Abrasion and Impact Resistance of Concrete under Different Curing Conditions

By

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Abstract

This study aims to assess the mechanical properties, impact resistance, and abrasion resistance of a series of self-consolidating concrete (SCC) and normal vibrated concrete (NVC) mixtures under different curing conditions. The studied variables included coarse-to-fine (C/F) aggregate ratio (0.7 and 1.2), water-to-cement (w/c) ratio (0.4 and 0.55), the addition of 0.35% steel fibers (SFs), and the use of different supplementary cementing materials (SCMs) types (metakaolin (MK) and silica fume (SLF)). The research program was divided into three stages. The first stage included trial mixtures to optimize a number of SCC mixtures with different proportions. In this stage, the appropriate percentages of SCMs (MK or SLF) and the maximum percentage of SFs that can be used to develop successful SCC were optimized. The second stage included evaluation of the compressive strength, splitting tensile strength, and impact resistance of the optimized mixtures. The third stage investigated the flexural strength, modulus of elasticity, and abrasion resistance of the same optimized mixtures. All studied samples were cured under four different curing conditions, including moisture curing conditions at 23º C, air curing at 23º C, and cold temperatures curing conditions at +5º C and -10º C.

Curing concrete at +5º C showed significant reductions in the abrasion strength, compressive strength, splitting tensile strength (STS), and impact resistance, when compared to moisture curing at 23º C. The magnitude of these reductions significantly increased when curing concrete at -10º C. Mixtures with higher C/F ratio, or higher w/b ratio, or mixtures with SFs or SCMs were more affected by the cold curing compared to the control mixture. The results also showed that cold temperature curing had a more pronounced negative effect on the impact resistance and STS compared to the compressive strength.

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Sara Seyedfarizani

Disclaimer

It is to be noticed that in order to satisfy the thesis format, the published versions of each paper presented in Chapters 2, and 3 have been slightly modified

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List of Symbols, Nomenclature or Abbreviations

ASTM	is the American Society for Testing and Materials
C1	is Moisture curing condition at 23º C
C2	is Air Curing condition at 23º C
C3	is Air Curing condition at +5º C
C4	is Air Curing condition at -10º C
C/F	is Coarse to Fine ratio
f'c	is Compressive strength.
FS	is Flexural strength
HRWRA	is the High Range Water Reducer Admixtures
ITZ	is Interfacial Transition Zone
ME	is Modulus of Elasticity
MK	is Metakaolin
N	is the number of drops
NVC	is Normal Vibrated Concrete
SCC	is Self-Consolidated Concrete
SCMs	is Supplementary Cementitious Materials
STS	is Splitting Tensile Strength
SFs	is Steel Fiber
SLF	is Silica Fume
STS	is Split Tensile Strength
w/b	is Water to Binder ratio

Co-Authorship Statement

I, Sara Seyedfarizani, hold the principal author status for all the manuscript chapters in this thesis. However, the manuscripts are co-authored by my supervisor (Dr. Assem A. A. Hassan) and my co-researcher (Dr. Basem H. AbdelAleem). Described below is a detailed breakdown of the work facilitated by my team and me.

- Paper 1 in chapter 2: Seyedfarizani, Sara, AbdelAleem, Basem H. and Hassan, Assem A. A., (2021). “Impact Resistance and Mechanical Properties of Concrete under Cold Curing Conditions”. Submitted in Magazine of Concrete Research in September 2021.

I was the primary author, with authors 2 - 3 contributing to the idea, its formulation and development, and refinement of the presentation.

- Paper 2 in chapter 3: Seyedfarizani, Sara, AbdelAleem, Basem H. and Hassan, Assem A. A., (2021), “Abrasion Resistance of Concrete with Different Mixture Compositions at Cold Curing Temperatures”, Submitted to ACI materials Journal in September 2021.

I was the primary author, with authors 2 - 3 contributing to the idea, its formulation and development, and refinement of the presentation.

Sara Seyedfarizani October 2021

Chapter 1: Introduction and overview

1.1 Background

Self-compacting concrete, also known as self-consolidating concrete (SCC), is one of the most widely used concrete types, primarily due to its self-compacting ability. SCC offers many advantages in terms of placement and production in comparison with traditional normal vibrated concrete (NVC), including higher flowability and workability, elimination of vibration for compacting, enhanced bonding with congested reinforcement, and better pumpability (Kashani & Ngo, 2020). These advantages make SCC a better option wherever concrete placement is challenging, such as concrete structures with congested reinforcement that require high compaction. Therefore, in this study, most of the mixtures were developed as SCC to better understand the behavior of SCC, especially under different curing conditions, which can be useful for engineers/researchers concerned with concrete in cold regions.

