, which are typically exposed to freezing and thawing in the presence of salt, are also exposed to the abrasive effects of sand, gravel, rocks, and ice flow in addition to impact loading from iceberg and ship collisions (Ismail and Hassan, 2016a; AbdelAleem et al., 2018; Chen and May, 2009). This combined effect of damage may induce significant deterioration, negatively affecting the durability and service life of the structure. Therefore, this sheds light on the need to develop mixtures with maximum impact and abrasion resistance in the presence of salt-scaling action.

1.2 Research Objectives and Significance

Several previous studies have investigated the abrasion and impact resistance of different concrete mixtures under normal temperatures. Moreover, the salt scaling resistance of different concrete mixtures was also extensively investigated. However, some concrete structures are exposed to abrasion and impact loads after exposing to salt scaling. And, similarly, some concrete structures may experience salt scaling after exposure to abrasion and impact loads.

The current study aims to investigate the interplay of abrasion, impact, and salt scaling damage in fiber reinforced concrete. In addition, the effect of cold temperatures on the mechanical properties, impact resistance, and abrasion resistance of concrete mixtures was also investigated.

The main objectives of this study were as follows:

- Study the salt scaling resistance of abraded and non-abraded concrete surfaces.
- Investigate the abrasion resistance and impact resistance of concrete before and after exposure to salt scaling.
- Providing a comprehensive investigation regarding the mechanical properties and impact resistance of different concrete mixtures under cold temperatures.
- Providing an information regarding the effect of SFs on alleviating the brittleness of concrete and enhancing the overall performance under cold temperatures.
- Investigate the effect of cold temperature on the abrasion resistance of concrete mixtures with different saturation conditions.

The first two objectives were discussed in more detail in Chapters 2. The third and fourth objectives were investigated in more detail in Chapter 3. The fifth objective is discussed in detail in Chapter 4. The fifth objective elaborated at length in chapter 4. The current research investigated the combined effect of abrasion/impact loading with the exposure to salt scaling in addition to evaluating the concrete performance at subnormal temperature using different types, lengths, and volumes of SFs, which have not been studied in previous researches.

1.3 Thesis Outline

The thesis consists of five chapters described as follows:

Chapter 1 presented the background, objectives, significance and the scope the research.

Chapter 2 "The interplay of abrasion, impact, and salt scaling damage in fiber reinforced concrete" discussed the effect of salt scaling on abrasion resistance and impact resistance of concrete in detail.

Chapter 3 "Mechanical properties and impact resistance of fiber reinforced concrete under cold temperature" has a detailed study on the mechanical properties and impact resistance of concrete at low temperature.

Chapter 4 "Abrasion resistance of fiber reinforced concrete under cold temperature" studied in detail the abrasion resistance and mechanical properties of steel fiber reinforced concrete with different saturation conditions under cold temperature.

Chapter 5 contains the summary of this study.

1.4 Chapter References

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2 The Interplay of Abrasion, Impact, and Salt Scaling Damage in Fiber Reinforced Concrete

2.1 Abstract

This investigation aims to study the abrasion and impact resistance of fiber reinforced concrete before and after exposure to salt scaling. Different types of steel fibers (SFs) and different mixture compositions were used to improve the strength and resistance of the tested mixtures. The variables were the type of SFs, surface condition of SFs (coated and uncoated), length of SFs (35 mm and 60 mm), volume of SFs in the mixture (0%, 0.35%, and 1%), ends condition of SFs (single-hooked ends (SH) and double-hooked ends (DH)), coarse aggregate size (10 mm and 20 mm), coarse-to-fine aggregate ratio (C/F) (0.7 and 2), and cement content (300 kg/m^3 and 550 kg/m^3). The results indicated that after the exposure to salt scaling, the uncoated SFs experienced some rust, causing more deterioration and higher surface scaling compared to coated SFs. The results also revealed that the samples that were exposed to salt scaling showed a noticeable reduction in the abrasion and impact resistance compared to samples that were not exposed to salt scaling. Adding SFs, however, alleviated this reduction and contributed to enhancing the impact and abrasion resistance of salt scaled concrete surfaces.

2.2 Introduction

The durability of concrete structures in cold regions is affected by the exposure to freezing and thawing cycles in the presence of salt. Exposing concrete to freezing and thawing in the presence of salt can result in damage to the bond between aggregate and cement paste, which leads to cracking and surface crumbling (Shang et al., 2009; Sutter et al., 2008; Mu et al., 2002). The deterioration of the concrete surface also increases the probability of saline water penetration, which can induce corrosion of the steel reinforcement. Concrete surfaces can also be subjected to abrasion loading. Continuous abrasion of concrete surfaces eventually causes the complete wearing of concrete cover and disintegration of aggregate particles at the surface, which leads to a severe decay in concrete strength (Ridgley et al., 2019; Sonebi and Khayat, 2001). In addition to abrasion and salt scaling, concrete may also be subjected to impact loading. For example, offshore structures, bridge piers, and harbor platforms in cold regions, which are typically exposed to freezing and thawing in the presence of salt, are also exposed to the abrasive effects of sand, gravel, rocks, and ice flow in addition to impact loading from iceberg and ship collisions (Ismail and Hassan, 2016; AbdelAleem et al., 2017; Chen and May, 2009). This combined effect of damage may induce significant deterioration, negatively affecting the durability and service life of the structure. Therefore, this sheds light on the need to develop mixtures with maximum impact and abrasion resistance in the presence of salt-scaling action.

Salt scaling of concrete can be defined as a superficial damage resulting from freezing a saline solution on the surface of the concrete (Valenza and Scherer, 2007; Ghazy and Bassuoni, 2018). This damage is not analogous to conventional freeze and thaw damage, which decays the stiffness and strength of concrete. However, the surface damage makes the concrete surface more sensitive to the ingress of fluids and chemical attacks, which can significantly deteriorate the concrete integrity. In addition, the damage of concrete surface is not visually pleasing due to the exposure of coarse aggregate. Using supplementary cementitious materials (SCMs) can help enhance the resistance of concrete surfaces to salt scaling (Bouzoubaa et al., 2008; Hassan et al., 2000; Blomberg, 2008). Metakaolin (MK) is one of the SCMs that has the ability to reduce concrete porosity and increase the fracture toughness of interfacial transition zone (ITZ), which helps to enhance concrete strength and, in turn, increase resistance to salt scaling (Nili and Zaheri, 2011; Ismail and Hassan, 2016; Abouhussien and Hassan, 2015). Hassan et al. (2012) studied the effect of using different percentages of MK and silica fume (as a partial replacement of cement) on the salt scaling resistance of concrete. Their results indicated that the salt scaling resistance of concrete increased as the percentage of MK increased up to 20%, while further increase in the percentage of MK beyond 20% showed lower salt-scaling resistance.

Although using steel fibers (SFs) have shown an insignificant effect on the resistance of concrete to salt scaling, adding SFs to concrete mixtures contributed to improving the impact and abrasion resistance of concrete (Quanbing and Beirong, 2005; Alavi Nai et al., 2012; Ismail et al., 2018; Atis et al., 2009). The volume of SFs in the mixture was found to influence the abrasion resistance of concrete. For example, Atis et al. (2009) studied the effect of using different volume of SFs on the abrasion resistance of concrete. Their results indicated that the abrasion resistance of concrete increased as the volume of SFs increased, in which using 0.25%, 0.5%, 1%, and 1.5% SFs reduced the mass loss by 6.7%, 7.5%, 25.2%, and 29.5%, respectively, indicating higher abrasion resistance. The strength of coarse aggregate has also proven to be an important factor in abrasion resistance of concrete. The high strength and hardness of coarse aggregate can provide high abrasion resistance to concrete. Laplante et al. (1991) investigated the abrasion resistance of concrete developed with different types of aggregates including granite, dolomite, and limestone. Their study indicated that the highest abrasion resistance was recorded when granite aggregate (with the highest strength and hardness) was used, while the lowest resistance was observed when limestone (with the lowest strength and hardness) was used.

Adding SFs to concrete mixtures showed a significant improvement in the mechanical properties such as compressive strength, splitting tensile strength (STS), and impact resistance (Song and Hwang, 2004; Olivito and Zuccarello, 2010; Khaloo et al., 2014; Erdem et al., 2011). Nia et al. (2012) studied the impact resistance of vibrated concrete reinforced with different percentages of SFs. Their research reported that using 0.5% and 1% SFs increased the impact resistance by 8.6% and 9.8%, respectively. Ismail and Hassan (2017) investigated the effect of using different SF lengths on the impact resistance of rubberized concrete mixtures. They found that increasing the SF length from 35 mm to 60 mm at the same volume of SFs slightly increased the number of drops to produce initial crack and failure crack. Using double-hooked ends SFs was also found to have some effects on the mechanical properties of concrete. An increase of up to 60% and 88% in the STS and flexural strength, respectively, was found when 1% double-hooked ends SFs was used in recycled aggregate concrete (Afroughsabet et al., 2017).

In this study, the combined effect of salt scaling and abrasion or impact loading was investigated. The tested properties were (a) salt scaling resistance of pre-abraded and non-abraded concrete specimens; (b) abrasion resistance of salt scaled and non-scaled concrete specimens; and (c) impact resistance of salt scaled and non-scaled concrete specimens. The investigated mixtures included two coarse aggregate sizes (10 mm and 20 mm), two coarse-to-fine aggregate ratios (0.7 and 2), and different types, lengths, and volumes of SFs.

2.3 Research Significance

Several research studies have investigated the impact and abrasion resistance of different concrete mixtures in the lab environment. Also, many research studies have investigated the behavior of different concrete mixtures under salt scaling. However, some concrete structures are subjected to either abrasion or impact loads after enough exposure to salt scaling. Similarly, some concrete structures may be exposed to salt scaling after the exposure to abrasion or impact loads. By reviewing the current literature, no available research studies have investigated the combined effect of abrasion/impact loading with the exposure to salt scaling. This research covers this knowledge gap and presents some recommendations to improve the abrasion and impact resistance before and after the exposure to salt scaling by using different types, lengths, and volumes of SFs in mixtures. The authors believe that this study will immensely help to improve the durability of concrete mixtures in cold regions.

2.4 Experimental Program

2.4.1 Material Properties

Type GU Portland cement similar to ASTM C150 (2012b), fly ash (FA) similar to ASTM C618 Type F (2012a), and metakaolin (MK) similar to ASTM C618 class N (2012) were used as binders in the developed mixtures. The chemical and physical properties of these materials are shown in Table 2-1 Crushed stones, with a maximum aggregate size of 10 mm and 20 mm, and natural sand were used as coarse and fine aggregate, respectively. These aggregates had a specific gravity of 2.6 and absorption of 1%. Figure 2-1 shows the gradation of 10 mm and 20 mm crushed stones and natural sand. Four types of steel fibers

(SFs) were used in this investigation. The first type of SFs is needle fibers (NYCON-SF) with a length of 13 mm (SF13) and coated with copper to resist corrosion. The second and third types of SFs are single-hooked ends SFs (Dramix 3D) with a length of 35 mm and 60 mm, respectively (SF35 and SF60). The fourth type is double-hooked ends SFs (Dramix 5D) with a length of 60 mm (SF60-DH). Table 2-2 shows the physical and mechanical properties of SFs used, and Figure 2-2 shows their configuration and geometry. The required flowability of tested mixtures was obtained by using polycarboxylate-based high-range water-reducer admixture (HRWRA) similar to ASTM C494 (2013) with a specific gravity of 1.2, volatile weight of 62%, and pH of 9.5.

Table 2-1 Chemical and physical properties of SCMs used

Chemical properties (%)	Cement	FA	MK
SiO_2	19.64	52	51-53
Al_2O_3	5.48	23	42-44
Fe_2O_3	2.38	11	<2.2
CaO	62.44	5	<0.2
MgO	2.48	-	<0.1
Na_2O	-	-	<0.05
K_2O	-	2	<0.40
C_3S	52.34	-	-
C_2S	16.83	-	-
C_3A	10.50	-	-
C_4AF	7.24	-	-
Loss on ignition	2.05	0.21	0.95
Physical properties			
Specific gravity	3.15	2.38	2.56
Blaine fineness (m^2/kg)	410	20000	1390

Table 2-2 Characteristics of the fibers used

Fibers used	Type	Length (mm)	Diameter/Equivalent Diameter (mm)	Specific Gravity	Tensile Strength (Mpa)	End Conditions
SF13	Steel fiber	13	0.2	7.85	1900	Needle
SF35	Steel fiber	35	0.55	7.85	1150	Single hooked
SF60	Steel fiber	60	0.9	7.85	1150	Single hooked
SF60-DH	Steel fiber	60	0.9	7.85	1150	Double hooked

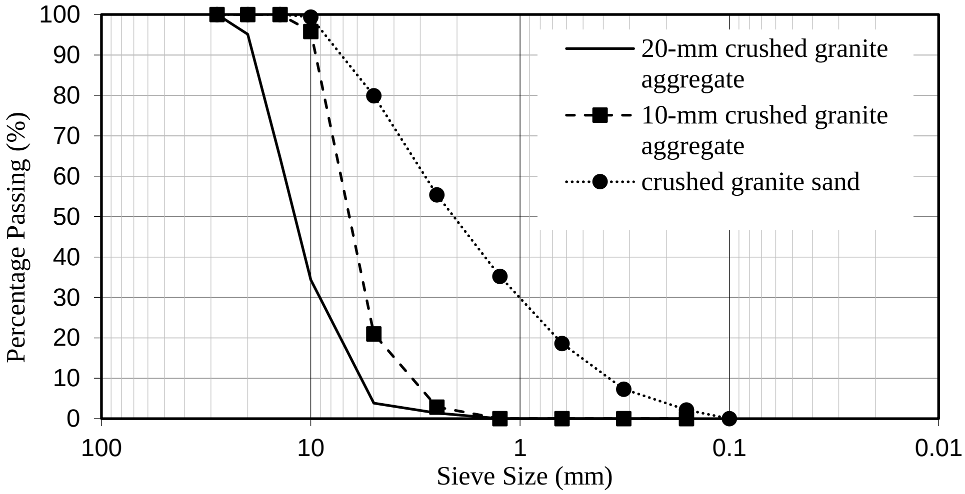

Figure 2-1 Gradation curves for both fine and coarse aggregates

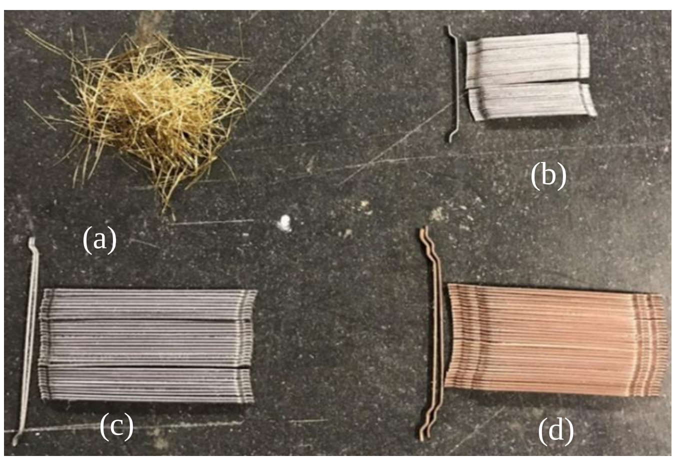

Figure 2-2 Configuration and geometry of fibers used: (a) SF13, (b) SF35, (c) SF60, (d) SF60-DH

2.4.2 Mixtures Development

The main objective of this investigation was to study the effect of using SFs on the impact and abrasion resistance of concrete before and after exposure to salt scaling. The tested mixtures consisted of two self-consolidating concrete (SCC) mixtures, two SF self-consolidating concrete mixtures (SFSCC), four vibrated concrete (VC) mixtures, and three SF vibrated concrete (SFVC) mixtures. In order to ensure enough flowability with a target slump flow of 700 ± 50 mm and no visual sign of segregation, both SCC and SFSCC mixtures needed a total binder content of at least 550 kg/m^3 and a minimum water-to-binder ratio (w/b) of 0.4. The binder content (550 kg/m^3) consisted of 50% cement, 30% FA, and 20% MK. These ratios were selected based on preliminary trial mixtures to satisfy the requirement of the flowability, passing ability, and particle suspension as per European Guidelines for Self-Consolidating Concrete EFNARC (2005). The maximum percentage of SFs that could be used in SFSCC mixtures was found to be 0.35%. Further increase in the percentage of SFs resulted in a significant drop in the fresh properties of concrete mixtures. Table 2-3 shows the mixtures compositions for all tested mixtures.

The experimental program was designed based on the following:

- Mixture M2 compared to M1. These mixtures were selected to study the effect of using different coarse aggregate sizes on the abrasion and impact resistance of concrete before and after exposing to salt scaling.
- Mixtures M3 and M4 were SFSCC developed to investigate the effect of using different fiber types on the combined and uncombined action of salt scaling with abrasion or impact resistance of concrete.

- Mixtures M6 compared to M5. These two mixtures are VC selected to study the effect of using a larger coarse-to-fine aggregate ratio (C/F) on the investigated properties.
- Mixtures M7 and M8 were SFVC developed with the maximum percentage of SFs that could be used without any sign of fiber clumping, but with different fiber lengths to investigate the effect of fiber length on the studied properties.
- Mixtures M8 and M9 were SFVC developed with the same percentage of SFs and same fiber length, but the end conditions were different. The fibers used in mixture M9 were double-hooked ends, which may provide better bonds with concrete matrix compared to single-hooked fibers used in M8. These mixtures were selected to study the effect of ends condition on the impact and abrasion resistance of salt scaled and non-scaled concrete.
- Mixtures M10 and M11 were VC mixtures developed with different cement content (300 kg/m^3 and 550 kg/m^3) and no supplementary cementing materials. Meanwhile, the w/b ratio and C/F ratio were kept the same for both mixtures (0.4 and 0.7, respectively). These mixtures were selected to examine the effect of different concrete strengths on the impact and abrasion resistance of concrete before and after salt scaling action.

It should be noted that M6 to M11 where selected as VC as it was not possible to obtain the required self-compactability of SCC with such high C/F ratio or high percentage of SFs in the mixture. The mixtures were designated according to the type of concrete (SCC and VC) and the different mixture parameters (C/F ratio, coarse aggregate size, volume/length of SFs, and SFs ends condition). For example, the SCC mixture with 20 mm coarse aggregate size would be labelled SCC-20, while the VC mixture with 1% 60 mm double-hooked SFs would be labelled VC-1SF60-DH. It is worth noting that the fiber percentage (1%) in this stage was based on a preliminary trial mixtures stage to obtain acceptable mixture consistency (no visual sign of fiber clumping) and reasonable compressive strengths for structural application (more than 30 MPa). Table 3 shows the mixture proportions of all tested mixtures.

The compressive strength and splitting tensile strength (STS) tests were conducted as per ASTM C39 (2011a) and ASTM C496/C496M (2011b) standards, respectively. Each test was conducted on three identical cylinders, with a diameter of 100 mm and height of 200 mm, for each mixture after being moist cured for 28 days.

Table 2-3 Proportion details of tested mixtures

Mix #	Mixture	Cement (kg/m^3)	SCM (Type)	SCM (kg/m^3)	C/F ratio	w/b	C. A. (kg/m^3)	F. A. (kg/m^3)	Fiber (V_f%)
M1	SCC	275	MK+FA	110+165	0.7	0.4	620.3	886.1	-
M2	SCC-20	275	MK+FA	110+165	0.7	0.4	620.3	886.1	-
M3	SCC-0.35SF13	275	MK+FA	110+165	0.7	0.4	620.3	886.1	0.35
M4	SCC-0.35SF35	275	MK+FA	110+165	0.7	0.4	620.3	886.1	0.35
M5	VC	275	MK+FA	110+165	0.7	0.4	620.3	886.1	-
M6	VC-2C/F	275	MK+FA	110+165	2	0.4	1006	503	-
M7	VC-1SF35	275	MK+FA	110+165	0.7	0.4	620.3	886.1	1
M8	VC-1SF60	275	MK+FA	110+165	0.7	0.4	620.3	886.1	1
M9	VC-1SF60-DH	275	MK+FA	110+165	0.7	0.4	620.3	886.1	1
M10	VC-300	300	--	--	0.7	0.4	840.2	1200.2	-
M11	VC-550	550	--	--	0.7	0.4	648.1	925.9	-

2.4.3 Salt Scaling Test

All specimens were moist cured for 28 days. After the curing process was completed, a salt scaling resistance test was conducted on pre-abraded and non-abraded samples. The pre-abraded samples were subjected to both rotating-cutter and sandblasting abrasion tests before the salt scaling, while the non-abraded samples were exposed to salt scaling right after the end of the curing time. The abrasion tests were carried out to study the effect of abrasion on the resistance of concrete to salt scaling. In the salt scaling test, the surface of the samples was covered with approximately 6 mm of calcium chloride solution, then subjected to 50 cycles of freezing and thawing. At the end of the test, the deterioration of the sample surface was determined using mass loss and visual rating (1-5) according to ASTM C672 (2003).

2.4.4 Abrasion Resistance Test

Two abrasion tests have been conducted to evaluate the abrasion resistance of concrete mixtures before and after exposure to salt scaling. The tests were carried out as follows:

1. Rotating-cutter test: This test was performed according to ASTM C944 (2012) to evaluate the behavior of concrete subjected to abrasion force such as heavy traffic on highways and concrete bridges. In this test, the concrete sample was first weighed to the nearest 0.1 g, then fastened securely in a rotating-cutter drill press. At the end of the test, the concrete specimen was removed from the device and air-blown to remove debris then the weight of the specimen was determined. These procedures were repeated on two different surface areas of concrete specimens (See **Figure 2-3**).

2. Sandblasting test: This test was conducted according to ASTM C418 (2012a) and was used to simulate the action of waterborne abrasives and abrasives under traffic on concrete surfaces. In this test, the concrete sample was initially weighed to the nearest 0.1 g, then placed in the sandblast cabinet normal to the nozzle axis at a distance of 75 ± 2.5 mm. At the end of the test, the final weight of the specimen was determined to the nearest 0.1 g to calculate the mass loss (See Figure 2-3).

Figure 2-3 Tested specimen in abrasion test

2.4.5 Impact Resistance Test

The impact resistance test in this investigating was conducted according to ACI committee 544 (1999). This test was conducted on salt scaled samples (exposed to salt scaling) and non-scaled samples (not exposed to salt scaling) to study the effect of salt scaling on the impact resistance and surface indentation/shattering. In this test, a 4.45 kg hammer was dropped from a height of 457 mm on a 63.5 mm steel ball rested at the center of the top surface of the concrete specimen. While the test was running, the surface indentation was observed and the average indentation depth was measured. The number of drops that resulted in initial crack and failure crack recorded, and the impact energy (IE) was calculated using Eq. (1):

$$IE = N\,mgh \tag{1}$$

Where N is the number of drops, m is the mass of the drop hammer (4.45 kg), g is the gravity acceleration (9.81 m/s2), and h is the drop height (457 mm).

2.5 Discussion of Test Results

2.5.1 Compressive Strength and Splitting Tensile Strength

Figure 2-4 shows the 28-day compressive strength and STS for all tested mixtures. From the figure, it can be seen that using a larger coarse aggregate size reduced the compressive strength and STS of concrete mixtures. For example, increasing the coarse aggregate size from 10 mm to 20 mm reduced the compressive strength and STS strength by 5.5% and 6.7%, respectively. Meanwhile, increasing the C/F ratio showed a considerable reduction in the compressive strength and STS. For instance, increasing the C/F ratio from 0.7 to 2 reduced the compressive strength and STS by 12.1% and 14.6%, respectively. This may be attributed to the increase in the volume of interfacial transition zone (ITZ) between mortar and coarse aggregate, which heightened the weakest part of the concrete matrix and, in turn, negatively affected the concrete strength. It should be noted that although increasing the coarse aggregate size and C/F ratio have a similar effect on increasing the volume/size of the ITZ, the reduction in the compressive strength and STS was more pronounced when the C/F ratio increased. This may be attributed to the fact that the difference between the two aggregate sizes (10 mm and 20 mm) was not significant compared to the large increase of the C/F aggregate ratios (2 compared to 0.7). The results also showed that using SFs in general slightly improved the compressive strength while greatly enhanced the STS. For example, adding SF35 to the SCC mixture slightly increased the compressive strength by 1.25%, while the enhancement in the STS reached up to 28.9%. This may be attributed to the ability of fibers to transfer stress across the cracked section, which, in turn, greatly enhanced the tensile strength of the concrete. By comparing needle fibers SF13 to hooked-ends SF35, it can be noticed that both fibers had a comparable effect on the compressive strength, while hooked-ends SF35 showed better enhancement to the STS compared to needle fibers SF13. This may be related to the longer length of SF35 compared to SF13, which may provide better bond between fibers and concrete matrix and, in turn, enhance the tensile strength of concrete. In addition, the different ends condition of SF35 (hooked ends) compared to SF13 (needle fibers) may have played an important role in providing sufficient bond between fibers and concrete matrix. Figure 4 also indicates that increasing the fiber length from 35 mm to 60 mm showed a slight reduction in the compressive strength and STS that reached up to 0.5% and 6.5%, respectively. This can be attributed to the fact that at the same fiber volume fraction, the mixture with shorter fibers will have a higher number of single fibers that may be oriented perpendicularly to the cracks, which can boost the fiber-bridging mechanism and, in turn, enhance the concrete strength.

For mixtures with the same fiber volume and lengths but with different fiber ends condition, it can be noticed that mixtures with double-hooked ends SFs (M9) exhibited a better enhancement in the STS compared to mixtures with single-hooked ends SFs (M8). This may be related to the higher bond between SF60-DH and concrete matrix compared to SF60 due to the different ends condition, which promoted the stitching mechanism of fibers and, in turn, enhanced the concrete strength.

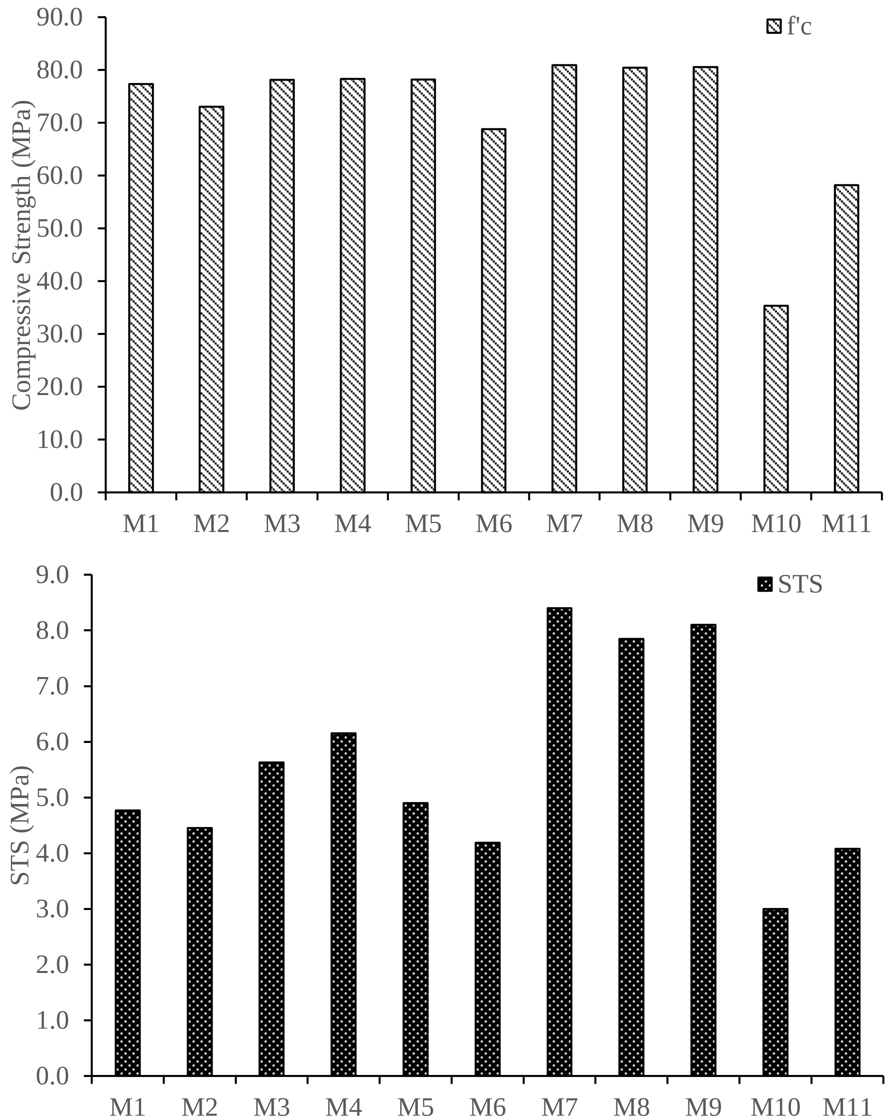

Figure 2-4 28-day compressive and STS strengths of tested mixtures

2.5.2 Salt Scaling Resistance of Non-Abraded and Abraded Concrete Surface

2.5.2.1 Salt Scaling Resistance of Non-Abraded Concrete Surface

Figure 2-5 and Figure 2-6 show the surface damage and the mass loss, respectively, of all tested mixtures after exposure to 50 cycles of salt scaling. By looking at the surface damage of all tested mixtures, it can be noticed that the control mixture (mixture 1) showed moderate scaling (visual rating of 3), in which some of the coarse aggregates were visible from the surface. It should be noted that changing the concrete type from SCC to VC (mixture 5 compared to mixture 1) exhibited a comparable surface damage (visual rating of 3), indicating similar resistance to salt scaling. The results also revealed that increasing the coarse aggregate size from 10 mm to 20 mm did not have a noticeable effect on the surface resistance to salt scaling as shown in Figure 2-5a (M2 compared to M1). On the other hand, increasing the C/F aggregate ratio exhibited a significant deterioration in the concrete resistance to salt scaling. This can be clearly observed by comparing M6 to M5, in which the mixture with C/F ratio of 0.7 (M5) showed a visual rating of 3 while the mixture with C/F ratio of 2 (M6) exhibited a visual rating of 4-5, indicating moderate to severe surface damage. Similarly, by observing the mass loss of M6 compared to M5, it can be seen that increasing the C/F ratio from 0.7 to 2 increased the mass loss by 38.2%. This can be attributed to the fact that increasing the C/F aggregate ratio contributed to developing higher volume of ITZ, which is considered the weakest part in the concrete matrix (Hassan et al. 2015, Larbi 1993, Monteiro et al. 1985, Akçaoğlu et al. 2004) and, in turn, increases the chance of coarse aggregate removal under the effect of salt scaling.

Figure 2-6 also presented the effect of using SFs on the resistance of concrete to salt scaling. By investigating the SCC mixtures with different types of SFs (M3 and M4), it can be observed that using SF13 showed insignificant reduction in the concrete resistance to salt scaling (visual rating of 3-4) compared to the control mixture (visual rating of 3). On the contrary, the deterioration in the concrete surface turned into a moderate to severe scaling (visual rate of 4) when SF35 was used. This difference in surface damage between SF13 and SF35 may be related to the fact that SF13 has a copper coating, which protects the fiber from corrosion (compared to non-coated SF35) under the effect of salt scaling. This can be confirmed by looking at Figure 2-5b, in which SF35 showed a higher level of corrosion compared to SF13. The corrosion of the uncoated SFs reduced the bond between the fibers and concrete, which made it easier for the fibers to disintegrate under the effect of scaling, resulting in more deterioration of the surface compared to uncoated fibers. The results also revealed that increasing the volume of uncoated SFs significantly reduced the concrete's resistance to salt scaling. For example, increasing the SF35 volume from 0.35% (M4) to 1% (M7) increased the mass loss by 27.7% (visual rating 5). This may be related to the higher volume of corroded SFs in the mixture. In a similar manner, using shorter SFs (SF35) led to a higher surface damage compared to using longer SFs (SF60). The mass loss in the mixture with shorter SFs reached up to 8.7% higher than that seen with longer SFs (M8 compared to M7). It should be noted that at the same fiber volume, using shorter fibers increased the number of single fibers in the mixture compared to longer fibers. On the other hand, using different ends condition of SFs appeared to have an insignificant effect on the concrete surface scaling (M9 compared to M8).

Figure 2-6 also indicates that the mixture with lower cement content had a lower resistance to salt scaling. For example, decreasing the cement content from 550 kg/m^3 to 300 kg/m^3 resulted in an increase in mass loss of up to 70.6% and an increase in the visual rating of surface damage from 2 to 4 (see Figure 2-5a).

Figure 2-5 (a-k) Visual inspection of salt scaled specimens for the 11 mixtures after exposure to 50 cycles of salt scaling; (l and m) difference between SF13 and SF35 in corrosion resistance

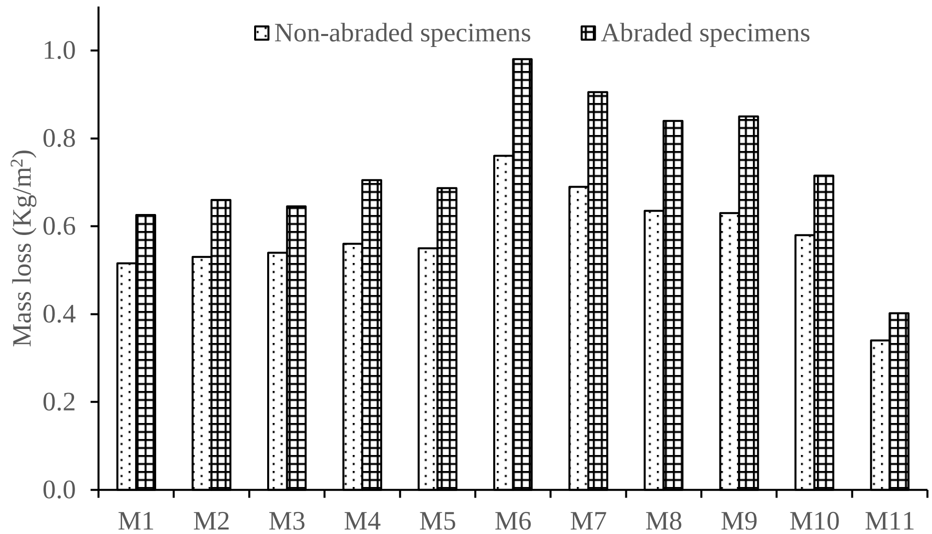

Figure 2-6 Mass loss after 50 cycles of salt scaling

2.5.2.2 Salt Scaling Resistance of Pre-Abraded Concrete Surface

Figure 2-6 presents the mass loss for pre-abraded concrete samples after exposure to 50 cycles of salt scaling. From the figure, it can be noted that the mass loss of pre-abraded concrete samples followed the same trend as that of non-abraded samples but with higher values compared to non-abraded samples, indicating lower scaling resistance. By investigating all tested mixtures (M1-M11), it can be seen that the samples with pre-abraded surfaces showed a higher mass loss, reaching up to 26.67% on average, compared to their counterparts with non-abraded surfaces. Moreover, the minimum and maximum increase in the mass loss of pre-abraded samples reached up to 21.3% and 34.9%, respectively, compared to non-abraded samples. This can be confirmed by visual inspection of concrete samples shown in Figure 2-7, in which the effect of salt scaling appeared to be more pronounced on the pre-abraded surface parts (either by rotating-cutter or sandblasting tests) compared to non-abraded surface parts.

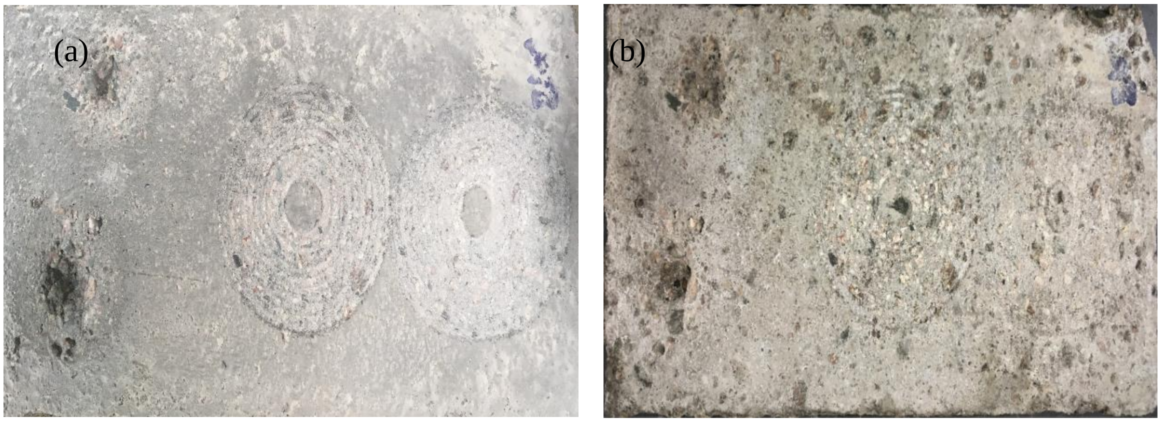

Figure 2-7 Sample of pre-abraded specimens (a) before salt scaling and (b) after salt scaling

From Figure 2-6, it can be seen that the salt scaling resistance of pre-abraded samples slightly decreased when the coarse aggregate size increased from 10 mm to 20 mm. On the other hand, increasing the C/F aggregate ratio from 0.7 to 2 significantly decreased the salt scaling resistance of pre-abraded samples. By comparing mixtures with different fiber types, it can be seen that using SF13 increased the mass loss by 3.1% compared to the control mixture (M1), while the increases reached up to 12.6% when SF35 was used. It should be noted that increasing the fiber volume resulted in a significant reduction in the concrete salt scaling, in which the mass loss increased by 28.2% when the fiber volume increased from 0.35% to 1%. Changing the ends condition of SFs did not show a considerable effect on the mass loss of pre-abraded concrete samples, indicating a comparable salt scaling resistance. Decreasing the cement content from 550 kg/m^3 to 300 kg/m^3 increased the mass loss of pre-abraded concrete samples by 78.8% (M11 compared to M10).

2.5.3 Abrasion Resistance of Concrete Mixtures Before and After Exposure to Salt Scaling

2.5.3.1 Abrasion Resistance of Non-scaled Concrete Surface

Figure 2-8 shows the mass loss results obtained from the rotating-cutter and sandblasting tests for all mixtures. As shown in the figure, the mixture with larger coarse aggregate size (20 mm) exhibited a slight decrease in the mass loss that reached up to 1.5% and 5.5% in the rotating-cutter and sandblasting tests, respectively, compared to the mixture with smaller aggregate size (10 mm) (M2 compared to M1). On the other hand, using larger C/F aggregate ratio showed a significant reduction in the mass loss obtained from both rotating-cutter and sandblasting tests (Figure 8). This can be attributed to the fact that using higher C/F aggregate ratio (2) led to an increase in the volume of coarse aggregate compared to the volume of cement mortar and, in turn, increased the chance of exposing the coarse aggregate to the abrasion force rather than cement mortar. Since the coarse aggregates used in this investigation (crushed granite) have a high strength and hardness compared to the mortar, the overall hardness of concrete surface and abrasion resistance appeared to be enhanced. It should be noted that the use of weaker coarse aggregates such as dolomite or limestone may show opposite results.

By investigating the mixtures with SFs, it can be seen that adding SFs generally decreased the mass loss of the rotating-cutter and sandblasting tests, indicating enhanced abrasion resistance. For example, adding SF35 to SCC mixture decreased the mass loss of rotating-cutter and sandblasting abrasion tests by 13.2% and 19.3%, respectively, compared to control mixture (M4 compared to M3). Adding fibers ties the concrete matrix together and reduces the pullout of concrete particles under the effect of abrasion. In addition, mixtures with SFs will likely have some fibers exposed at the surface, resisting the abrasion effect during the test. Since steel is tougher than concrete, mixtures with SFs should have more resistance to abrasion compared to mixtures without SFs. Figure 8 also shows that using SF13 showed lower improvement in the abrasion resistance of concrete compared to SF35. This could be due to the effect of the surface coating of SF13, which may have reduced the bond between the fibers. The results also revealed that increasing the fiber volume exhibited a significant increase in the abrasion resistance of concrete. On the contrary, increasing the fiber length from 35 mm to 60 mm at the same fiber volume (reduced the number of single fibers in the mixture), slightly increased the mass loss of the rotating-cutter and sandblasting tests by 7.2% and 10.5%, respectively, indicating a lower improvement in the abrasion resistance of concrete (M8 compared to M7). From Figure 8, it can also be noted that at the same fiber length, type, and volume, changing the SFs ends condition (double-hooked compared to single-hooked SFs) showed insignificant effect on the abrasion resistance of concrete (M9 compared to M8). Decreasing the cement content from 550 kg/m^3 to 300 kg/m^3 increased the mass loss resulting from the rotating-cutter and sandblasting by 16.5% and 29.9%, respectively (M11 compared to M10). This can be related to the significant drop in the compressive strength when cement content decreased, which negatively affected the abrasion resistance of concrete.

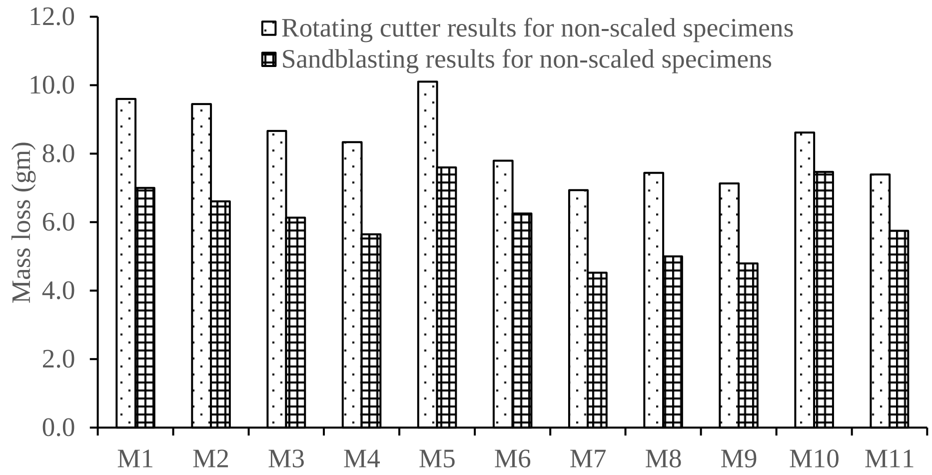

Figure 2-8 Abrasion mass loss of non-scaled concrete specimens

2.5.3.2 Abrasion Resistance of Salt Scaled Concrete Surface

The ratio between the abrasion mass loss before and after exposure to salt scaling was calculated as shown in Eq. (2):

$$SAR = M_{La} / M_{Lb} \quad (2)$$

Where SAR is the scaling factor related to the abrasion resistance, M_{La} is the abrasion mass loss after exposure to salt scaling, M_{Lb} is the abrasion mass loss before exposure to salt scaling.

By investigating the effect of salt scaling on the abrasion resistance of all tested mixtures, it can be seen that salt scaling, in general, had a negative effect on the abrasion resistance of concrete. This was confirmed by examining the value of S_{AR} for all tested mixtures, in which the calculated values of S_{AR} exceeded 1 in all mixtures. This is related to the effect of salt scaling in deteriorating the surface of concrete, developing a fragile surface that can be disintegrated easily under the effect of abrasion force. Figure 2-9 shows the SAR values for all tested mixtures. From the figure, it can be seen that the mixture with larger coarse aggregate size (M2) exhibited a slight increase in the SAR values, in both rotating-cutter and sandblasting tests, compared to the control mixture. On the contrary, increasing the C/F aggregate ratio from 0.7 to 2 resulted in a considerable increase in the SAR values, which reached up to 1.83 and 3.09 in the rotating-cutter and sandblasting tests, respectively. This effect is because the mixture with higher C/F aggregate ratio has a higher total volume of ITZ (Koehler and Fowler 2007, Mehta and Monteiro 1993). Since the ITZ is the weakest area in the concrete matrix, it will be more affected by salt scaling, resulting in easier designation of aggregate from concrete and, consequently, higher mass loss and higher SAR values.