The idea of using SCC was firstly formed in Japan in the 1980s (Kosmatka & Wilson, 2011). SCC technology in Japan was based on using amount of fine materials and the same amount of water content (compared with NVC), which could alter the rheological properties of the concrete. In addition, for ensuring acceptable flowability and passing ability in SCC, several measures were proposed. These measures can be included as adding plasticizer in the SCC mixture (a high-range water reducer based on polycarboxylate ethers), optimize w/b ratio, using supplementary cementing materials (SCMs) or adding higher amount of fine materials to the concrete mixture to satisfy the desired flowability of (RMCAO, 2009).

SCC is highly popular in North America as the use of SCC can be time-saving, offers greater flexibility in design, and provides great aesthetics (provides high-quality surface finishes). Meanwhile, developing acceptable SCC is highly dependent on providing proper curing techniques. This is mostly because of the higher volume of paste in SCC and the lower water bleed at the surface, which makes it sensitive to surface drying (RMCAO, 2009). Therefore, it is important to ensure the proper curing of SCC mixtures. Particularly, curing should start as soon as possible and should extend for sufficient period to maintain the desired humidity and temperature for the mixture in order to reach the target strength and durability (PCA, 2019; CSA-A23.1, 2019). Generally, the curing process is defined as a method to provide appropriate moisture, temperature and time to allow the concrete to attain the desirable strength and durability. And based on the surrounding environment, concrete may be cured with different techniques, including moisture curing, air curing or curing at subzero or high temperatures, which can entirely alter the properties of SCC. In fact, providing appropriate curing conditions for concrete allows a longer period for the hydration of cementitious materials, which extends the duration of strength gain and improves the mechanical properties and durability in concrete.

However, sometimes providing adequate temperature and moisture for proper curing conditions can be a challenging task due to the climatic condition of the project. For example, providing a favourable temperature for concrete curing in wintertime or offshore concrete structures in arctic regions exposed to harsh permanent environments is challenging. Some of the mitigation measures to address this concern may include optimizing the concrete mixture proportion and using additives and/or SCMs to enhance the mechanical properties and behavior of concrete under cold-curing conditions which are discussed in chapters 2 and 3 of this study.

On the other hand, concrete structures in cold regions are subjected to frequent impact loads of iceberg or wave collisions, which can result in the initiation of cracks in concrete (Abid, Abdul-Hussein, Ayoob, & Ali, 2020). Besides, abrasive loads of rocks, sand, and ice flow may also result in the wearing away of concrete surface in these types of structures, which can significantly reduce the ultimate strength of concrete. Therefore, evaluating the impact and abrasion resistance of such concrete under different curing conditions (especially cold-curing conditions) is required.

Impact resistance of concrete can be defined as the capability of concrete to resist frequent blows and absorb energy without spalling or cracking (Muda, 2013). Several tests can be conducted to evaluate the impact resistance of concrete, including the explosive test, weighted pendulum Charpy type impact test, and drop weight test (repeated or single cycle). The impact resistance of samples can be calculated by several methods, including calculating the amount of energy needed to break the concrete sample or assessing the number of drops that can result in the sample's failure. In this study, evaluating the impact resistance of samples under different curing conditions, comparing the results and details of conducting impact tests are thoroughly discussed in chapter 2. In addition, the impact resistance of samples is evaluated using the flexural impact test and drop weight impact test on series of cylinders and prisms samples. The reason for choosing the drop weight tests (either flexural or drop impact test) is mainly because this type of test is recognized as one the most common methods to assess the impact resistance of concrete (ACI, 2008).

The ability of the concrete surface to resist wearing force due to rubbing or friction of abrasive loads is defined as abrasion resistance (Scott & Safiuddin, 2015). Abrasion is generally considered a natural attack that may result in progressive loss of concrete mass and extensive reduction in concrete strength (Zaki, AbdelAleem, Hassan, & Colbourne, 2019). Using concrete in an Arctic environment with heavy ice flow contributes to high levels of surface abrasion. Therefore, these types of concrete structures need to have higher resistance to abrasive loads. The abrasion resistance can be influenced by mortar strength, course to fine aggregate ratio (C/F), water to binder ratio (w/b), proper surface finishing, and type of aggregates. It also can be highly influenced by changing the curing conditions, since proper curing conditions can highly increase the toughness and strength of concrete. Previous studies reported that abrasion resistance is improved by enhancing the compressive strength of concrete (Ismail, Hassan, & Lachemi, 2019; Ibrahim, 2017). In this study, the surface abrasion resistance of samples was assessed with two different tests, including the rotating cutter method (as per ASTM C944) and sandblasting method (as per ASTM C418). The detailed explanation of these tests and discussion on abrasion results for all mixtures under several curing conditions are discussed in-depth in chapter 3.