The results also showed that adding SFs to concrete mixtures enhanced the abrasion resistance of concrete after exposure to salt scaling compared to the control mixture without SFs (M3 and M4 compared to M1). Comparing the mixture with SF13 to that with SF35 (M3 compared to M4) shows that the negative effect of salt scaling on the abrasion resistance of concrete appeared to be less when SF13 was used compared to when SF35 was used. This can be observed in the values of SAR, in which SF13 exhibited SAR values of 1.09 and 1.14 in the rotating-cutter and sandblasting tests, respectively, while SAR values reached up to 1.2 and 1.26, respectively, when SF35 was used. Exposing concrete to salt scaling contributed to destroying the top layer of mortar, allowing the SFs to become exposed on the surface, and increasing the chance of SFs to become corroded. The corrosion of SFs decreased the bond between SFs and concrete matrix, allowing SFs to be easily pulled out under the action of abrasion force. Although both SF13 and SF35 are steel fibers, SF13, with the coated layer, has a lower chance of becoming corroded and, in turn, a better performance in the abrasion resistance of salt scaled concrete compared to uncoated

SF35. It can also be noted that increasing the volume of SFs slightly increased SAR values in both rotating-cutter and sandblasting tests, indicating lower improvement in the abrasion resistance on salt scaled samples compared to non-scaled ones. This can be attributed to the higher number of fibers that may get corroded due to the action of salt scaling when the volume of SFs was increased (see Figure 2-5a). Similarly, using shorter SFs showed lower enhancement in the abrasion resistance of salt scaled mixtures compared to non-scaled mixtures. It should also be noted that using different ends condition (single-hooked ends versus double-hooked ends) showed comparable SAR results (M9 compared to M8). Using lower cement content also contributed to decreasing the bond between aggregate and surrounding mortar, and showed SAR values of 1.65 and 2.15 when 300 kg/m^3 was used compared to SAR values of 1.23 and 1.91 when 550 kg/m^3 was used.

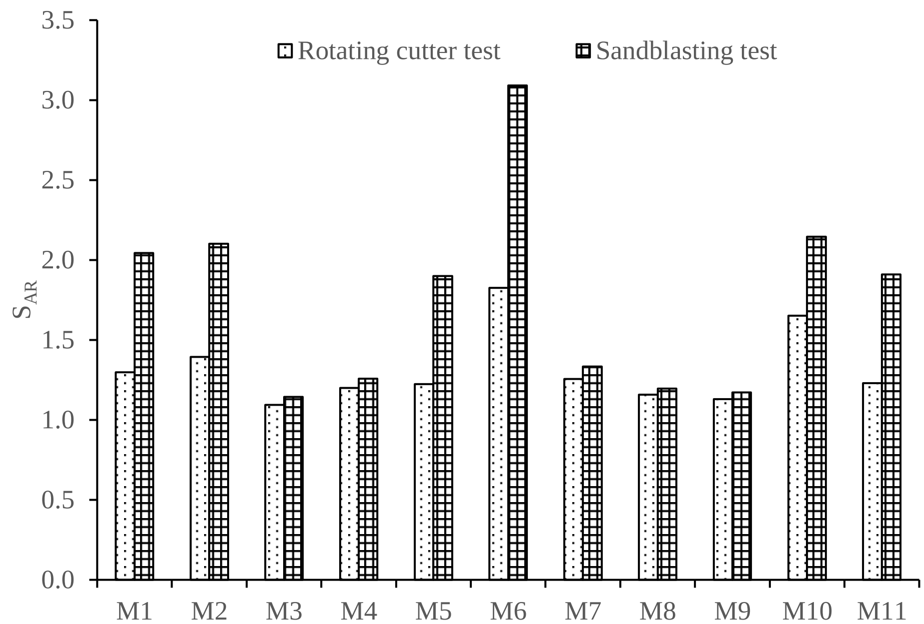

Figure 2-9 Effect of surface scaling on abrasion resistance of tested mixtures

2.5.4 Impact Resistance of Concrete Mixtures Before and After Exposure to Salt Scaling

2.5.4.1 Impact Resistance of Non-scaled Concrete Surface

Figure 2-10 shows the impact resistance results under drop-weight test for all tested mixtures. From the figure, it can be seen that increasing the coarse aggregate size slightly decreased the impact resistance in terms of number of drops required to cause first crack (N1) and failure crack (N2). For example, increasing the coarse aggregate size from 10 mm to 20 mm decreased N1 and N2 by 7.4% and 7.9%, respectively, compared to the control mixture (M2 compared to M1). On the other hand, increasing the C/F aggregate ratio from 0.7 to 2 significantly decreased N1 and N2 by 20.3% and 19.5%, respectively (M6 compared to M5), indicating lower impact resistance. This can be attributed to the reduction in the compressive strength that resulted from increasing C/F aggregate ratio.

The results also indicated that adding SFs in general significantly enhanced the impact resistance of concrete mixtures. For example, using SF35 in SCC mixtures increased N1 and N2 by 79.9% and 106.8%, respectively, compared to the control mixture (M4 compared to M1), indicating a significant enhancement in impact resistance. This can be related to the stitching mechanism of fibers, which contributed to transferring the stress across the cracked section, as well as the ability of fibers to enhance the tensile strength and delay the initiation of cracks in concrete mixtures (see STS results in Figure 2-4). It should be noted that the addition of fibers significantly increased the difference between N1 and N2, indicating higher ductility and post-cracking behavior. By comparing SF13 to SF35 (M3 compared to M4), it can be seen that SF13 showed lower improvement in the impact resistance of concrete compared to SF35. This can be related to the higher enhancement of concrete tensile strength when SF35 was used compared to SF13. The figure also indicates that increasing the fiber volume appeared to significantly improve the impact resistance of concrete mixtures. By looking at mixtures M7 compared to M4, increasing the volume of SFs from 0.35% to 1% increased N1 and N2 by 67.6% and 72.7%, respectively. The results also showed that, at the same volume of SFs, using shorter SFs (35 mm) slightly increased the impact resistance in terms of N1 and N2 compared to longer fibers (60 mm) (M8 compared to M7). This can be attributed to the same reasons discussed in the section on compressive strength and STS. In a similar manner, at the same volume and lengths of SFs, using DH-SFs showed a slight enhancement in the impact resistance of concrete mixtures compared to SH-SFs (M9 compared to M8). This can be explained by the fact that DH end conditions contributed to enhancing the bond between SFs and concrete matrix, which increased the concrete tensile strength and, in turn, enhanced the impact resistance of concrete. Using lower cement content reduced the impact resistance in terms of N1 and N2, in which decreasing cement content from 550 kg/m^3 to 300 kg/m^3 decreased N1 and N2 by 14% and 14.9%, respectively (M11 compared to M10). This can be attributed to the same reasons discussed in previous sections.

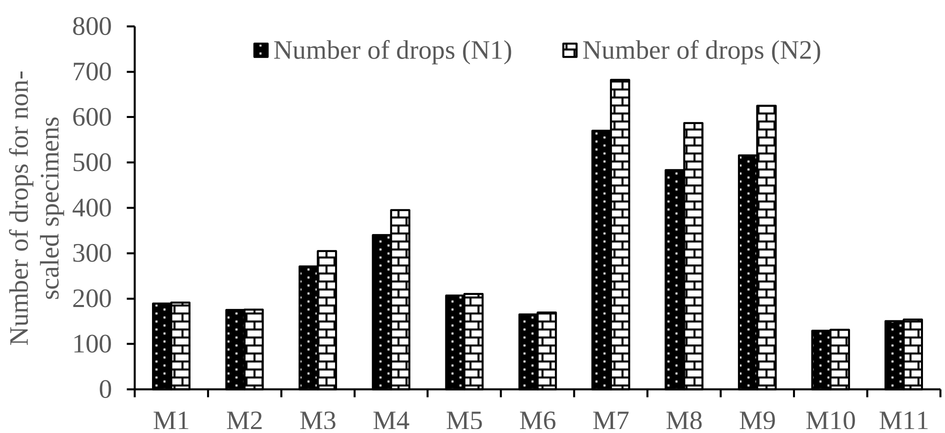

Figure 2-10 Impact resistance of non-scaled concrete specimens

2.5.4.2 Impact Resistance of Salt Scaled Concrete Surface

The ratio between the absorbed impact energy before and after exposure to salt scaling was measured to evaluate the negative effect of salt scaling on the impact resistance of concrete. This ratio was calculated as shown in Eq. (3):

$$SIE = I_{Ea}/I_{Eb} \quad (3)$$

Where, S_{IE} = scaling factor associated with absorbed impact energy, I_{Ea} = absorbed impact energy after exposure to salt scaling, and I_{Eb} = absorbed impact energy before exposure to salt scaling.

Figure 2-11 shows the SIE factor for all tested mixtures. Exposing concrete to salt scaling had a negative effect on the impact resistance of all tested mixtures. This can be clearly observed from the values of SIE, in which the values of SIE for all tested mixtures are below the value of 1. By comparing the mixtures with different aggregate size (M2 compared to M1), it can be noticed that increasing the coarse aggregate size from 10 mm to 20 mm slightly decreased the value of SIE from 0.85 to 0.8. The reduction in the value of SIE indicated the reduction in the impact resistance of salt scaled samples compared to non-scaled ones. In a similar manner, increasing the C/F aggregate ratio from 0.7 to 2 showed a higher reduction in the impact resistance of salt scaled samples compared to non-scaled ones. This can be attributed to the effect of salt scaling in deteriorating the bond between aggregate and surrounding mortars, initiating small cracks in the concrete matrix, which contributed to decaying the impact resistance of concrete.

The results also showed that although using SFs in concrete mixtures exhibited a significant enhancement in the impact resistance of concrete, this enhancement appeared to be less in the case of salt scaled samples compared to non-scaled ones. This can be attributed to the effect of salt scaling on the corrosion of SFs, which can reduce the bond between SFs and concrete matrix and, in turn, reduce the effect of fibers on improving the impact resistance of concrete. Mixtures with SFs showed values of SIE factor reaching up to 0.95, 0.91, 0.87, 0.89, and 0.9 (mixtures M3, M4, M7, M8, and M9, respectively).

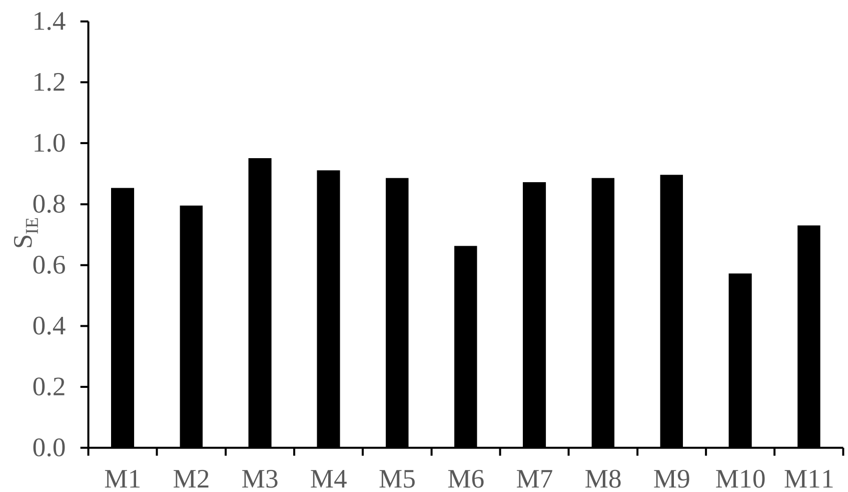

Figure 2-11 Effect of surface scaling on impact resistance of tested mixtures

It should be noted that exposing concrete to salt scaling negatively affected the surface layer more than the deeper layers of concrete samples. Therefore, the indentation depth resulted from impact-weight drops was tracked and measured for the first 25, 50, and 100 drops to evaluate the effect of salt scaling on successive layers of the concrete sample. Error! Reference source not found. shows the ratio between indentation depth of salt scaled specimens to that of non-scaled specimens at 25, 50, and 100 drops. In general, the indentation depth that occurred in the salt scaled specimens was higher than in their non-scaled counterparts. This can be attributed to the effect of salt scaling on crumbling the top layers of concrete specimens, inducing higher indentation compared to non-scaled specimens. The results also showed that as the number of drops increased, the ratio between the indentation depths of salt scaled to non-scaled specimens decreased. This can be confirmed in that the indentation depth ratios ranged from 1.24-1.4, 1.15-1.3, and 1.09-1.24 for 25, 50, and 100 drops, respectively. These results can be explained such that for the first 25 drops, the weight dropped on the weak surface, inducing higher indentation, while at higher number of drops, the weight dropped on the stronger deeper layers, inducing lower indentation.

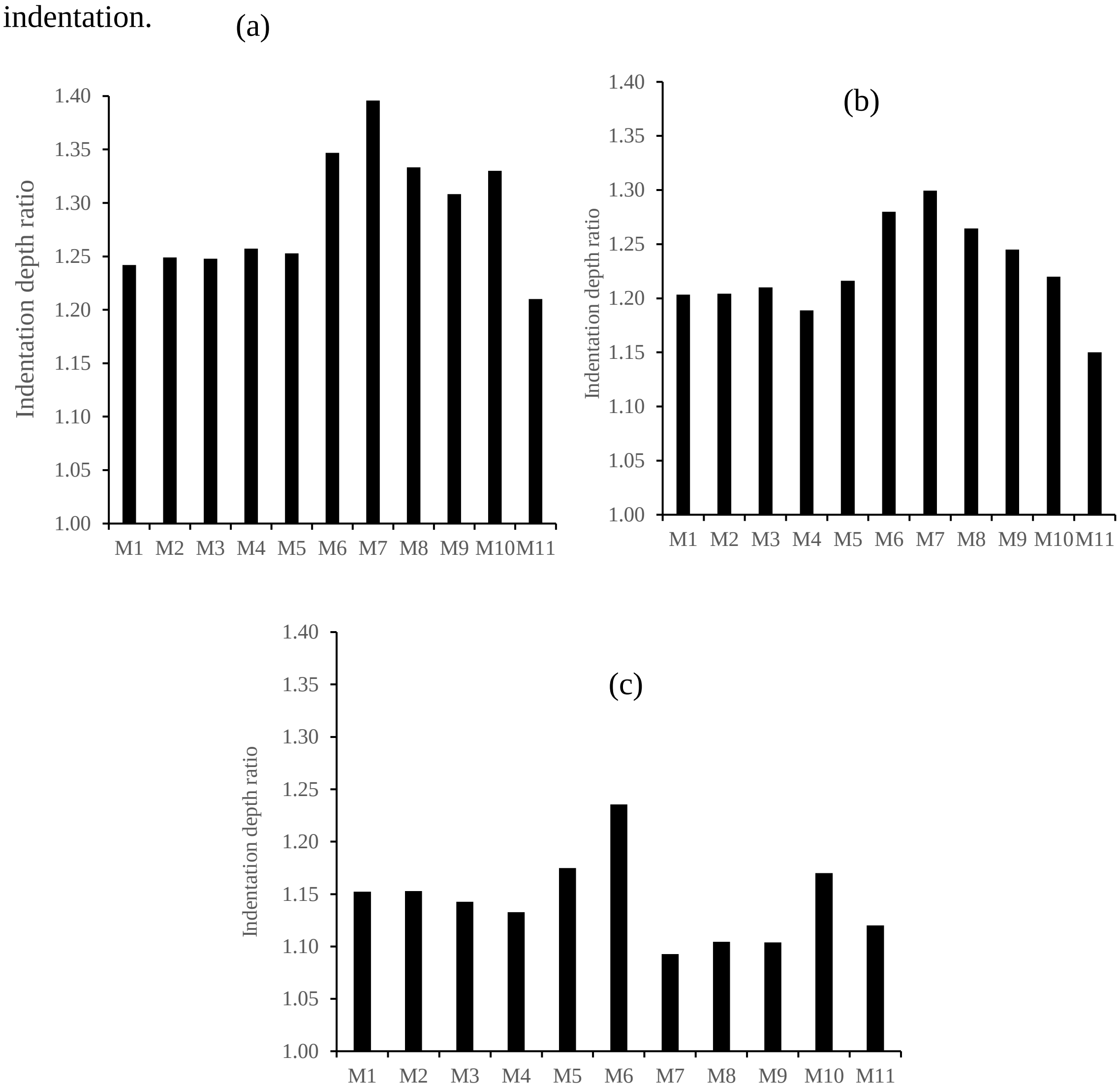

Figure 2-12 Indentation depth ratio (a) at 25 drops, (b) 50 drops, (c) 100 drops

2.6 Conclusions

This study presented the effect of using SFs on enhancing the impact and abrasion resistance of concrete mixtures before and after exposure to salt scaling. The effect of different coarse aggregate sizes, C/F aggregate ratios, and concrete strengths was also investigated. From the experimental work presented in this investigation, the following conclusions can be drawn:

1. Increasing the coarse aggregate size from 10 mm to 20 mm showed a comparable surface resistance to salt scaling for both abraded and non-abraded samples. On the other hand, increasing the C/F aggregate ratio exhibited a significant deterioration in the surface resistance to salt scaling of abraded and non-abraded samples.
2. Uncoated SFs corroded under the action of salt scaling resulted in a reduction in the bond between the fibers and cement matrix. This reduction in the bond made it easier for the fibers to disintegrate under the effect of salt scaling, resulting in a higher surface scaling. For the same reason, increasing SF volume significantly reduced the concrete resistance to salt scaling for abraded and non-abraded surfaces. Similarly, using shorter SFs at the same SF volume (higher number of single fibers distributed in the mixture) led to a reduction in the concrete resistance to salt scaling for abraded and non-abraded concrete surfaces.
3. For all tested mixtures, the samples with pre-abraded surfaces showed a higher mass loss that ranged from 21.3% to 35% higher than their counterparts with non-abraded

surfaces, indicating lower salt scaling resistance of abraded samples compared to non-abraded ones.

4. Using larger aggregate size slightly enhanced the abrasion resistance of non-scaled concrete surfaces. Meanwhile, increasing the C/F aggregate ratio from 0.7 to 2 significantly improved the abrasion resistance of non-scaled concrete surfaces.On the other hand, decreasing the cement content from 550 kg/m^3 to 300 kg/m^3 significantly decreased the abrasion resistance of concrete.
5. Using shorter SFs (higher number of SFs at the same volume of SFs) contributed to significantly enhance the abrasion resistance of concrete mixtures in both rotating-cutter and sandblasting tests for non-scaled specimens. No significant change in the abrasion resistance of concrete was observed when different ends condition of SFs were used.
6. For all tested mixtures, the salt scaling action had a negative effect on the abrasion resistance of concrete, in which the calculated values of SAR for all tested mixtures exceeded 1. The effect of salt scaling in reducing the abrasion resistance of concrete appeared to be more pronounced when uncoated SFs were used compared to coated ones.
7. Adding SFs to concrete mixtures significantly enhanced the impact resistance of non-scaled concrete specimens. However, this enhancement appeared to be less in the salt scaled concrete specimens compared to non-scaled ones. This can be attributed to the corrosion of the SFs that occurred after the exposure to salt scaling. This corrosion may have reduced the bond between the fibers and concrete matrix, which reduced the effect of SFs on enhancing the impact resistance.

8. Salt scaled samples appeared to have higher surface deterioration in term of indentation depth under the effect of impact loads, compared to non-scaled ones. This was more pronounced at the surface of the specimens compared to deeper layers as the ratio between the indentation depths of salt scaled to non-scaled specimens decreased after 100 drops compared to 25 drops.

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3 Mechanical Properties and Impact Resistance of Fiber Reinforced Concrete under Cold Temperature

3.1 Abstract

This study investigates the mechanical properties and impact resistance of steel fiber reinforced concrete at cold temperatures. The studied parameters include: types of steel fibers (SFs) (needle fibers, single-hooked ends (SH), and double-hooked ends (DH)), lengths of SFs (35 mm and 60 mm), volumes of SFs (0%, 0.35%, and 1%), coarse aggregate size (10 mm and 20 mm), coarse to fine aggregate ratio (C/F) (0.7 and 2), and cement content (300 kg/m^3 and 550 kg/m^3). The results indicate that, for all tested mixtures, decreasing the temperature to subnormal levels (0º C, -10º C, -20º C) yields improvement in the compressive strength, flexural strength, and impact resistance. However, the mode of failure is more brittle at cold temperatures. The results also show that using SFs improves the mechanical properties and impact resistance of concrete at cold temperatures and reduces the low temperature brittleness of the concrete.

3.2 Introduction

The behavior of materials generally changes significantly when the temperature drops from ambient temperature to subnormal levels. Previous studies have shown that the mechanical properties of all materials are significantly affected by cold temperatures (Lee et al. 1988, Gardner et al. 2005). For example, Duthil (2015) found that decreasing the temperature generally increased modulus of elasticity and yield strength, while the fracture toughness of materials was decreased. Similar to any other material, the compressive strength, splitting tensile strength (STS), modulus of elasticity, and brittleness index of concrete are affected by temperature (Eranti and Lee 1986, Krstulovic-Opara 2007, Kogbara et al. 2013, Dahmani et al. 2007). Many previous studies have focused on the performance of concrete at cryogenic temperatures (typically for liquefied natural gas storage). However, a limited number of studies have investigated the behavior of concrete under terrestrial temperatures typical of cold northern regions. Lee et al. (1988) conducted an experimental study to investigate the effect of decreasing the temperature from room temperature to -70° C on compressive strength, STS, and modulus of elasticity of high and normal strength concrete. Their results indicated that decreasing the temperature increased the compressive strength by 150% and 200% for high strength and normal strength concrete, respectively. Their results also revealed that the effect of cold temperature was more pronounced in normal strength concrete, compared to high strength concrete. Montejo et al. (2008) studied the effect of low temperature on the seismic behavior of concrete columns under reversed cyclic loading. Their study indicated that decreasing the temperature from 20° C to -40° C increased the flexural strength and elastic stiffness by 15% and 90%, respectively, while the displacement capacity decreased by 20%, indicating more brittle failure.

Despite the beneficial effects of low temperature on strength and stiffness properties, concrete is shown to be more brittle at low temperature (Montejo et al. 2008, Rostasy and Wiedemann 1981, Kim et al. 2017). Sloan (2005) studied the seismic behavior of reinforced concrete members at low temperature. His research reported that decreasing the temperature from room temperature to -40° C led to a sudden failure of concrete samples once they reached the maximum compressive strength, indicating a brittle failure at low temperature. One technique that could be used to alleviate brittleness in concrete at low temperature is the addition of fibers to concrete mixtures. Using fibers in concrete has been shown to greatly enhance the ductility, energy absorption, impact resistance, and toughness of concrete under normal temperature (Yap et al. 2014, Bolat et al. 2014, Ababneh et al. 2017). Steel fibers (SFs) and polypropylene fibers are the most common types of fibers used in concrete. However, SFs have an advantage over polypropylene fibers, because polypropylene fibers become more brittle at low temperatures due to the low glass transition temperature of polypropylene fibers (segard et al. 2002). This can negatively affect the ductility of a concrete matrix.

Previous studies have shown the beneficial effect of using SFs in improving the compressive strength, STS, flexural strength (FS), and flexural toughness of concrete under normal temperature (Altun and Aktas 2013, Nia et al. 2012, Khaloo et al. 2014). For example, Ismail and Hassan (2016) investigated the effect of different SFs lengths and volumes on the mechanical properties and impact resistance of rubberized concrete mixtures. Their results showed that increasing the SFs volume up to 1% increased the compressive strength, STS, FS, and impact resistance by 1.07, 1.93, 1.75, and 4 times, respectively, compared to a control mixture without fiber. They also found that increasing the SFs length from 35 mm to 60 mm increased the initial visible crack and failure crack resistance by 17.7% and 19%, respectively. Another study by Nataraja et al. (2005) also reported that using 0.5% SFs enhanced the impact resistance of a concrete mixture, with 30MPa compressive strength, by 3-4 times compared to a similar mixture without fibers, while the fiber enhancement reached up to 7-10 times in mixtures with 50 MPa compressive strength. Adding SFs to concrete mixtures also showed a significant enhancement in the ductility, energy absorption, and crack resistance at normal temperatures. AbdelAleem and

Hassan (2019) studied the effect of SFs on enhancing the structural performance of rubberized beam-column joints under cyclic loading. They observed that using 0.35% SFs with 35 mm length increased the ductility, energy dissipation, and load carrying capacity by 22.4%, 50.5%, and 15.6%, respectively. The effects of different types of SFs on the flexural strength and impact resistance of concrete under normal temperature were studied by Murali et al. (2016). Their results revealed that at the same fiber volume fraction, crimped SFs increased the flexural strength and impact resistance by 50.7% and 63% respectively, while this enhancement reached up to 55% and 72%, respectively, when hooked-end SFs was used.

The mechanical properties of concrete under normal temperature are also influenced by the properties of aggregates, including coarse to fine aggregate ratio (C/F) and coarse aggregate size. Past studies have investigated the effect of increasing C/F aggregate ratio and coarse aggregate size on the mechanical properties of concrete mixtures. Hassan and Mayo (2014) reported that increasing the C/F aggregate ratio up to 0.9 increased the compressive strength of concrete mixtures, while further increase in the C/F aggregate ratio beyond 0.9 showed a reduction in the concrete strength. The study also indicated that using larger coarse aggregate size had a negative impact on the compressive strength of concrete mixtures.

In this study, the mechanical properties and impact resistance of different concrete mixtures were investigated at cold temperatures. The effects of adding different types, lengths, and volumes of SFs in mitigating the brittleness and further enhancing mechanical properties and impact resistance at low temperatures were also investigated. The tested properties were compressive strength, FS, drop weight impact resistance, and flexural impact resistance. The investigated mixtures were developed with different coarse aggregate size, C/F aggregate ratio, different SFs' types, lengths, and volumes, and various cement contents.

3.3 Research Significance

Previous studies indicate that decreasing the temperature of concrete below temperate values leads to enhancements in the compressive and tensile strengths of concrete. However, exposing concrete to cold temperatures also increases the brittleness. There are few studies that investigate the effect of cold temperature on the mechanical properties of concrete and none investigating the effect of cold temperature on impact resistance. Furthermore, there are no available studies covering the effect of SFs in enhancing concrete performance at cold temperatures, especially when different types, and lengths of SFs are used. This study investigates the effect of SFs in enhancing the mechanical properties and impact resistance of concrete at low temperatures and in alleviating the brittleness of concrete at low temperatures. The authors believe that this research will significantly help in developing fiber reinforced concrete mixtures with high resistance to impact loads that will be useful in applications specifying cold temperatures, typical of those found in northern regions.

3.4 Experimental Program

3.4.1 Material Properties

General use Portland cement, Metakaolin (MK), and fly ash (FA) similar to ASTM C150 (ASTM 2012), ASTM C618 class N (ASTM 2012a), and ASTM C618 Type F (ASTM 2012a), respectively, were used as binders to develop the tested mixtures. The chemical and physical properties of the materials are shown in Table 3-1 Natural crushed stone with maximum aggregate sizes of 10 mm and 20 mm, and natural sand were used as coarse and fine aggregates. Each type of aggregate had a specific gravity of 2.6 and absorption of 1%. The aggregate gradations of the 10 mm and 20 mm crushed stones, and natural sand are presented in Figure 3-1 Four types of steel fibers (SFs) were used in this investigation. The first type of SFs is needle fiber (NYCON-SF) coated with copper to resist corrosion and with a length of 13 mm (SF13). The second and third types of SFs are single-hooked end SFs (Dramix 3D) with a length of 35 mm and 60 mm (SF35 and SF60). The fourth type is a 60 mm SFs (SF60-DH) with double-hooked ends (Dramix 5D). The physical and mechanical properties of the SFs are presented in Table 3-2, and their configuration and geometries are shown in Figure 3-2 A polycarboxylate-based high-range water-reducer admixtures (HRWRA) similar to ASTM C494 Type F (ASTM 2013) with a specific gravity of 1.2, volatile weight of 62%, and pH of 9.5 was used to achieve the required slump flow of mixtures.

3.4.2 Mixtures Development

This investigation was designed to study the effect of cold temperatures on the mechanical properties and impact resistance of concrete mixtures developed with different types of SF. The tested mixtures consisted of two self-consolidating concrete (SCC) mixtures, two SFs reinforced self-consolidating concrete mixtures (SFSCC), four vibrated concrete (VC) mixtures, and three SFs reinforced vibrated concrete (SFVC) mixtures. Developing SCC and SFSCC mixtures requires a balanced viscosity to improve the particle suspension and decrease the risk of segregation without affecting the mixtures' flowability.

Table 3-1 Chemical and physical properties of SCMs used

Chemical properties (%)	MK	FA	Cement
SiO_2	51-53	52	19.64
Al_2O_3	42-44	23	5.48
Fe_2O_3	<2.2	11	2.38
CaO	<0.2	5	62.44
MgO	<0.1	-	2.48
Na_2O	<0.05	-	-
K_2O	<0.40	2	-
C_3S	-	-	52.34
C_2S	-	-	16.83
C_3A	-	-	10.50
C_4AF	-	-	7.24
L.O.I	0.95	0.21	2.05
Physical properties			
Specific gravity	2.56	2.38	3.15
Blaine fineness (m^2/kg)	1390	20000	410

Table 3-2 Characteristics of the fibers used

Fibers used	Type	Diameter/Equivalent Diameter (mm)	Length (mm)	Tensile Strength (Mpa)	End Conditions
SF13	Steel fiber	0.2	13	1900	Needle
SF35	Steel fiber	0.55	35	1150	Single hooked
SF60	Steel fiber	0.9	60	1150	Single hooked
SF60-DH	Steel fiber	0.9	60	1150	Double hooked

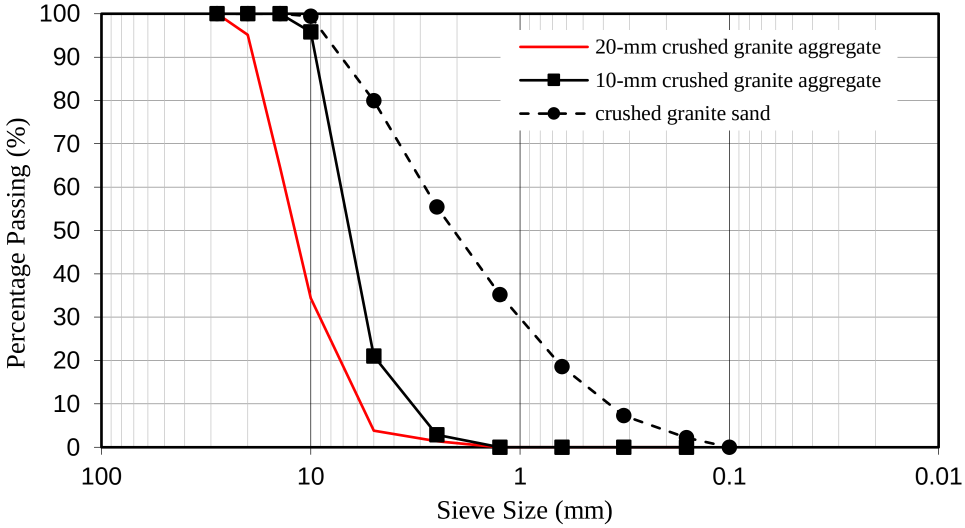

Figure 3-1 Gradation curves for both fine and coarse aggregates

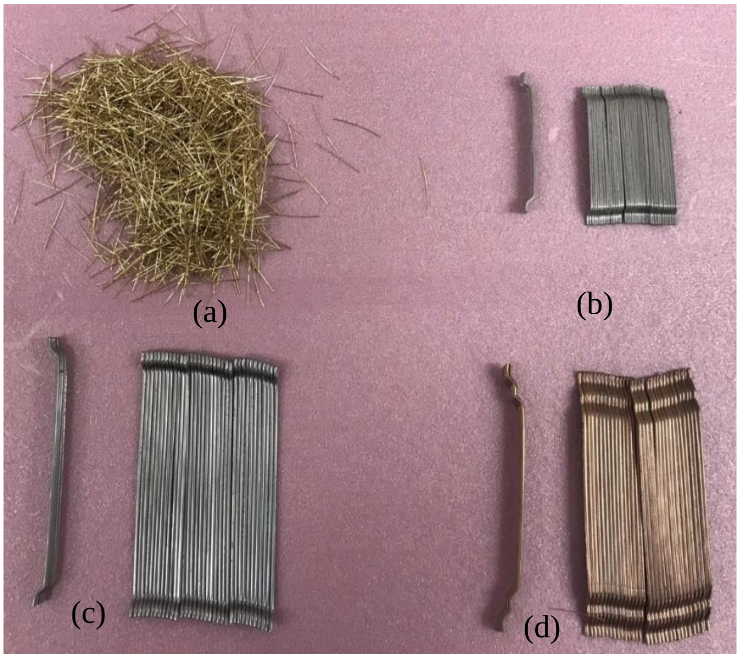

Figure 3-2 Configuration and geometry of fibers used: (a) SF13, (b) SF35, (c) SF60, (d) SF60-DH

A total binder content of at least 550 kg/m^3 and a minimum water-to-binder ratio (w/b) of 0.4 were found to be necessary to ensure sufficient flowability with a target slump of 700

± 50 mm and no visual sign of segregation. The binder content (550 kg/m^3) consisted of 50% cement, 30% FA, and 20% MK. These ratios were selected based on preliminary trial mixtures to satisfy the requirement of the flowability, passingability, and particle suspension as per European Guidelines for self-consolidating concrete (EFNARC 2005). In particular, the use of FA was necessary to improve the flowability of the mixture while the use of MK was necessary to improve the mixture viscosity and particle suspension. Trial mixtures also indicated that 0.35% is the maximum percentage of SFs that could be used in SFSCC mixtures, in which further increase in the percentage of SFs resulted in a significant drop in the fresh properties of the mixtures. The compositions for all tested mixtures are presented in Table 3-3 The experimental program was designed based on the following:

- Mixture M2 compared to M1. These mixtures were selected to study the effect of cold temperature on the mechanical properties and impact resistance of mixtures with different aggregate size.
- Mixtures M3 and M4 are SFSCC developed with different SFs types to investigate the effect of using different SFs types on the mechanical properties and impact resistance under cold temperatures.
- Mixtures M6 compared to M5. These two mixtures are VC, selected to study the effect of cold temperatures on the mechanical properties and impact resistance of mixtures with different coarse to fine aggregate ratios.
- Mixtures M7 and M8 are SFVC developed with the maximum percentage of SFs that could be used to ensure uniform distribution of SFs without any sign of fiber

clumping. M7 was developed with 35 mm fiber length, while M8 was developed with 60 mm fiber length to investigate the effect of fiber length on the studied properties at subnormal temperatures.

- Mixtures M8 and M9 are SFVC. These mixtures were developed with the same percentage and length of SF, but with different SFs end conditions. Double-hooked end SFs (SFs-DH) was used in mixture M9, while single-hooked end SFs was used in M8. These mixtures were selected to study the effect of SFs end conditions on the impact resistance and mechanical properties of concrete at cold temperatures.
- Mixtures M10 and M11 are VC mixtures selected to examine the effect of concrete strengths on the mechanical properties and impact resistance of concrete under low temperatures. M10 and M11 were developed with different cement content (300 kg/m^3 and 550 kg/m^3) and no supplementary cementing materials. However, the water to binder ratio (w/b) and C/F aggregate ratio were kept the same for both mixtures (0.4 and 0.7, respectively).

It was not possible to develop mixtures M6 to M11 as SCC mixtures due to the high C/F aggregate ratio or high percentage of SFs used in these mixtures. All mixtures were designated according to the type of concrete (SCC or VC), C/F aggregate ratio, coarse aggregate size, volume/length of SF, and SFs end conditions. For example, the VC mixture with C/F aggregate ratio of 2 is labelled VC-2C/F, while the SCC mixture with 20 mm coarse aggregate size is labelled SCC-20. In mixtures with SF, the mixture with 1% 60 mm double-hooked SFs would be labelled VC-1SF60-DH. The material proportions of all tested mixtures are presented in Table 3-3.

3.5 Testing Program

3.5.1 Mechanical Properties Tests

Mechanical properties tests included compressive strength and Flexural strength (FS). The compression test was conducted using three identical concrete cylinders (100 mm diameter x 200 mm height) as per ASTM C39 (ASTM 2011), Meanwhile, a concrete prism of 100-mm x 100-mm cross section and 400-mm in length was tested by using a four-point loading test to assess the FS, according to ASTM C78 (ASTM 2010). All tested mixtures samples were moist cured at standard conditions for 28 days and then put into a cold room with the specified temperatures (-20° C, -10° C, 0° C) for 48 hours to reach a steady temperature state (Cai et al. 2011, Lee et al. 1989).

3.5.2 Impact Resistance Tests

Two impact tests were conducted to evaluate impact resistance as follows:

1 Drop weight test: this test was performed according to ACI 544 (1999) on three specimens 150 mm in diameter and 63.5 mm thick. These specimens were cut from concrete cylinders with 150 mm diameter and 300 mm height after removing the top layer of the cylinder using a diamond cutter. A 4.45 kg hammer was dropped from a height of 457 mm onto a steel ball with a diameter of 63.5 mm located at the center of the top surface of the sample. The number of drops to initiate the first visible crack (N1) was recorded. In addition, the number of drops to cause failure (N2) was also recorded to obtain the ultimate crack resistance.

Table 3-3 Proportion details of tested mixtures

Mix #	Mixture	Cement (kg/m^3)	SCM (Type)	SCM (kg/m^3)	C/F ratio	C. A. (kg/m^3)	F. A. (kg/m^3)	Fiber (V_f%)	w/b	Air content
M1	SCC	275	MK+FA	110+165	0.7	620.3	886.1	-	0.4	1.3
M2	SCC-20	275	MK+FA	110+165	0.7	620.3	886.1	-	0.4	1.5
M3	SCC-0.35SF13	275	MK+FA	110+165	0.7	620.3	886.1	0.35	0.4	1.45
M4	SCC-0.35SF35	275	MK+FA	110+165	0.7	620.3	886.1	0.35	0.4	1.6
M5	VC	275	MK+FA	110+165	0.7	620.3	886.1	-	0.4	1.2
M6	VC-2C/F	275	MK+FA	110+165	2	1006	503	-	0.4	1.55
M7	VC-1SF35	275	MK+FA	110+165	0.7	620.3	886.1	1	0.4	1.3
M8	VC-1SF60	275	MK+FA	110+165	0.7	620.3	886.1	1	0.4	1.5
M9	VC-1SF60-DH	275	MK+FA	110+165	0.7	620.3	886.1	1	0.4	1.45
M10	VC-300	300	--	--	0.7	840.2	1200.2	-	0.4	2.4
M11	VC-550	550	--	--	0.7	648.1	925.9	-	0.4	1.9

Note: SCM = supplementary cementing materials; FA = fly ash; MK = metakaolin; C. A. = coarse aggregate; F. A. = fine aggregate; V_f = volume fraction

2 Flexural Impact test: this test used three-point flexural loading to evaluate the energy absorption of beams made with the developed mixtures. For each mixture, three beams; 400 mm length, 100 x 100 mm cross section, and 350 mm loading span, were tested. A 4.45 kg hammer was dropped from a height of 150 mm onto the mid-span of the tested beams.

The SCC/VC beams in this test suddenly broke into two halves. On the other hand, the beams reinforced with SFs (SFSCC and SFVC) were difficult to break into two halves, therefore, the ultimate failure of SFSCC and SFVC beams was identified when the maximum crack width reached 5 mm.

In both tests the impact energy was calculated according to Eq. (1):

$$IE = Nmgh \quad (1)$$

Where N = number of drops; m = mass of the dropped hammer (4.45 kg); g = gravity acceleration (9.81 m/s^2); and h = drop height (150 or 457 mm).

3.6 Discussion of Test Results

3.6.1 Compressive Strength

3.6.1.1 Evaluation of Compressive Strength for Tested Mixtures at Room Temperature

Table 3-4 shows the 28-day compressive strength at different temperatures for all tested mixtures. It can be seen that increasing the coarse aggregate size showed a slight negative effect on the compressive strength of the concrete mixtures. For example, the mixture with

20 mm coarse aggregate size showed a reduction in compressive strength up to 5.5% compared to the mixture with 10 mm aggregate size (M2 compared to M1). Meanwhile, using higher C/F aggregate ratio (2 compared to 0.7) decreased the compressive strength by 15.4% (M6 compared to M7). This can be related to the increasing volume of the aggregate-paste interfacial zone (more porous and weaker area) with increasing the C/F aggregate ratio. These areas are the weakest part of a concrete matrix and the relatively higher volume of weak material negatively affected the overall concrete strength (Hassan et al. 2015, Larbi 1993). It should be noted that, increasing the aggregate size can also contribute to increasing the thickness of the aggregate-paste interfacial zone which also negatively affects the compressive strength (Basheer et al. 2005). However, the difference between the two sizes of the tested coarse aggregates in this investigation (20mm compared to 10mm) might not have been large enough to demonstrate the negative effect on the compressive strength. The results also indicate that increasing the fiber volume has a slight effect on enhancing the compressive strength. For example, increasing SFs volume from 0% to 1% slightly increases the compressive strength by 4.7%. Higher volume of SFs increases the ability of SFs to restrain crack propagation, reduce stress concentration at crack tips, and change crack direction, all of which tend to enhance the concrete strength. Increasing the SFs length from 35 mm to 60 mm shows a slight negative effect on the compressive strength of the developed mixtures (M8 compared to M7). This may be attributed to the fact that using longer SFs contributed to entrap higher air content compared to shorter SFs (see Table 3-3), which can cause a reduction in compressive strength. For mixtures with the same fiber volume and length, changing the fiber end conditions from single-hooked ends to double-hooked ends appeared to have insignificant effect on the

compressive strength. Table 3-4 also shows that increasing the cement content from 300 kg/m^3 to 550 kg/m^3 (M10 compared to M11) significantly increases the compressive strength by 45.7%.

Table 3-4 Mechanical properties tests at different temperatures

Mix #	Mixture	Compressive Strength (MPA)				FS (MPA)			
		Room	0	-10	-20	Room	0	-10	-20
1	SCC	66.83	70.30	73.68	84.37	5.4	5.75	6.15	6.715
2	SCC-20	63.19	67.23	71.58	82.16	5.1	5.7	6.15	6.75
3	SCC-0.35SF13	67.49	75.49	80.00	90.55	5.85	6.9	7.5	8.21
4	SCC-0.35SF35	68.10	74.91	78.91	89.70	6.4	7.1	7.65	8.6
5	VC	67.53	69.95	72.53	82.82	5.8	6.05	6.29	6.95
6	VC-2C/F	57.13	56.77	61.71	70.67	5.05	5.6	5.95	6.75
7	VC-1SF35	70.67	79.83	84.39	93.98	9.29	10.8	11.7	13.85
8	VC-1SF60	69.57	80.87	84.95	95.17	8.65	10.6	11.5	13.65
9	VC-1SF60-DH	70.03	80.23	83.13	91.06	9	10.2	10.9	12.85
10	VC-300	34.83	38.57	42.21	47.99	3.95	4.6	4.98	5.7
11	VC-550	50.73	52.67	55.96	60.98	5.1	5.35	5.6	6.1

3.6.1.2 Effect of Low Temperatures on the Compressive Strength of Tested Mixtures

The ratios between the compressive strength at subnormal temperatures and compressive strength at room temperature were calculated using Eq. 2:

$C_{T\text{-}20} = f_c\ @\text{-}20°/ f_c\ @\ \text{room},\quad C_{T\text{-}10} = f_c\ @\text{-}10°/ f_c\ @\ \text{room},\quad C_{T0} = f_c\ @\ 0°/ f_c\ @\ \text{room}$ (2)

Where $C_{T\text{-}20}$, $C_{T\text{-}10}$, C_{T0} are the compressive strengths corresponding to cold temperatures at -20° C, -10° C, and 0° C, respectively, f_c is the compressive strength at specified temperature.

Figure 3-3 shows the values of C_{T-20}, C_{T-10}, and C_{T0} for all tested mixtures. It can be seen that the compressive strength of all mixtures is improved when the temperature is decreased below room temperature. For example, decreasing the temperature of the control mixture (M1) from room temperature to 0° C, -10° C, and -20° C shows an increase in the compressive strength of 5.2%, 10.2%, and 26.1%, respectively. This can be attributed to a temperature-dependent decrease in the atomic distance, which increases the attractive force between atoms and in turn helps to enhance the concrete strength (Cai et al. 2011, Banthia et al. 1998). Moreover, at low temperature, the free water in concrete pores changes into ice, which can decrease inherent weakness in concrete by limiting micro-cracks and ITZ (Lee et al. 1988, Montejo et al. 2008, Berry et al. 2017). In addition, the strength of ice itself can help to enhance the concrete compressive strength. However, despite the enhancement in the compressive strength with decreasing temperature, the failure mode was observed in visual inspection of failed samples to be more brittle.

Figure 3-3a shows the C_{T-20}, C_{T-10}, and C_{T0} values for mixtures with different coarse aggregate size and different C/F aggregate ratio. It can be seen that the using larger coarse aggregate size (M2) gives a slight increase in the values of C_{T-20}, C_{T-10}, and C_{T0} compared to the control mixture with smaller aggregate size (M1). The effect of cold temperatures on the compressive strength is more pronounced when the C/F aggregate ratio increases from 0.7 to 2. For example, in the mixture with a C/F aggregate ratio of 0.7, decreasing the temperature from 0 to -20° C increases the compressive strength by 22.6%, but this increase improves to 29.5% when the C/F aggregate ratio of 2 is used. This can be attributed to increasing the volume/size of the cement-aggregate interface (weaker and more porous area) when using larger aggregate or higher C/F aggregate ratio, which augments the effect of ice formed in these areas, leading to higher concrete strength at lower temperatures.

Figure 3-3b shows the effect of SFs in enhancing compressive strength at lower temperature. It can be seen that adding SFs to concrete mixtures generally enhances the compressive strength at cold temperatures. For instance, adding SF35 to a SCC mixture shows C_{T-20}, C_{T-10}, and C_{T0} values of 1.29, 1.16, and 1.1, respectively, while these values reach 1.26, 1.1, and 1.05, respectively in the control mixture (M4 compared to M1). This can be explained by the fact that decreasing the temperature from room temperature to sub normal temperatures leads to shrinkage in the concrete, which causes a reduction in the atomic distance. This contributes to increasing the grip force around the SFs (higher bond with the concrete matrix) and hence improved concrete strength

By comparing SCC mixtures with different types of SFs (M3 and M4), it can be seen that SF13 exhibits higher enhancement in the compressive strength under cold temperature compared to SF35. This can be attributed to the difference in end conditions between SF35 (hooked ends) and SF13 (needle fibers). The hooked ends of SF35 provide a mechanical anchorage with the concrete, which overrides the advantage of better concrete gripping around the fibers at low temperature. This compares to SF13 which does not have hooked ends and thus depends mainly on the bond with the concrete matrix to prevent slipping. For the same reason, SF60 with single-hooked ends has a higher compressive strength enhancement factor at cold temperatures compared to the SF60 with double-hooked ends at the same fiber length (M9 compared to M8).

The results also indicate that increasing the SFs volume further increases the enhancement in the compressive strength at low temperatures. For example, increasing the SF35 volume from 0.35% (M4) to 1% (M7) increases the values of C_{T-20}, C_{T-10}, and C_{T0} from 1.29, 1.16, and 1.10 to 1.33, 1.19, and 1.13, respectively. Similarly, increasing the SFs length from 35 to 60, at the same end conditions shows higher improvement in the compressive strength under cold temperatures. This can be related to the higher effect of gripping force for longer SFs compared to shorter ones, when the concrete shrinks at the low temperatures. Among all types, lengths, and volumes of SF, the 1% SF60 shows the highest enhancement in the compressive strength under cold temperatures, while 0.35% SF35 shows the lowest enhancement.

Figure 3-3a also indicates that the mixture with lower cement content shows a noticeable improvement in the compressive strength at cold temperatures compared to the mixture with higher cement content. The mixture with 550 kg/m^3 cement content yields C_{T-20}, C_{T-10}, and C_{T0} values of 1.2, 1.1, and 1.04, respectively, while these values reach 1.38, 1.21, and 1.11, respectively, in the mixture with 300 kg/m^3 cement content (M11 compared to M10). As mentioned earlier, when the free water in the concrete pores changes into ice at low temperature, some of the inherent weakness factors of concrete are reduced. As the cement content increases, the hydration products are increased, and the concrete becomes more dense, leaving less room for ice to form in the concrete pores, which decreases the effect of cold temperature in enhancing the concrete strength.

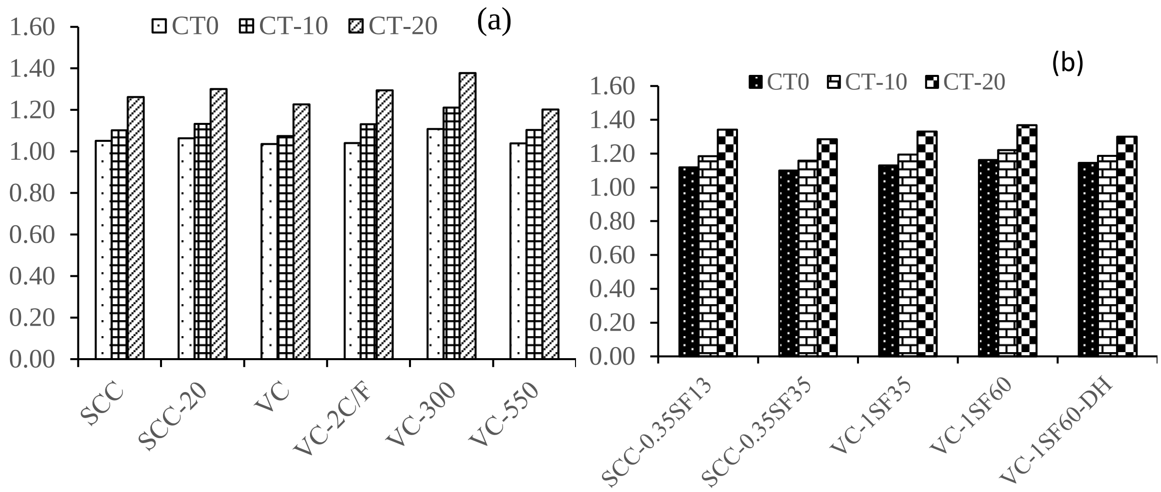

Figure 3-3 Effect of cold temperatures on the compressive strength of tested mixtures.

3.6.2 Flexural Strength

3.6.2.1 Investigating the Flexural Strength for Developed Mixtures at Room Temperature

Table 3-4 shows the 28-day FS for all tested mixtures. It can be seen that increasing the coarse aggregate size slightly reduces the FS of concrete mixtures. For example, using 20 mm coarse aggregate size reduces the FS by 6 %, compared to the mixture with 10 mm coarse aggregate size. In the meantime, the higher C/F aggregate ratio shows a noticeable reduction in the FS. For instance, increasing the C/F aggregate ratio from 0.7 to 2 reduces the FS by 11% (M6 compared to M5). This can be attributed to the same factors discussed in the compressive strength section.

The results also show that adding SFs to concrete mixtures significantly improves the FS. For example, using SF35 in the SCC mixture increases the FS by 19%. The addition of fibers helps to transfer the stress across the cracked section, which in turn helps enhance the FS. By looking at mixtures with different SFs types (M3 compared to M4), it can be seen that SF35 shows a better enhancement in the FS compared to SF13. This may be attributed to the hooked ends of SF35 which provide a better bond with the concrete matrix and further enhance the tensile strength compared to SF13 with straight ends (see **Figure 3-2**). Table 3-4 also shows that increasing the SFs volume up to 1% shows a further enhancement in the FS, which reaches 60% compared to the mixture without fibers (M7 compared to M5). By comparing mixtures with different SFs lengths (M8 compared to M7), it can be seen that increasing the SFs length from 35 mm to 60 mm shows a slight reduction in the FS. For a given volume of SFs, using shorter fibers increases the number of single fibers that can be oriented across a crack section, which improves the fibers stitching mechanism and therefore, enhances the tensile strength. Changing the fiber end conditions from single-hooked to double-hooked ends shows a slight enhancement in the FS of up to 4% (M9 compared to M8). This can be attributed to the better mechanical bond between the SFs and concrete matrix provided by the double-hooked ends compared to single-hooked ends. The results also show that increasing the cement content from 300 kg/m^3 to 550 kg/m^3 provides an increase in the FS of up to 29% (M11 compared to M10).

Prior to mixing, the coarse aggregate, cement, SCMs, CR, and sand were placed in a rotary mixer and then dry-mixed for approximately 1.5 minutes. For fiber mixtures, fibers were gradually added during the dry-mixing process to obtain well-distributed fibers and avoid the formation of fiber balls in the mixture. Next, around 65% of the required amount of water was added to the dry materials and remixed for another 1.5 minutes. The remaining water was first mixed with the required dosage of HRWRA and then added to the mixer and remixed for another 2.5 ± 0.5 minutes. After obtaining the target slump flow diameter (700 ± 50 mm) for SCC/SCRC/FRSCRC mixtures.

3.6.2.2 Effect of Cold Temperatures on the FS of Developed Mixtures

The ratios between the FS at cold temperatures and FS at room temperature were calculated as shown in Eq. 3:

F_{T-20} = FS @-20°/ FS @ room, F_{T-10} = FS @-10°/ FS @ room, F_{T0} = FS @ 0°/ FS @ room (3)

Where F_{T-20}, F_{T-10}, F_{T0} are the FS factors related to cold temperatures of -20° C, -10° C, and 0° C, respectively, FS is the flexural strength at the specified temperature.

The values of F_{T-20}, F_{T-10}, and F_{T0} for all tested mixtures are shown in **Figure 3-4** Decreasing the temperature shows enhancement in the FS of all concrete mixtures. This was confirmed by looking at the values of F_{T-20}, F_{T-10}, and F_{T0} which exceed 1 in all mixtures. Decreasing the temperature helped to change the water in the pores of the concrete into ice, which enhances the strength of concrete (Montejo et al. 2008, Cai et al. 2011). Moreover, forming ice in concrete can fill the micro-cracks and un-compacted zones, which mitigates the effects of these latent defects in concrete and thus enhances the concrete strength. Figure 3-4a shows the effect of cold temperature on the FS of mixtures with different C/F aggregate ratios and different coarse aggregate sizes. Increasing the coarse aggregate size from 10 mm to 20 mm increases the values of F_{T-20}, F_{T-10}, and F_{T0} by 1.06, 1.05, and 1.04, respectively, and these ratios reach 1.12, 1.09, and 1.06, respectively when the C/F aggregate ratio increases from 0.7 to 2. This can be attributed to the effect of ice formed in the aggregate-paste interfacial zone, which contributes to controlling micro-cracks width and improving the bond between aggregate and mortar, both of which enhance the concrete strength.

Figure 3-4b shows the effect of cold temperatures on the FS of mixtures reinforced with different SFs lengths, types, and volumes. Using SFs generally showed a higher enhancement in the FS at cold temperatures compared to mixtures without SF. For example, SF35 exhibits F_{T-20}, F_{T-10}, and F_{T0} values of 1.34, 1.2, and 1.11, respectively, while the control mixture without fibers shows values of 1.24, 1.14, and 1.06, respectively (M4 compared to M1). This may be attributed to the shrinkage of concrete at cold temperatures helping to improve the bond between the SFs and the concrete matrix, which increases the crack arresting capability of the fibers thus improving the concrete tensile strength. Shrinkage of the concrete at low temperature also controls micro-cracks widths and limits crack propagation, which in turn helps improve the tensile strength (Richardson and Ovington 2017). The results also show that needle fibers, SF13, show higher enhancement in the FS at cold temperatures compared to hooked end fibers SF35. This can be attributed to the effect of concrete gripping, which is more effective on the needle fibers than the hooked end fibers. The results in fig. 4b show that further enhancement in the FS at cold temperatures is achieved when the percentage of SFs increases from 0.35% to 1%. For example, when 1% SF35 is used, the values of F_{T-20}, F_{T-10}, and F_{T0} reach 1.49, 1.26, and 1.16, respectively, while when 0.35% SF35 is used these values are 1.34, 1.2, and 1.11, respectively. Similar to the compressive strength, the effect of cold temperatures on the FS was less significant when double-hooked end SFs was used, compared to single-hooked end SFs (M9 compared to M8).

Figure 3-4a also shows that using lower cement content leads to better improvement in the FS at cold temperatures when compared to mixtures with higher cement content. For example, the mixture with 300 kg/m^3 cement content shows a higher enhancement in the FS under -20° C, -10° C, and 0° C reaching 21%, 15%, and 11%, respectively, compared to the mixture with 550 kg/m^3.

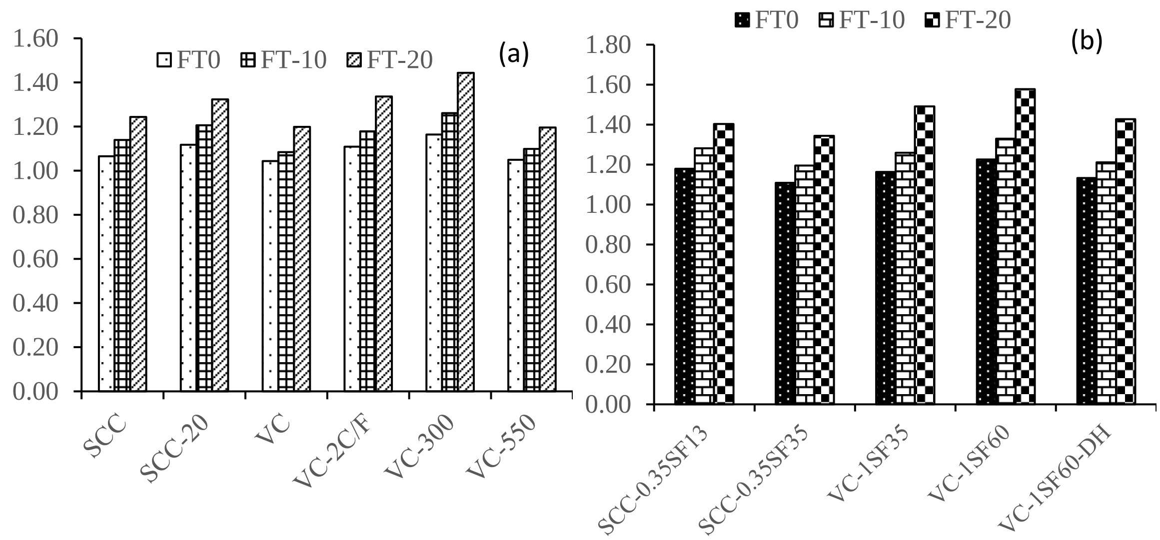

Figure 3-4 Effect of cold temperatures on the flexural strength of tested mixtures.

3.6.3 Impact Resistance of Tested Mixtures

3.6.3.1 Impact Resistance at Room Temperature

Table 3-5 and Table 3-6 show the results of drop weight impact resistance and flexural impact resistance for all tested mixtures. Table 3-5 presents the energy required to cause a first crack (E1), energy required to cause failure (E2), and the difference between E2 and E1, which indicates the post cracking behavior under impact. Table 3-6 shows the energy required to cause failure (E) in the flexural impact test, which is defined as the energy required to break the prisms into two halves, in normal concrete, or the energy required to cause a crack of 5 mm width, in fiber reinforced concrete. Using SFs significantly enhances both the drop weight impact resistance and the flexural impact resistance. However, the enhancement in the flexural impact resistance is more significant. This can be associated with the previous results in that, flexural impact is more aligned with FS, while the drop weight impact is more aligned with compressive strength. Similarly, since the effect of SFs is more significant for the FS compared to the compressive strength, the enhancement in the flexural impact (due to the addition of SF) was more pronounced when compared to the drop weight impact. For mixtures reinforced with SF, higher ductility and better post cracking behavior leads to more significant differences between E1 and E2, compared to mixtures without fiber. Comparing all mixtures, the 1% SF35 provides the highest improvement in impact resistance, under both drop weight impact and flexural impact loading. Meanwhile, the lowest enhancement is observed for 0.35% SF13. The results also show that increasing SFs volume from 0.35% to 1% increases E1 and E2 by 67.6% and 72.5%, respectively, for the drop weight test. Changing the fiber end conditions from single-hooked ends to double-hooked ends provides a slight enhancement in the impact resistance under both drop weight impact and flexural impact. Double-hooked end SFs shows a better enhancement in the bond between SFs and the concrete matrix compared to single-hooked end SF. On the other hand, longer SFs shows a slight reduction in the impact resistance, compared to shorter fibers. For example, using SF60 increases E1, E2, and E by 2.3, 2.8, and 3.66 times, respectively, when compared to the control mixture (M8 compared to M5), while these values of E1, E2, and E reach 2.8, 3.2, and 4.13 respectively, when SF35 is used (M7 compared to M5).

Table 3-5 Drop weight impact results at different temperatures

Mix #	Mixture	Drop weight Impact results											
		Room			0			-10			-20		
		E1	E2	E2-E1	E1	E2	E2-E1	E1	E2	E2-E1	E1	E2	E2-E1
M1	SCC	3392	3431	40	3970	3990	20	4888	4908	20	7222	7222	0
M2	SCC-20	3172	3192	20	3870	3890	20	4788	4788	0	7082	7082	0
M3	SCC-0.35SF13	4868	5486	618	7062	7920	858	9516	10713	1197	14444	16160	1716
M4	SCC-0.35SF35	6105	7102	998	8878	9915	1037	11431	12569	1137	17955	19352	1397
M5	VC	3711	3771	60	4329	4369	40	5047	5067	20	7501	7501	0
M6	VC-2C/F	2953	3032	80	3870	3870	0	4888	4888	0	7002	7002	0
M7	VC-1SF35	10234	12249	2015	17037	19032	1995	22344	25137	2793	32738	36149	3411
M8	VC-1SF60	8678	10534	1855	16100	18494	2394	22145	25536	3392	34035	38304	4269
M9	VC-1SF60-DH	9277	11232	1955	15761	17915	2155	20349	23541	3192	29646	33716	4070
M10	VC-300	2314	2354	40	3810	3830	20	5207	5207	0	7142	7142	0
M11	VC-550	2753	2813	60	3910	3950	40	5107	5127	20	6524	6524	0

Table 3-6 flexural impact results at different temperatures

Mix #	Mixture	Flexural impact results under different temperatures			
		Room	0	-10	-20
		E	E	E	E
M1	SCC	1476	2075	3491	4329
M2	SCC-20	1297	1915	3272	4070
M3	SCC-0.35SF13	3052	5486	10055	12668
M4	SCC-0.35SF35	3910	6683	11372	14564
M5	VC	1636	2234	3631	4589
M6	VC-2C/F	1197	1855	3332	3810
M7	VC-1SF35	6763	16359	24718	29626
M8	VC-1SF60	5985	16100	23342	27531
M9	VC-1SF60-DH	6324	15741	22943	26514
M10	VC-300	938	1736	2993	3990
M11	VC-550	1157	1796	2893	3591

3.6.3.2 Impact Resistance at Cold Temperature

The ratios between the energy required to cause failure in the concrete samples at cold temperatures and the comparable energy at room temperature were calculated using Equations 4 and 5:

Ed_{T-20} = E2 @-20°/ E2 @ room, Ed_{T-10} = E2 @-10°/ E2 @ room, Ed_{T0} = E2 @ 0°/ E2 @ room (4)

E_{T-20} = E @-20°/ E @ room, E_{T-10} = E @-10°/ E @ room, E_{T0} = E @ 0°/ E @ room (5)

Where Ed_{T-20}, Ed_{T-10}, and Ed_{T0} are the E2 factors measured at temperatures of -20° C, -10° C, and 0° C, respectively, E2 is the energy required to cause failure in the drop weight test. Meanwhile, E_{T-20}, E_{T-10}, and E_{T0} are the Energy absorption factors related to cold temperatures of -20° C, -10° C, and 0° C, respectively, E is the energy absorption required to cause failure in the Flexural impact test.

Figure 3-5 shows the values of Ed_{T-20}, Ed_{T-10}, and Ed_{T0} for all mixtures. Also, the values of E_{T-20}, E_{T-10}, and E_{T0} for all tested mixtures are shown in Figure 3-6. Decreasing the temperature below room temperature generally enhances the impact resistance of the concrete mixtures. The values of Ed_{T-20}, Ed_{T-10}, Ed_{T0}, E_{T-20}, E_{T-10}, and E_{T0} exceed 1 for all mixtures. However, the mode of failure for samples without fibers is more brittle under cold temperatures. This is confirmed by examining the difference between E2 and E1 at room temperature and at the cold temperatures. For example, the difference between E2 and E1 of the control mixture (M1) at room temperature is 39.9 kN-mm, while decreasing the temperature to -20° C shows no difference between E2 and E1, which indicates more brittle failure. The effect of cold temperature on the flexural impact results is more significant compared to that in the drop weight impact results. This can be attributed to the stronger influence of the enhanced flexural strength (resulting from cold temperature) in the flexural impact results compared to the drop weight impact results.

The results also indicate that using SFs contributes to the effect of cold temperature in enhancing both flexural impact resistance and drop weight impact resistance. Figure 3-5b and Figure 3-6b show that using 1% SF60 yields the highest enhancement in the values of Ed_{T-20}, Ed_{T-10}, Ed_{T0}, ET_{-20}, E_{T-10}, and E_{T0} compared to all other mixtures with SFs. Meanwhile, the lowest enhancement in these values is observed for 0.35% SF35. In mixtures without SFs, as the temperature decreases the difference between E2 and E1 also decreases, indicating brittle failure. On the other hand, in mixtures reinforced with SFs, the difference between E2 and E1 increases as the temperature decreases, indicating a more ductile failure. By comparing the post cracking behavior of mixtures with different SFs, it can be seen that mixture with 1% SF60 shows the best post cracking behavior at cold temperatures, while the worst post cracking behavior is observed for 0.35% SF35. Increasing SFs volume and/or SFs length shows a further enhancement in the impact resistance at cold temperatures. This can be observed by comparing M7 to M4, in which the values of Ed_{T0}, Ed_{T-10}, and Ed_{T-20} reach 1.55, 2.05, and 2.95, respectively, with 1% SF35 compared to 1.39, 1.77, and 2.7, respectively, with 0.35% SF35. Similar behavior is observed in the results of E_{T-20}, E_{T-10}, and E_{T0} under flexural impact testing, when SFs volume/length increases. Figure 3-5b and Figure 3-6b also show that using single hooked end SFs enhances the impact resistance of concrete compared to double-hooked end SF. This can be related to the improved FS of mixtures with single-hooked end SFs under cold temperatures compared to double-hooked ends SFs.

Figure 3-5a and Figure 3-6a show the effect of coarse aggregate size, C/F aggregate ratio, and cement content on the impact resistance at cold temperatures. Using larger coarse aggregate size slightly enhances the values of Ed_{T-20}, Ed_{T-10}, Ed_{T0}, ET_{-20}, E_{T-10}, and E_{T0} under both the drop weight impact and the flexural impact loading. A better improvement in the effect of cold temperature on impact resistance is observed when the C/F aggregate ratio is increased from 0.7 to 2. This can be attributed to the more pronounced effect of cold temperatures on both compressive strength and tensile strength when the C/F aggregate ratio is increased, compared to the increase in the coarse aggregate size.

The cement content also has a significant effect on the impact resistance under cold temperatures, in which using lower cement content significantly increases the values of Ed_{T-20}, Ed_{T-10}, and Ed_{T0} in the drop weight test and the values of ET_{-20}, E_{T-10}, and E_{T0} in the flexural impact test. For example, decreasing the cement content from 550 kg/m^3 to 300 kg/m^3 increases the values of Ed_{T-20}, Ed_{T-10}, and Ed_{T0} by 15.9%, 21.4%, and 30.8%, respectively, for the drop weight test. Meanwhile, the increase in the values of ET_{-20}, E_{T-10}, and E_{T0} reach 19.3%, 27.7%, and 37.2%, respectively, under the flexural impact test, when the cement content is decreased from 550 kg/m^3 to 300 kg/m^3.

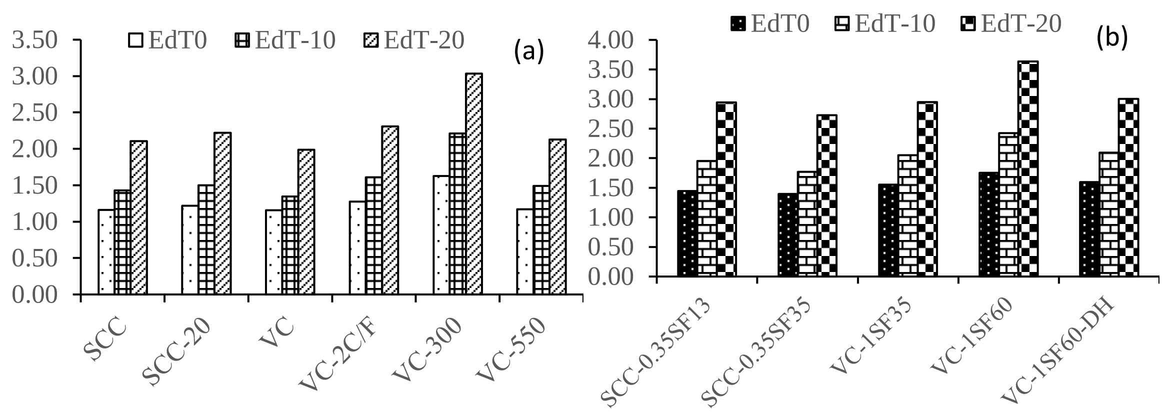

Figure 3-5 Effect of cold temperatures on drop weight impact resistance of tested mixtures

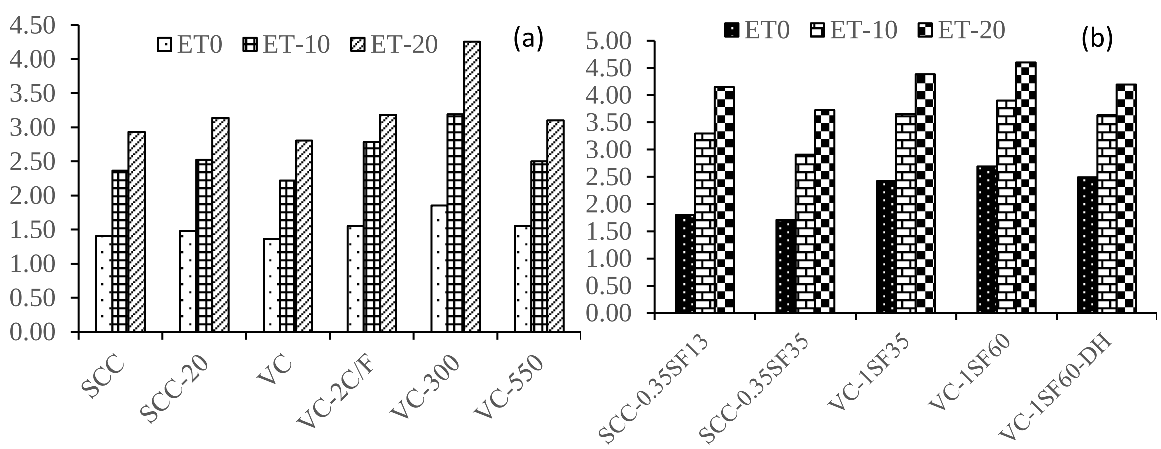

Figure 3-6 Effect of cold temperatures on flexural impact resistance of tested mixtures.

3.7 Conclusions

This study presents the effect of low temperatures on the mechanical properties and impact resistance of concrete mixtures reinforced with different types, lengths, and volumes of SFs. The effect of low temperatures on mixtures with different coarse aggregate sizes, C/F aggregate ratios, and cement content was also studied. The following conclusions can be drawn:

1. For all tested mixtures, decreasing the temperature of concrete samples below the room temperature shows an improvement in the compressive strength, FS, and impact resistance. However, the failure mode of concrete samples without fibers is more brittle as the temperature decreases.
2. The effect of cold temperatures on enhancing the mechanical properties and impact resistance is higher when the C/F aggregate ratio or coarse aggregate size increases. However, the effect of increasing the C/F aggregate ratio from 0.7 to 2 was more pronounced when compared to the effect of increasing the coarse aggregate size from 10 mm to 20 mm.
3. Adding SFs to concrete mixtures augmented the effect of cold temperature in enhancing the compressive strength, FS, and impact resistance. For example, using SF35 increased the values of C_{T-20}, F_{T-20}, and EdT_{-20} by 4.3%, 8%, and 29.5%, respectively, compared to the control mixture without SFs.

4. Among all mixtures reinforced with different types, lengths, and volumes of SFs, using 1% SF60 showed the highest enhancement in the compressive strength, FS, and impact resistance at cold temperatures, while the lowest enhancement was observed for 0.35% SF35.
5. Using SFs enhanced the post cracking behavior under the drop weight impact test in cold temperature. For example, in mixtures without SFs, the difference between E2 and E1 decreased as the temperature decreased indicating brittle failure at lower temperatures. Meanwhile, in mixtures reinforced with SFs, the difference between E2 and E1 increased as the temperature decreased, which highlights the effect of SFs in alleviating the brittleness that resulted from decreasing the temperature.
6. The effect of cold temperatures is more pronounced in enhancing the compressive strength, FS, and impact resistance of mixtures with low cement content (300 kg/m^3) compared to those with higher cement content (550 kg/m^3).

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4 Abrasion Resistance of Fiber-Reinforced Concrete under Cold Temperatures

4.1 Abstract

This study aimed to investigate the effect of cold temperatures on the abrasion resistance and mechanical properties of fiber-reinforced concrete mixtures with different saturation conditions. The studied variables included types of steel fibers (SFs) (needle fibers, single hooked ends, and double hooked ends), volumes of SFs (0%, 0.35%, and 1%), lengths of SFs (35 mm and 60 mm), coarse-to-fine aggregate ratios (C/F) (0.7 and 2), coarse aggregate sizes (10 mm and 20 mm), and cement content (300 kg/m^3 and 550 kg/m^3). The results indicated that decreasing the temperature below the normal temperature generally enhanced the abrasion resistance of concrete. On the other hand, all saturated samples showed a better enhancement in the abrasion resistance and mechanical properties under cold temperatures compared to unsaturated samples. The behavior of saturated samples compared to unsaturated samples under cold temperatures was obviously affected by C/F aggregate ratio and cement content. Among all mixtures reinforced with different types, lengths, and volumes of SFs, using 1% 60 mm single hooked ends SFs showed the highest improvement in the mechanical properties and abrasion resistance under cold temperatures. Meanwhile, the lowest enhancement was recorded when 0.35% 35 mm SFs were used.

4.2 Introduction

Concrete structures in Arctic regions, especially offshore structures, are exposed to several loading conditions under critical low temperatures. For example, bridge piers, lighthouses, and harbor platforms in cold regions are typically exposed to abrasive loads of sand, gravel, rocks, and ice flow in addition to impact loading from ship and iceberg collisions. The mechanical properties, impact resistance, and abrasion resistance of concrete under normal temperature has become well known. However, at cold temperatures, particularly below freezing, the properties of concrete can be quite different, since the mechanisms that control the mechanical properties of concrete vary significantly with temperature (Piegeon and Cantin,1998; Xie and Yan, 2018). Previous studies have indicated that compressive strength, tensile strength, Young's Modulus, and elastic stiffness increased as the temperature decreased below the ambient temperature (Lee et al. 1988; Eranti and Lee, 1986; Dahmani et al. 2007; Kogbara et al. 2013; Krstulovic-opara, 2007). Despite this, there are several studies that have focused on the behavior of concrete under extremely low temperatures typical for liquid nitrogen gas storage concrete tanks; however, there are few studies that have investigated the behavior of concrete under cold temperatures typical for cold regions. Montejo et al. (2008) investigated the effect of decreasing the temperature from 20° C to -40° C on the seismic performance of concrete columns under cyclic loading. Their results revealed that the flexural strength and elastic stiffness increased by 15% and 90%, respectively, while the displacement capacity decreased by 20% when the temperature increased from 20° C to -40° C.

Concrete under ambient temperature is characterized by insufficient ductility, low energy absorption, and low tensile strength. The low tensile strength of concrete at ambient temperature can also significantly affect the abrasion resistance of concrete, in which the low tensile strength can result in easy disintegration of aggregate from concrete surface under the abrasion force. The abrasion resistance of concrete is also affected by the concrete paste's hardness, aggregate type, and aggregate/paste bond (Papenfus, 2003; Yazici and Sezer, 2007; Beshr et al. 2003). Kilic et al. (2008) studied the abrasion resistance of high-strength concrete developed with five types of coarse aggregate (gabbro, basalt, quartzite, limestone, and sandstone). Their study indicated that the highest abrasion resistance was observed when gabbro coarse aggregate was used, while sandstone coarse aggregate showed the lowest abrasion resistance. Laplante et al. (1991) studied the effect of using different coarse aggregate types including granite, dolomite, and limestone on the abrasion resistance of concrete. Their results revealed that granite coarse aggregate with the highest strength and hardness showed the highest abrasion resistance, while the lowest abrasion resistance was recorded when limestone was used.

Using fibers in concrete mixtures has proven to enhance mechanical properties, ductility, energy absorption, impact, and abrasion resistance of concrete under normal temperatures (Bolat et al. 2014; Yap et al. 2014; Ababneh et al. 2017). By reviewing the literature, it can be observed that different types of fibers including steel fibers (SFs) and polypropylene fibers were used to enhance the mechanical properties and abrasion resistance of concrete. However, SFs appeared to be more useful in cold temperatures compared to polypropylene fibers. This is because of the low glass transition temperature of polypropylene fibers, which can negatively affect the ductility of concrete at low temperatures. Previous studies have indicated that the length and volume of SFs in the mixture significantly affected the ductility, cracking behavior, compressive strength, tensile strength, and abrasion resistance of concrete. For example, Ismail and Hassan (2016) studied the mechanical properties and cracking behavior of rubberized concrete reinforced with different volumes and lengths of SFs. Their study indicated that using up to 1% SFs exhibited an enhancement in the compressive strength, splitting tensile strength (STS), and flexural strength (FS) reaching up to 1.07, 1.93, and 1.75 times, respectively, compared to the mixture without fibers. They also observed that using longer SFs (60 mm) increased the first crack and failure crack resistance by 1.17 and 1.19 times, respectively, than the shorter SFs (35 mm). Atis et al. (2009) investigated the abrasion resistance of concrete reinforced with different volumes of SFs including 0.25%, 0.5%, 1%, and 1.5%. Their results revealed that using higher volumes of SFs showed a higher abrasion resistance of concrete, in which the reduction in mass loss of the concrete sample reached up to 6.7%, 7.5%, 25.2%, and 29.5% when 0.25%, 0.5%, 1%, and 1.5% SFs were used. Using different SF types also showed an impact on the mechanical properties of concrete. For instance, Murali et al. (2016) studied the effect of two different types of SFs on the flexural strength of concrete. Their study indicated that using crimped SFs increased the flexural strength by 50.7% compared to mixtures without fibers, while this increase reached up to 55% when hooked ends SFs were used. Another study by Afroughsabet et al. (2017) also reported that using 1% double hooked ends SFs increased the STS and FS by 60% and 88%, respectively, compared to mixtures without SFs. Since SFs showed several benefits in enhancing the ductility, mechanical properties, and abrasion resistance of concrete under normal temperatures, use of SFs is also expected to further enhance the concrete behavior under cold temperatures.

This study investigated the abrasion resistance and mechanical properties of concrete with different saturation conditions under cold temperatures. The effect of using SFs to further enhance the abrasion resistance of concrete under cold temperatures was also investigated. The tested properties were compressive strength, STS, and abrasion resistance under rotating-cutter and sandblasting abrasive effect. The studied mixtures were developed with different coarse aggregate sizes, different coarse to fine aggregate ratios (C/F), and different types, lengths, and volumes of SFs, and various cement content.

4.3 Research Significance

Offshore concrete structures in cold regions such as bridge piers and harbor platforms are exposed to tidal cycles and different water levels, which result in different saturation conditions of concrete elements. In addition, these concrete elements are also subjected to abrasive force by sand, gravel, rocks, and ice flow in cold temperatures. Despite the fact that some research studies have investigated the mechanical properties and abrasion resistance of concrete under normal temperatures, the effect of cold temperatures on the abrasion resistance of concrete, especially with different saturation conditions, is still unknown. In addition, there are no available studies that have investigated the effect of cold temperatures on the abrasion resistance of concrete when different types, lengths, and volumes of SFs are used. This study shows the significant influence of using different mixture composition on enhancing the abrasion resistance under cold temperatures. The authors believe that this study will contribute greatly to developing fiber-reinforced concrete mixtures with high resistance to abrasive force that will be beneficial for concrete structures in Arctic regions.

4.4 Experimental Program

4.4.1 Material Properties

GU Portland cement similar to ASTM C150 (ASTM 2012a), metakaolin (MK) similar to ASTM C618 (ASTM 2012b) class N, and fly ash (FA) similar to ASTM C618 (ASTM 2012b) Type F were used as binders for all developed mixtures. Table 4-1 shows the physical and chemical properties of the materials used. Natural sand and natural crushed stone with 10 mm and 20 mm maximum aggregate sizes were used as fine and coarse aggregates. All aggregate types had a specific gravity of 2.6 and absorption of 1%. Figure 4-1 presents the gradation of the natural sand: 10 mm and 20 mm crushed stones. Four types of SFs were used: a) needle fibers (NYCON-SF) coated with copper to resist corrosion with a length of 13 mm (SF13); b) two types of single hooked ends SFs (Dramix 3D) with a length of 35 mm and 60 mm (SF35 and SF60); and c) double hooked ends SFs (Dramix 5D) with a length of 60 mm (SF60-DH).

Table **4-2** presents the mechanical and physical properties of SFs, while the geometric configurations of SFs are shown in Figure 4-2. A polycarboxylate-based high-range water-reducer admixture (HRWRA) similar to ASTM C494 type F (ASTM 2013) with a specific gravity of 1.2, volatile weight of 62%, and pH of 9.5 was used to achieve the required slump flow of mixtures.

Table 4-1 Chemical and physical properties of SCMs used

Chemical properties (%)	FA	MK	Cement
SiO_2	52	51-53	19.64
Al_2O_3	23	42-44	5.48
Fe_2O_3	11	<2.2	2.38
CaO	5	<0.2	62.44
MgO	-	<0.1	2.48
C_2S	-	-	16.83
C_3A	-	-	10.50
C_4AF	-	-	7.24
L.O.I	0.21	0.95	2.05
K_2O	2	<0.40	-
C_3S	-	-	52.34
Physical properties			
Specific gravity	2.38	2.56	3.15
Blaine fineness (m^2/kg)	20000	1390	410

Table 4-2 Characteristics of the fibers used

Fibers used	Type	End Conditions	Length (mm)	Diameter/Equivalent Diameter (mm)	Tensile Strength (Mpa)
SF13	Steel fiber	Needle	13	0.2	1900
SF35	Steel fiber	Single hooked	35	0.55	1150
SF60	Steel fiber	Single hooked	60	0.9	1150
SF60-DH	Steel fiber	Double hooked	60	0.9	1150

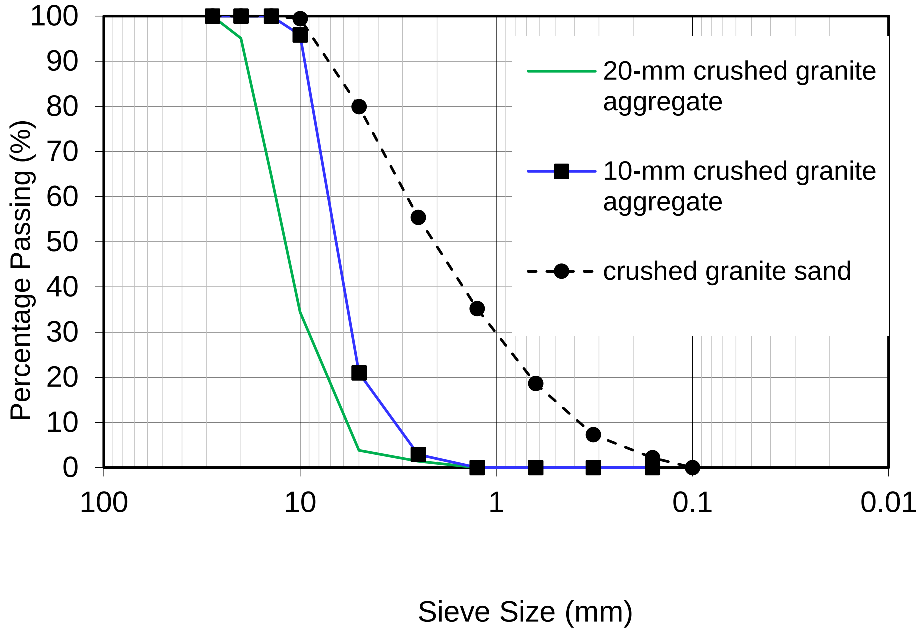

Figure 4-1 Gradation curves for both fine and coarse aggregates

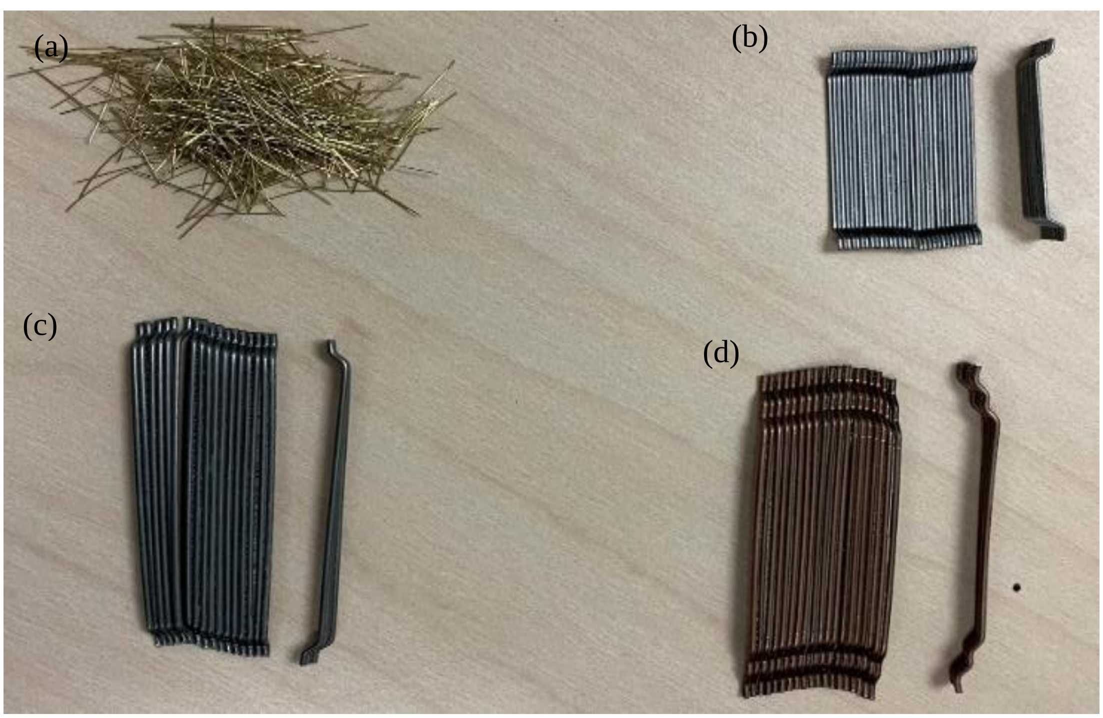

Figure 4-2 Configuration and geometry of fibers used: (a) SF13, (b) SF35, (c) SF60, (d) SF60-DH

4.4.2 Mixtures Development

This investigation was designed to study the effect of cold temperatures on the abrasion resistance of concrete mixtures developed with different types of SFs. The developed mixtures consisted of two self-consolidating concrete (SCC) mixtures, two SCC mixtures reinforced with SFs (SFSCC), four vibrated concrete (VC) mixtures, and three VC mixtures reinforced with SFs (SFVC). A preliminary trial mixture stage was performed to optimize the selected mixtures. The results of the trial mixture stage indicated that in order to obtain a balanced viscosity and adequate flowability (slump of 700 ± 50 mm) with no visual sign of segregation for SCC mixtures with/without SFs, a total binder content of at least 550 kg/m^3 and a minimum water-to-binder ratio (w/b) of 0.4 should be used. The binder content (550 kg/m^3) consisted of 50% cement, 30% FA, and 20% MK. These ratios were selected to satisfy the requirements of the flowability, passing ability, and segregation resistance as per the European Guidelines for Self-Consolidating Concrete (EFNARC 2005). In particular, MK was used to enhance the mixture viscosity and particle suspension, while the use of FA was necessary to improve the flowability of the mixture. Trial mixtures also indicated that the maximum percentage of SFs that could be used in SFSCC mixtures was 0.35%, and further increases beyond 0.35% significantly reduced the fresh properties (especially the passing ability). Table 4-3 shows the mixture compositions for all developed mixtures.

All mixtures were designated according to the type of concrete (SCC or VC), C/F aggregate ratio, coarse aggregate size, volume/length of SFs, and end conditions of SFs. For example, the VC mixture with cement content of 300 kg/m^3 was labeled VC-300, while the SCC mixture with 20 mm coarse aggregate was labeled SCC-20. In mixtures with SFs, the mixture with 1% 60 mm double hooked SFs was labeled VC-1SF60-DH. Table 4-3 presents the material proportions of all tested mixtures.

The experimental program was designed based on the following:

- Mixtures M2 and M1 were typical except that M2 used 20 mm coarse aggregates (instead of 10 mm in M1). These mixtures were selected to study the effect of cold temperatures on the abrasion resistance of mixtures with different aggregate sizes.
- Mixtures M3 and M4 were developed as SFSCC to investigate the effect of using different types of SFs on the abrasion resistance of concrete under cold temperatures.
- Mixtures M5 and M6 were developed to investigate the effect of increasing the C/F aggregate ratio on the abrasion resistance of concrete under cold temperatures.
- Mixtures M7 compared to M8 were selected to study the effect of cold temperatures on the abrasion resistance of concrete with different SF lengths (35 mm and 60 mm). It should be noted that, because of the long length of SF60, it was not possible to develop M8 as SCC. These long fibers got stuck between the L-box vertical bars and significantly reduced the passing ability of M8. Therefore, M8 and M7 were developed as SFVC. And since these two mixtures were developed with the absence of SCC fresh properties restrictions (especially passing ability), these mixtures were also developed with maximized percentage of SFs (maintaining uniform distribution of SFs without any sign of fiber clumping) to manifest the effect of SFs on the abrasion resistance of mixtures under cold temperatures.

- Mixtures M8 and M9 were SFVC developed with the same length (60 mm) and percentage (1%) of SFs, but with different SF end conditions. M8 was developed with single hooked ends SFs, while M9 was developed with double hooked ends SFs (SFs-DH). These mixtures were selected to study the effect of SFs end conditions on the studied properties at cold temperatures.
- Mixtures M10 and M11 were VC mixtures developed with different cement content (300 kg/m^3 and 550 kg/m^3) and no supplementary cementing materials. However, the w/b and C/F aggregate ratio were similar in both mixtures (0.4 and 0.7, respectively). These mixtures were selected to study the effect of cement content on the abrasion resistance of concrete under cold temperatures.

It should be noted that it was not possible to develop mixtures M6 to M11 as SCC mixtures due to the high C/F aggregate ratio or high percentage of SFs used in these mixtures.

4.5 Testing Program

4.5.1 Fresh and Mechanical Properties Tests

The fresh properties of SCC/SFSCC were evaluated using slump flow, J-ring, V-funnel, L-box, and sieve segregation resistance tests as per (EFNARC 2005). The flowability of mixtures was evaluated by recording V-funnel time, the time to reach 500 mm slump flow diameter (T50), and the time to reach 500 mm J-ring diameter (T50J). The ratio of H2/H1 of the L-box test was measured to assess the passing ability. Sieve segregation resistance tests were performed to measure the segregation resistance of SCC/SFSCC mixtures. The workability of VC/SFVC mixtures was evaluated by measuring the slump test according to

ASTM C143 (ASTM 2015). Three identical concrete cylinders (100 mm diameter x 200 mm height) were used to evaluate each of compressive strength and STS as per ASTM C39 (ASTM 2011a) and ASTM C496 (ASTM 2011b), respectively. All tested samples were stored in cold rooms with the target temperatures (-20° C, -10° C, 0° C) for 48 hours to reach a steady temperature state before testing. It is worth noting that the saturated samples were oven dried first to make sure that the samples are fully dried, then immersed in the water for 24 hours to reach the full saturation level and then followed the freezing procedures applied on the unsaturated samples.

Table 4-3 Proportion details of tested mixtures

Mix #	Mixture	Cement (kg/m^3)	SCM (kg/m^3)	SCM (Type)	F. A. (kg/m^3)	C. A. (kg/m^3)	Fiber (V_f%)	w/b	C/F ratio	Air content	Water absorbed (gm)
M1	SCC	275	110+165	MK+FA	886.1	620.3	-	0.4	0.7	1.3	110.5
M2	SCC-20	275	110+165	MK+FA	886.1	620.3	-	0.4	0.7	1.5	108
M3	SCC-0.35SF13	275	110+165	MK+FA	886.1	620.3	0.35	0.4	0.7	1.45	123.7
M4	SCC-0.35SF35	275	110+165	MK+FA	886.1	620.3	0.35	0.4	0.7	1.6	116.6
M5	VC	275	110+165	MK+FA	886.1	620.3	-	0.4	0.7	1.2	93.7
M6	VC-2C/F	275	110+165	MK+FA	503	1006	-	0.4	2	1.55	141.3
M7	VC-1SF35	275	110+165	MK+FA	886.1	620.3	1	0.4	0.7	1.3	118.8
M8	VC-1SF60	275	110+165	MK+FA	886.1	620.3	1	0.4	0.7	1.5	120.9
M9	VC-1SF60-DH	275	110+165	MK+FA	886.1	620.3	1	0.4	0.7	1.45	115.3
M10	VC-300	300	--	--	1200.2	840.2	-	0.4	0.7	2.4	201.3
M11	VC-550	550	--	--	925.9	648.1	-	0.4	0.7	1.9	115.6

Note: SCM = supplementary cementing materials; FA = fly ash; MK = metakaolin; C. A. = coarse aggregate; F. A. = fine aggregate; Vf = volume fraction.

4.5.2 Abrasion Resistance Tests

Two abrasion tests were conducted to evaluate abrasion resistance as follows:

1. Rotating-cutter test: This test was conducting according to ASTM C944 (ASTM 2012a) to assess the performance of concrete under the action of abrasion force, such as heavy traffic on highways and concrete bridges. In this test, the concrete sample was first weighted to the nearest 0.1 g, then fixed securely in a rotating-cutter drill press. After performing the test, the concrete sample was air-blown to remove any fragments and then the final weight was determined.
2. Sandblasting test: This test was used to evaluate the abrasion resistance of concrete using sandblasting according to ASTM C418 (ASTM 2012b). Sandblasting action simulates waterborne abrasives and moving traffic on concrete surfaces. In this test, the sample was placed in the sandblasting cabinet perpendicular to the nozzle, at a distance of 75 ± 2.5 mm from the end of the nozzle. The surface of the concrete was subjected to air-pressure-driven silica sand type 0 for a period of 1 minute. These procedures were repeated on eight different spots on the concrete surface. After the test was completed, the abrasion holes were filled with oil-based modeling clay to determine the abraded volume. The abraded volume and the area of the abraded cavities were used to calculate the abrasion coefficient loss (A_c) using equation (1):

$$A_c = V/A \qquad (1)$$

Where A_c is the abrasion coefficient, cm^3/cm^2; V is the abraded volume, cm^3; and A is the area of abraded cavities, cm^2.

4.6 Discussion of Test Results

4.6.1 Summary of Fresh Properties

Table 4-4 shows the fresh properties results for SCC/SFSCC mixtures (M1-M4). From the table, it can be seen that the flowability of mixtures increased as the coarse aggregate size increased. This can be observed from the results of T50, T50J, and V-funnel times, in which increasing the coarse aggregate size from 10 mm to 20 mm decreased the T50, T50J, and V-funnel by 40%, 37.3%, and 34.9%, respectively. This can be attributed to the fact that increasing the coarse aggregate size reduced the total surface area of the coarse aggregate, which in turn helped to reduce the amount of water required to wet the aggregate surface and hence improve the flowability of the mixture. On the other hand, increasing the coarse aggregate size from 10 mm to 20 mm reduced the L-box ratio by 11.9% and increased the difference between slump and J-ring diameters by 30%, indicating a lower passing ability as the coarse aggregate size increased. This can be related to the higher blockage that occurred in the L-box and J-ring devices when larger coarse aggregates were used. These results are in agreement with those observed by other researchers (Ismail and Hassan, 2015; Salman and Hussian, 2008). Moreover, mixtures using larger coarse aggregate size showed a higher segregation resistance factor (SR) compared to those using lower coarse aggregate size. For example, using 20 mm coarse aggregate size increased the SR value by 21.9% compared to the mixture with 10 mm coarse aggregate size. However, the SR for mixtures with larger coarse aggregate size was below the upper limit of SR given by (EFNARC 2005) (SR ≤ 15%).

Table 4-4 Fresh Properties of tested mixtures

Mix #	Mixture	T50 (sec)	T50J (sec)	V-funnel (sec)	L-box	slump–J-ring diameters	SR%
1	SCC	1.95	2.63	7.4	0.92	10	2.01
2	SCC-20	1.17	1.65	4.82	0.81	13	2.45
3	SCC-0.35SF13	2.05	2.89	7.92	0.88	15	2.07
4	SCC-0.35SF35	2.2	3.2	8.6	0.82	25	2.15

The results also showed that adding SFs to SCC mixtures negatively impacted the fresh properties. For example, adding 0.35% SF35 increased the T50, T50J, and V-funnel times by 12.8%, 21.7%, and 16.2%, respectively, compared to the control mixture without fibers (M4 compared to M1). Adding SF35 also reduced the L-box ratio by 10.9% and increased the difference between slump and J-ring diameters by 2.5 times compared to the mixture without fibers (M4 compared to M1). The decay in flowability and passing ability of SCC with the addition of SFs could be attributed to the increased interference and blockage in the mixtures. The stability of mixtures was also negatively affected by the inclusion of SFs, in which the SR value increased by 3% and 7% when SF13 and SF35 were used, respectively, compared to the control mixture without fibers (M3 and M4 compared to M1). However, all tested mixtures met the acceptable range given by (EFNARC 2005)[24] [SR ≤ 15%]. By comparing mixtures with different SF lengths (M3 compared to M4), it can be seen that increasing the SF length showed a further reduction in the fresh properties of SFSCC mixtures.

4.6.2 Compressive Strength of Saturated and Unsaturated Samples under Cold Temperatures

The ratios between the compressive strength at cold temperatures and compressive strength at room temperature were calculated as follows:

$C_{T-20} = f_c$ @-20°/ f_c @ room, $C_{T-10} = f_c$ @-10°/ f_c @ room, $C_{T0} = f_c$ @ 0°/ f_c @ room

(2)

$S_{-20c} = f_{cs}$ @-20°/ f_c @-20°

(3)

Where C_{T-20}, C_{T-10}, C_{T0} are the compressive strength factors of unsaturated concrete samples corresponding to cold temperatures at -20° C, -10° C, and 0° C, respectively. f_c and f_{cs} are the compressive strength at specified temperatures for unsaturated and saturated concrete samples, respectively. S_{-20c} is the ratio between the compressive strength of saturated samples and the compressive strength of unsaturated samples at the temperature of -20° C. The compressive strength results shown in Table 4-5 present the compressive strength values at different cold temperatures and different water saturation conditions for all tested mixtures. The saturation conditions of tested concrete samples were selected to simulate the actual conditions of concrete structures (bridge piers as an example) in cold regions, which are subjected to tidal cycles and changing water levels. From the table, it can be observed that decreasing the temperature below room temperature generally enhanced the compressive strength for both saturated and unsaturated concrete samples. For example, decreasing the temperature of the control mixture (M1) from room temperature to -20° C increased the compressive strength of the unsaturated sample by 26.2%, while this increase reached up to 32% in the saturated sample. This can be related to the fact that under cold temperatures the porewater, gel water, and chemical-bounded water changed into ice, which can decrease the latent weakness by limiting the micro-cracks and filling the aggregate paste interface with ice, and in turn help to enhance the compressive strength. Moreover, the reduction in the atomic distance (when concrete shrinks) that resulted from decreasing the temperature below room temperature contributed to increasing the attractive force between atoms, thus enhancing the compressive strength (Cai et al. 2011; Banthia et al. 1998). The better enhancement in the compressive strength of saturated samples compared to unsaturated ones under cold temperatures may be attributed to the fact that in the unsaturated condition, the large and medium capillary pores might not be fully saturated. Therefore, when the water in capillary pores changed into ice, the pores could not be fully filled, and in turn the enhancement in the compressive strength was limited. On the other hand, in the saturated condition, the medium and large capillary pores were fully filled and compacted, which increased the area of cross-section subjected to compression load, and in turn showed a better enhancement of the compressive strength compared to unsaturated samples. The results also indicated that the improvement in the concrete strength of saturated samples under cold temperatures compared to unsaturated samples were directly related to the amount of water absorbed by saturated samples (see Table 4-3). For example, by comparing mixtures with different C/F aggregate ratios (M6 compared to M5), it can be seen that using C/F aggregate ratio of 0.7 showed S_{-20} value of 1.03, while this value reached up to 1.11 when C/F aggregate ratio of 2 was used (see Figure 4-3a). This can be attributed to the fact that the saturated sample with higher C/F aggregate ratio (2) absorbed a higher amount of water compared to its counterpart with lower C/F aggregate ratio (0.7) (see Table 4-3). This contributed to fully filling the concrete pores with water, which turned into ice at cold temperatures, and in turn enhanced the compressive strength. By looking at mixtures with different coarse aggregate sizes, it can be noticed that the mixture with 20 mm coarse aggregate size showed a comparable S_{-20} value to the mixture with 10 mm coarse aggregate size.

Table 4-5 and Figure 4-3b show the compressive strength results for mixtures with different types, lengths, and volumes of SFs at different cold temperatures and different saturation conditions. From the results, it can be observed that, in general, using SFs further enhanced the compressive strength at cold temperatures. For example, adding SF13 to SCC mixtures exhibited C_{T-20}, C_{T-10}, and C_{T0} values of 1.34, 1.19, and 1.12, respectively, while these values reached up to 1.26, 1.1, and 1.05, respectively, in the control mixture (M3 compared to M1). This can be related to the fact that when the temperature decreased from room temperature to cold temperatures, the concrete shrank and the atomic distance decreased, which helped to increase the grip around SFs and improve the concrete strength. By comparing all types and lengths of SFs, it can be observed that the difference in compressive strength between saturated and unsaturated samples under cold temperatures appeared to be constant. This can be related to the amount of water absorbed by the saturated samples, in which all mixtures reinforced with different types and lengths of SFs absorbed a similar amount of water in saturated condition (see Table 4-3).

The results also indicated that, in general, mixtures with low cement content showed better enhancement in the compressive strength under cold temperatures compared to mixtures with higher cement content (in both saturated and unsaturated samples). In addition, saturated samples exhibited a significant enhancement in the compressive strength under cold temperatures compared to unsaturated samples. Meanwhile, this enhancement appeared to be minimized when higher cement content was used. For example, the mixture with 550 kg/m^3 showed S_{-20} value of 1.08, while this value reached up to 1.2 in the mixture with 300 kg/m^3 cement content. This can be attributed to the fact that the mixture with low cement content absorbed more water compared to the mixture with higher cement content (see Table 4-3), which in turn enhanced the compressive strength.

Table 4-5 Mechanical properties results at different temperatures

Mix #	Mixture	Compressive strength (MPa)					STS (MPa)				
		-20S	-20	-10	0	Room	-20S	-20	-10	0	Room
1	SCC	88.2	84.4	73.7	70.3	66.8	7.3	6.21	5.68	5.25	4.77
2	SCC-20	85.3	82.2	71.6	67.2	63.2	7.5	6.25	5.65	5.20	4.45
3	SCC-0.35SF13	104.6	90.6	80.0	75.5	67.5	10.8	8.59	7.80	6.85	5.63
4	SCC-0.35SF35	98.0	89.7	78.9	74.9	68.1	10.8	8.67	7.76	6.97	6.19
5	VC	85.3	82.8	72.5	69.9	67.5	6.9	6.02	5.40	5.20	4.90
6	VC-2C/F	78.7	70.7	61.7	56.8	54.6	7.4	5.96	5.23	4.87	4.34
7	VC-1SF35	102.5	94.0	84.4	79.8	70.7	16.9	13.67	11.46	10.40	8.67
8	VC-1SF60	105.0	95.2	85.0	80.9	69.6	15.6	12.22	10.19	9.18	7.37
9	VC-1SF60-DH	97.9	91.1	83.1	80.2	70.0	15.1	12.51	10.52	9.52	8.10
10	VC-300	57.5	48.0	42.2	38.6	34.8	5.9	4.57	3.94	3.58	3.00
11	VC-550	65.9	61.0	56.0	52.7	50.7	5.9	5.05	4.57	4.35	4.05

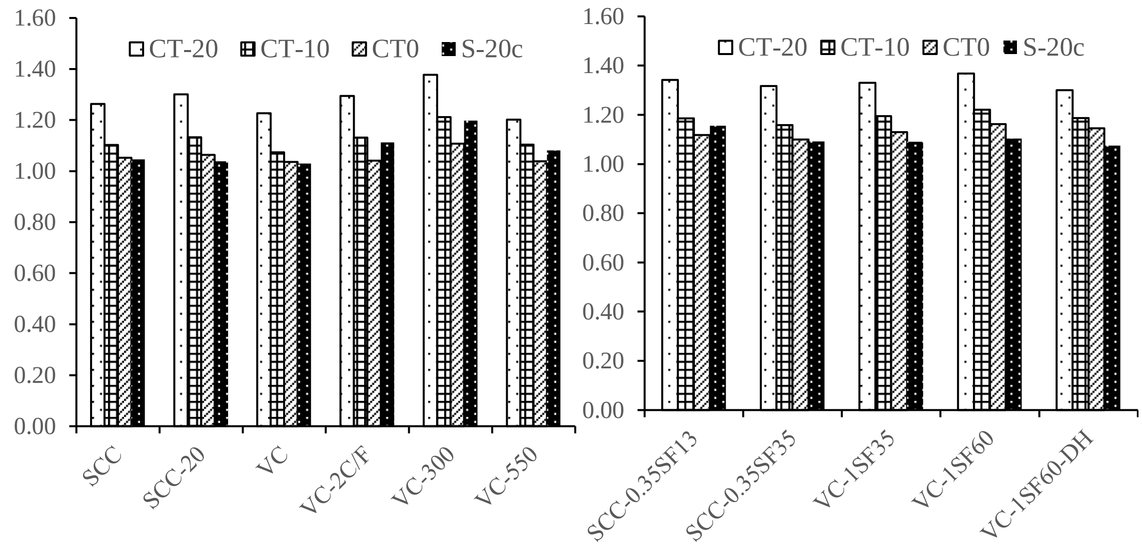

Figure 4-3 Compressive strength factors and saturation factors of tested mixtures at different temperatures

4.6.3 Splitting Tensile Strength of Saturated and Unsaturated Samples under Cold Temperatures

The ratios between the STS at cold temperatures and STS at room temperature were calculated as follows:

T_{T-20}= STS @-20° / STS @ room, T_{T-10} = STS @ -10°/ STS @ room, T_{T0} = STS @ 0°/ STS @ room (4)

S_{-20T} = STS_s @ -20° /STS @-20° (5)

Where T_{T-20}, T_{T-10}, and T_{T0} are the STS factors of unsaturated concrete samples corresponding to cold temperatures at -20° C, -10° C, and 0° C, respectively. STS and STS_s are the splitting tensile strengths at -20° C for unsaturated and saturated concrete samples, respectively. Also, S_{-20T} is the ratio between the STS of saturated samples and the STS of unsaturated samples at the temperature of -20° C.

Table 4-5 shows the STS values for all tested mixtures under different temperatures. From the figure, it can be observed that the STS values of all tested mixtures improved when the temperature decreased below room temperature. For example, decreasing the temperature from room temperature to -20° C, -10° C, and 0° C increased the STS of the control mixture (M1) by 1.3, 1.19, and 1.1, respectively. Moreover, the saturated samples in all tested mixtures appeared to have better STS results under cold temperatures compared to unsaturated samples. For instance, by decreasing the temperature of the control mixture (M1) from room temperature to -20° C, the unsaturated sample exhibited an increase in the STS of up to 1.3 times, while this increase reached up to 1.52 times in the saturated sample. This can be attributed to the same reasons discussed previously in the compressive strength section. Figure 4-4a shows the values of T_{T-20}, T_{T-10}, and T_{T0} for mixtures with different C/F aggregate ratios and different coarse aggregate sizes under cold temperatures. From the figure, it can be seen that the effect of cold temperature on the STS results appeared to be higher when larger coarse aggregate size or higher C/F aggregate ratios were used. For example, increasing coarse aggregate size from 10 mm to 20 mm increased the values of T_{T-20}, T_{T-10}, and T_{T0} by 1.08, 1.07, and 1.06, respectively, while these ratios reached up to 1.12, 1.09, and 1.06, respectively, when the C/F aggregate ratio increased from 0.7 to 2. Moreover, further enhancements in the STS results under cold temperatures were observed in the saturated sample compared to the unsaturated one. For instance, by looking at mixtures with different C/F aggregate ratios, it can be noted that the mixture with C/F aggregate ratio of 0.7 showed S_{-20T} value of 1.14, while this value reached up to 1.25 when

C/F aggregate ratio of 2 was used. This can be related to the higher amount of water absorbed by the saturated sample. This water turned into ice (under cold temperatures) in the aggregate paste interfacial zone and thus helped to improve the bond between aggregate and mortar, which enhanced the concrete strength.

Figure 4-4b shows the effect of cold temperatures on the STS results of mixtures reinforced with different lengths, types, and volumes of SFs. From the figure, it can be indicated that using SFs in concrete mixtures further enhanced the STS under cold temperatures compared to mixtures without SFs. For example, using SF13 in M3 exhibited T_{T-20}, T_{T-10}, and T_{T0} values of 1.53, 1.39, and 1.22, respectively, while the control mixture (M1) without fibers showed values of 1.3, 1.19, and 1.1, respectively. This may be related to the effect of cold temperature in shrinking the concrete, which increased the grip around SFs and in turn enhanced the bond strength between SFs and concrete composite. Moreover, shrinkage of concrete under cold temperatures also contributed to controlling the widening of micro-cracks and limited their propagation, which in turn enhanced the concrete tensile strength (Richardson and Ovington, 2017). By comparing all types, lengths, and volume of SFs, it can be noticed that using 1% SF60 showed the highest enhancement in the values of T_{T-20}, T_{T-10}, and T_{T0}. Meanwhile, the lowest enhancement in the values of T_{T-20}, T_{T-10}, and T_{T0} was observed when 0.35% SF35 was used. The results also indicated that there is no significant difference between mixtures reinforced with different types, lengths, and volumes of SFs when comparing samples in saturated condition with others in unsaturated condition. This can be related to the same reason discussed previously in the compressive strength section, in which all mixtures reinforced with different types, lengths, and volumes of SFs absorbed comparable amounts of water in saturated condition.

Figure 4-4a also shows the effect of cement content on the STS results under cold temperatures. Using lower cement content appeared to show increased improvement in the STS results under cold temperatures when compared to mixtures with higher cement content. For example, using 300 kg/m^3 showed T_{T-20}, T_{T-10}, and T_{T0} values of 1.52, 1.31, and 1.19, respectively, while these values reached up to 1.25, 1.13, and 1.07, respectively, when 550 kg/m^3 was used. Moreover, the mixture with lower cement content showed a higher S-$_{20T}$ value compared to the mixture with higher cement content. For instance, the mixture with 300 kg/m^3 exhibited S_{-20T} value of 1.28, while the mixture with 550 kg/m^3 showed S_{-20T} value of 1.16.

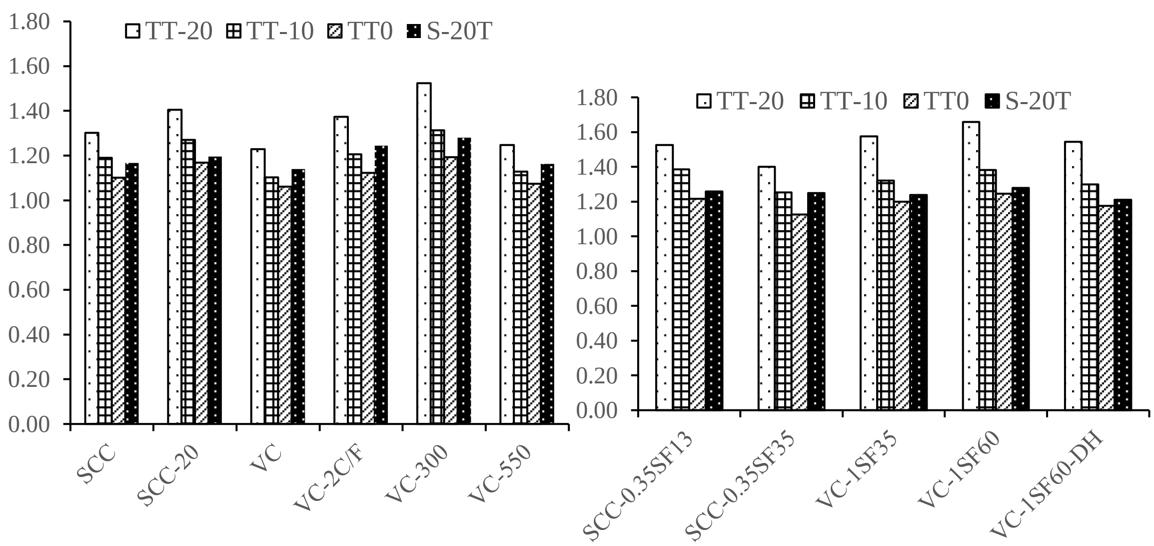

Figure 4-4 STS factors and saturation factors of tested mixtures at different temperatures

4.6.4 Abrasion Resistance under Cold Temperatures

The ratios between the abrasion resistance at cold temperatures and abrasion resistance at room temperature were calculated as follows:

M_{T-20} = M @-20° / M @ room, M_{T-10} = M @ -10°/ M @ room, M_{T0} = M @ 0°/ M @ room (6)

A_{T-20} = A @-20° / A @ room, A_{T-10} = A @ -10°/ A @ room, A_{T0} = A @ 0°/ A @ room (7)

S_{-20M} = M_s @ -20° / M @-20° S_{-20A} = A_s @ -20° / A @-20° (8)

Where M_{T-20}, M_{T-10}, and M_{T0} are the abrasion mass loss factors of unsaturated concrete samples after exposure to rotating-cutter test at cold temperatures of -20° C, -10° C, and 0° C, respectively; A_{T-20}, A_{T-10}, and A_{T0} are the abrasion coefficient factors of unsaturated concrete samples after exposure to sandblasting test at cold temperatures of -20° C, -10° C, and 0° C, respectively. Moreover, S_{-20M} is the ratio between abrasion mass loss of saturated samples and unsaturated samples at the temperature of -20° C (rotating-cutter test), while S_{-20A} is the ratio between abrasion coefficient of saturated and unsaturated samples at the temperature of -20° C (sandblasting test).

Table 4-6 shows the abrasion resistance results of all tested mixtures under cold temperatures. Figure 4-5 presents the values of M_{T-20}, M_{T-10}, and M_{T0} for all tested mixtures. Also, the values of A_{T-20}, A_{T-10}, and A_{T0} for all developed mixtures are shown in Figure 4-6. From the rotating-cutter and sandblasting results for all tested mixtures, it can be observed that decreasing the temperature below room temperature generally enhanced the abrasion resistance of concrete. This can be indicated from the values of M_{T-20}, M_{T-10}, M_{T0}, A_{T-20}, A_{T-10}, and A_{T0}, in which all values were less than 1. However, the enhancement in the abrasion resistance of concrete under cold temperatures was obviously affected by the mixture composition. For example, increasing the C/F aggregate ratio showed a more pronounced effect on the abrasion resistance of concrete under cold temperatures, while increasing the coarse aggregate size showed insignificant effect. This can be observed in the values of M_{T-20}, M_{T-10}, and M_{T0}, which decreased by 8.5%, 6.4%, and 3.4%, respectively, when the coarse aggregate size increased from 10 mm to 20 mm (M2 compared to M1). Meanwhile, the decreases in the values of M_{T-20}, M_{T-10}, and M_{T0} reached up to 17.2%, 13.6%, and 9.5%, respectively, when the C/F aggregate ratio increased from 0.7 to 2 (M5 compared to M6). Similar behavior was observed in the sandblasting test results. Increasing the C/F aggregate ratio increased the size/volume of cement-aggregate interface, which promoted ice formation in these areas, leading to a better control of the width of micro-cracks, and enhanced the bond between aggregate and surrounding mortar. This in turn helped to reduce the chance of pulling out the coarse aggregate from the concrete surface under the action of abrasion force. The results also showed that the saturated samples, in general, exhibited a better enhancement in the abrasion resistance under cold temperatures compared to unsaturated ones. Meanwhile, the effect of saturation condition in enhancing the abrasion resistance under cold temperatures appeared to be more significant in the mixture with higher C/F aggregate ratio compared to its counterpart with lower C/F aggregate ratio. For example, the mixture with C/F aggregate ratio of 2 showed S_{-20M} and S_{-20A} values of 0.86 and 0.85, respectively, while these values reached up to 0.93 and 0.91, respectively, when C/F aggregate ratio of 0.7 was used, Indicating lower mass loss of saturated samples compared to unsaturated samples at higher C/F aggregate ratio.

Table 4-6 Abrasion resistance results at different temperatures

Mix #	Mixture	Mass loss from rotating-cutter test (gm)					Abrasion coefficient from sandblasting test (cm^3/cm^2)				
		-20S	-20	-10	0	Room	-20S	-20	-10	0	Room
M1	SCC	3.3	3.5	4.1	5.8	9	0.26	0.29	0.35	0.43	0.52
M2	SCC-20	2.5	2.67	3.82	5.45	8.75	0.20	0.21	0.30	0.40	0.50
M3	SCC-0.35SF13	2.0	2.25	3.05	4.6	8.2	0.18	0.23	0.28	0.37	0.45
M4	SCC-0.35SF35	2.1	2.4	3.1	4.7	7.9	0.16	0.19	0.23	0.32	0.41
M5	VC	3.5	3.8	4.5	6.2	9.3	0.27	0.30	0.36	0.47	0.59
M6	VC-2C/F	1.7	2	2.76	4.24	6.6	0.15	0.17	0.22	0.29	0.39
M7	VC-1SF35	1.4	1.7	2.45	3.68	6.5	0.10	0.12	0.15	0.24	0.35
M8	VC-1SF60	1.4	1.67	2.1	3.4	7	0.10	0.12	0.16	0.26	0.39
M9	VC-1SF60-DH	1.3	1.6	2.2	3.4	6.4	0.12	0.14	0.18	0.27	0.38
M10	VC-300	2.4	3	3.9	5.18	10.5	0.27	0.35	0.50	0.73	1.02
M11	VC-550	3.8	4.1	4.8	6	9.6	0.28	0.32	0.38	0.48	0.60

Figure 4-5b and 6b show the effect of cold temperatures on the abrasion resistance of concrete mixtures reinforced with different types, lengths, and volumes of SFs. From the figures, the cold temperature appeared to augment the effect of SFs on enhancing the abrasion resistance of concrete. This can be clearly observed by examining the values of M_{T-20}, M_{T-10}, and M_{T0}, which reached up to 0.3, 0.39, and 0.59, respectively, with 0.35% SF35 (M4) compared to 0.39, 0.46, and 0.64 in the control mixture without fibers (M1). Similarly, the values of A_{T-20}, A_{T-10}, and A_{T0} reached up to 0.45, 0.57, and 0.77, respectively, with 0.35% SF35 (M4) compared to 0.55, 0.66, and 0.83, respectively, in the control mixture without fibers (M1). This can be attributed to the effect of cold temperatures on enhancing the bond between SFs and concrete matrix, which increased the grips around SFs when the concrete shrank under cold temperatures. Enhancing the bond between SFs and concrete helped to tie the concrete matrix together and reduce the pullout of concrete particles under the effect of abrasion. The results also showed that increasing the SF volume showed a further enhancement in the abrasion resistance of concrete under cold temperatures. For example, increasing the SF volume from 0.35% (M4) to 1% (M7) decreased the values of M_{T-20}, M_{T-10}, and M_{T0} from 0.3, 0.39, and 0.59 to 0.26, 0.37, and 0.57, respectively, indicating a lower mass loss under the rotating-cutter abrasion test. Similarly, increasing SF length from 35 mm to 60 mm showed a higher abrasion resistance under cold temperatures. This can be attributed to the fact that longer SFs are exposed to higher gripping effect from concrete compared to shorter ones when concrete shrinks under cold temperatures.

By comparing mixtures with different SF types, it can be seen that as the mechanical anchorage between fibers and concrete mixtures improved, the effect of cold temperatures on enhancing abrasion resistance decreased. For example, by comparing double hooked ends SF60 with single hooked ends SF60, it can be observed that double hooked ends SF60 showed A_{T-20}, A_{T-10}, and A_{T0} values of 0.37, 0.48, and 0.7, respectively, while these values reached up to 0.3, 0.42, and 0.65, respectively, when single hooked ends SF60 was used. This can be related to the fact that the better mechanical anchorage of double hooked ends SFs minimized the effect of concrete gripping around SFs compared to single hooked ends SFs, and in turn showed less enhancement in the abrasion resistance under cold temperatures. The effect of cold temperatures also appeared to be more pronounced on enhancing the abrasion resistance of fiber-reinforced concrete mixtures in saturated samples compared to unsaturated ones. For example, in the mixture with 1% SF60 (M8), the saturated sample showed a lower mass loss of 18% compared to unsaturated samples. This can be attributed to the same reasons discussed previously, in which the water absorbed by the saturated samples turned into ice, promoting the role of fibers in enhancing the abrasion resistance of concrete.

The cement content also showed a noticeable effect on the abrasion resistance of concrete under cold temperatures as shown in Figure 4-5a and Figure 4-6a. By examining the unsaturated samples, it can be seen that using lower cement content exhibited a higher abrasion resistance under cold temperatures compared to mixtures with higher cement content. For instance, the mixture with 550 kg/m^3 yielded M_{T-20}, M_{T-10}, and M_{T0} values of 0.43, 0.5, and 0.63, respectively, while these values reached up to 0.29, 0.37, 0.49, respectively, in the mixture with 300 kg/m^3 cement content (M11 compared to M10). This can be related to the fact that at higher cement content, the mixture appeared to be more dense (due to the increased hydration product), thus leaving less room for ice to form in concrete pores and in turn reducing the effect of cold temperatures on enhancing the abrasion resistance of concrete. By examining the saturated samples, it can be seen that the effect of saturation condition on further enhancing the abrasion resistance under cold temperatures seems to be more pronounced in mixtures with lower cement content. This is due to the fact that the mixture with higher cement content absorbed less water compared to the mixture with lower cement content.

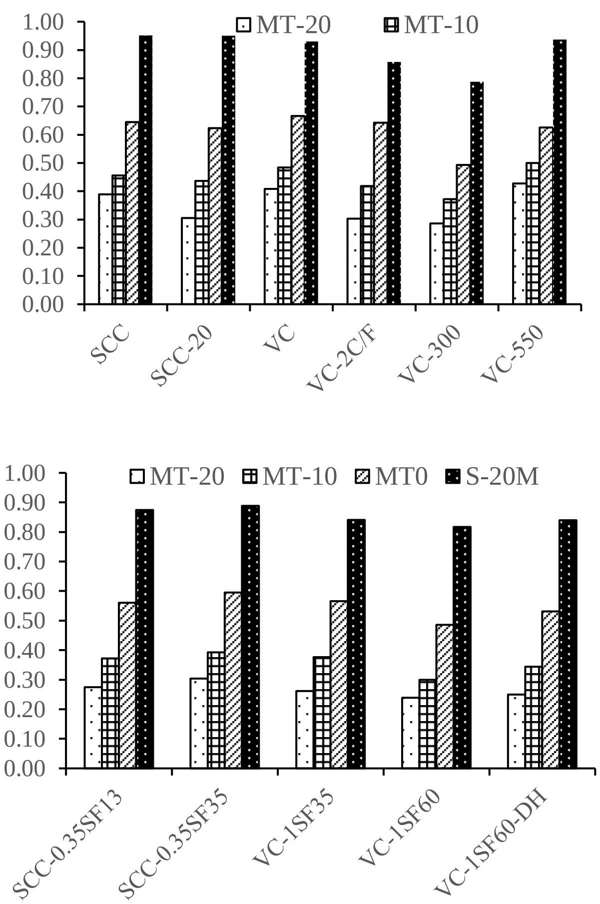

Figure 4-5 Mass loss factors and saturation factors of tested mixtures at different temperatures

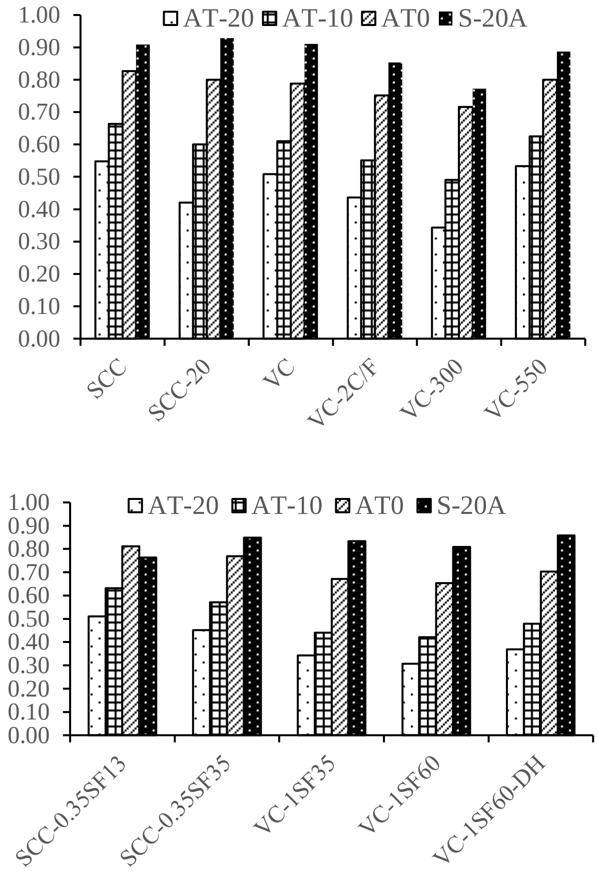

Figure 4-6 Abrasion coefficient factors and saturation factors of tested mixtures at different temperatures

4.7 Conclusions

This study investigated the effect of cold temperatures on enhancing the mechanical properties and abrasion resistance of concrete reinforced with different types, lengths, and volumes of SFs. Mixtures with different coarse aggregate sizes, C/F aggregate ratios, and cement content were also investigated. The effect of cold temperatures on the mechanical properties and abrasion resistance was also investigated in saturated samples compared to unsaturated samples in all tested mixtures. The following conclusions can be drawn:

1. Adding SFs to SCC mixtures appeared to heighten the interference and blockage between particles, which reduced the fresh properties of the mixtures, especially the passing ability. This in turn limited the maximum volume of SFs that can be used to develop successful SCC to 0.35% (when 550 kg/m^3 binder content is used).
2. Cold temperatures proved to enhance the abrasion resistance and mechanical properties of concrete, in general. The lower the temperature, the better the enhancement in both abrasion and mechanical properties.
3. Using a larger coarse aggregate or higher C/F aggregate ratio augmented the effect of cold temperatures on enhancing the abrasion resistance of concrete. However, the effect of increasing the C/F aggregate ratio from 0.7 to 2 appeared to be more significant when compared to the effect of increasing the coarse aggregate size from 10 mm to 20 mm.
4. Adding SFs to concrete mixtures further enhanced the abrasion resistance under cold temperatures. This may be related to the effect of concrete shrinkage under cold temperatures which increases the gripping force around the fibers. This improves tightening the concrete matrix together and reduces the pullout of concrete particles under the effect of abrasion.

5. Among all mixtures reinforced with different types, lengths, and volumes of SFs in this investigation, adding 1% single hooked ends SF60 exhibited the highest improvement in the rotating-cutter and sandblasting abrasion resistance tests under cold temperatures. This indicates better improvement in the abrasion resistance under cold temperatures when higher percentage of fibers and/or longer fibers are used in the mixture.
6. Using double hooked ends SFs with higher mechanical anchorage to concrete minimized the effect of concrete gripping around SFs, leading to less enhancement in the abrasion resistance under cold temperatures compared to using single hooked ends SFs.
7. Mixtures with lower cement content (300 kg/m^3) showed a higher improvement in the mechanical properties and abrasion resistance under cold temperatures compared to mixtures with higher cement content (550 kg/m^3).
8. For all tested mixtures, saturated samples, in general, showed a better enhancement in the abrasion resistance under cold temperatures compared to unsaturated samples. This enhancement was more pronounced in mixtures with higher C/F aggregate ratio and lower cement content.

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5 Summary and Recommendations

5.1 Summary

The previous chapters describe in detail the individual studies carried out for this research project. The project was divided into three parts to display the results in a straightforward manner. Chapter 2 studied the effect of salt scaling resistance of abraded and non-abraded concrete samples, in addition to studying the impact and abrasion resistance of fiber reinforced concrete samples before and after exposure to salt scaling. Chapter 3 and 4 investigated the mechanical properties, impact resistance, and abrasion resistance of fiber reinforced concrete mixtures under the effect of cold temperatures. This chapter aimed to summarize the main conclusions that can be obtained from this project including the mechanical properties, impact resistance, and abrasion resistance for steel fibers reinforced concrete under cold temperatures. Moreover, summarizing the results obtained regarding the durability of these mixtures against abrasion and impact resistance before and after exposure to salt scaling.

The experimental program included testing different concrete mixtures, fresh properties tests (flowability, passingability, segregation resistance), mechanical properties tests (compressive strength, splitting tensile strength, flexural strength), impact load tests (drop weight and flexural impact tests), and abrasion tests (rotating cutter and sand blasting tests). The analysis of the conducted studies in this thesis gave the following conclusions:

- Increasing coarse aggregate size from 10 mm to 20 mm exhibited an insignificant effect on the resistance of concrete to salt scaling for both abraded and non-abraded concrete samples. In the meantime, using larger coarse aggregate size showed inconsiderable enhancement in the mechanical properties, impact resistance, and abrasion resistance under cold temperatures compared to mixture with smaller aggregate size.

- A significant deterioration in the surface resistance to salt scaling for both abraded and non-abraded samples was observed when higher C/F aggregate ratio was used. Meanwhile, the abrasion resistance of non-scaled concrete surfaces was significantly enhanced when the C/F aggregate ratio increased. The effect of cold temperatures in enhancing the mechanical properties, impact resistance, and abrasion resistance of concrete appeared to be more pronounced when high C/F aggregate ratio was used compared to mixtures with lower C/F aggregate ratio.

- Using higher cement content significantly enhanced the salt scaling resistance of abraded and non-abraded concrete and reduced the deterioration level in the surface scaling under the effect of salt scaling. In addition, using higher cement content also showed a significant enhancement in the abrasion and impact resistance of concrete mixtures for both salt scaled and non-scaled concrete samples. In mixtures exposed to cold temperatures, using lower cement content showed to a better enhancement in the mechanical properties, impact resistance, and abrasion resistance under cold temperatures compared to those with higher cement content.

- Mixtures with uncoated SFs exhibited a lower salt scaling resistance compared to those reinforced with coated SFs. Similarly, using higher volume of SFs/ shorter SFs (at the same SFs volume) led to a reduction in the concrete resistance to salt scaling for both abraded and non-abraded concrete surfaces.

- Adding SFs in the concrete mixtures significantly enhanced the abrasion resistance and impact resistance for non-scaled concrete samples.

- Using SFs augmented the effect of cold temperatures in enhancing the mechanical properties, impact resistance, and abrasion resistance of concrete. Moreover, adding SFs to concrete mixtures enhanced the post cracking behavior under impact tests at cold temperatures, which highlights the effect of SFs in alleviating the brittleness of concrete.

- At cold temperatures, among all mixtures reinforced with different types, lengths, and volumes of SFs, using 1% SF60 showed the highest enhancement in the mechanical properties, impact, and abrasion resistance, while the lowest enhancement was observed for mixture with 0.35% SF35.

- Concrete samples with pre-abraded surfaces exhibited a lower salt scaling resistance compared to those with non-abraded concrete surfaces. In the meantime, the salt scaling action showed a negative effect on the abrasion and impact resistance of concrete, in which the salt scaled samples exhibited a higher mass loss and lower energy absorption compared to their counterpart with non-scaled surfaces.

- Decreasing the temperature below the room temperature generally enhanced the mechanical properties, impact resistance, and abrasion resistance of concrete. However, the failure mode of concrete samples without fibers was more brittle with colder temperature.

- Saturated concrete samples showed a better enhancement in the abrasion resistance under cold temperatures compared to unsaturated samples. This enhancement was more pronounced in mixtures with higher C/F aggregate ratio and lower cement content.

5.2 Potential Applications and Recommendations for Future Research

- Further investigations are needed to examine the durability of different concrete mixtures (such as rubberized concrete, lightweight concrete, and high-performance concrete) against abrasion, freezing-thawing action, chloride and sulfate attacks.
- Studying the behavior of concrete mixtures with different fibers types such as polymeric fibers under the effect of cold temperatures and freezing and thawing action.
- Evaluating the behavior of full-scale concrete elements subjected to flexural, shear, and cyclic loading under arctic conditions.
- Studying the impact resistance of concrete that already subjected to abrasion and salt scaling.

5.3 Limitations of research

The results obtained from this study were typically affected by the properties of the used materials. Therefore, any changed in the physical and/or chemical properties of the fine aggregate, coarse aggregate, cement, SCMs, admixtures, and SFs may affect the mixtures' properties in the fresh and hardened states. In studies (study 1, 2, and 3), comparative investigations were conducted to evaluate the durability, mechanical properties, impact resistance, and abrasion resistance of concrete under cold temperatures. All tests were conducted based on the available facilities in Memorial University's labs. However, in some tests, such as the impact test, using advanced instruments may result in better measurements with further details.

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