Multiple measures were suggested to improve the impact resistance, abrasion resistance, and mechanical properties of concrete. Some of these measures include adding fibers and/or SCMs to the mixture and/or optimizing the w/b and C/F ratios. For example, it has been proven that adding fibers to concrete can highly improve the splitting tensile strength

(STS), flexural strength (FS), durability, impact strength, and abrasion resistance of concrete (Ismail & Hassan, 2017; Khaloo, Raisi, Hosseini, & Tahsiri, 2014; Zaki R. A., AbdelAleem, Hassan, & Colbourne, 2020). In addition, SCMs (such as MK, SLF) can highly boost the resistance of concrete to impact and abrasive loads, as well as enhancing the mechanical properties of concrete in regular curing conditions (Ismail & Hassan, 2016; Duan, Shui, Chen, & Shen, 2013; Hassan, Lachemi, & Hossain, 2012). For instance, using MK and SLF can improve the micro-structure, durability, and mechanical properties of concrete the high pozzolanic reactivity of such SCMs (Ismail & Hassan, 2016; Abouhussien & Hassan, 2015; Hassan, Lachemi, & Hossain, 2012). Moreover, SLF can also provide higher resistance to chemical attacks from chlorides, acids, nitrates, and/or sulphates (EUROALLIAGES, 2020)

However, there are insufficient studies that have investigated the effect of using fibers and SCMs on the impact and abrasion resistance of concrete, especially under different curing temperatures. Therefore, the effect of adding SFs (as on the most commonly used fiber) and SCMs (MK and SLF) on impact and abrasion resistance of mixtures under various curing conditions (especially cold-curing conditions) are thoroughly discussed in chapters 2 and 3; since more study in this area is needed.

Optimization of the w/b and C/F ratios in the mixture can be other measures that greatly affect the strength development of concrete. These factors are extensively discussed in chapters 2 and 3 under different curing conditions and temperatures. Generally, increasing the w/b ratio can increase the capillary porosity, which reduces the compressive strength of concrete (Kosmatka & Wilson, 2011). Using less water in the mixture also proved to increase the FS strengths of concrete and improve the bond between the aggregates and cement matrix (Kosmatka & Wilson, 2011). On the other hand, previous studies proved that increasing the C/F ratio reduces the mechanical properties of concrete under normal curing condition (AbdelAleem, Ismail, & Hassan, 2017; Ismail & Hassan, 2019). However, more study is required to evaluate the behavior of concrete (especially impact and abrasion resistance) under cold-curing conditions with different w/b and C/F ratios.

1.2 Research objectives and significance

Despite the importance of studying the impact and abrasion resistance of concrete, there are very limited studies in this area. Particularly, no available research has been conducted to evaluate the effect of using SCMs and/or SFs on the impact and abrasion resistance of concrete, especially under cold curing conditions. Therefore, this research was conducted to fill this gap by assessing the impact and abrasion resistance of SCC with different mixture compositions (such as adding SCMs and SFs) at various curing conditions and temperatures.

Four different curing conditions, including i,) moisture-curing condition at 23ºC, ii) air curing condition at 23ºC, iv) curing at +5º C and, v) Curing at -10º C were applied to all mixtures for 28 days. In this study, seven different mixtures were developed. These mixtures included six SCC mixtures and one NVC mixture to compare the performance of SCC with NVC. The investigated SCC mixtures were developed with different w/b ratios and C/F ratios, two different SCMs (MK and SLF), and the addition of SFs.

The author expects that this study will give a better understanding of the effect of different curing conditions and temperatures on the durability and strength of concrete. This study also introduces some measures to nearly compensate for the negative effect of cold curing conditions on the impact and abrasion resistance of concrete by enhancing the mixture composition through using SCMs and/or fibers.

1.3 Scope of research

The main objectives of this study can be categorized as follows:

a. Optimize and develop a series of SCC mixtures with different mixture compositions.
b. Investigate the impact resistance, compressive strength, and splitting tensile strength of the optimized mixtures at four different curing conditions.
c. Provide a comprehensive investigation on the abrasion resistance, flexural strength, and modulus of elasticity of the optimized mixtures at different curing conditions (particularly cold-curing conditions)

The first objective is discussed thoroughly in chapters 2 and 3, while the second objective is discussed in chapter 2 and the third objective in chapter 3.

1.4 Thesis outline

The structure of this thesis is composed of four chapters, as follows:

Chapter 1 describes the research background, objective and significance of the research and introduces the overall program of this study.

Chapter 2 includes a review of the literature with a focus on the role of changing curing conditions on impact resistance, compressive strength and STS of different mixtures.

Chapter 3 discusses in detail the effect of applying four different curing conditions on the abrasion resistance and mechanical properties of the different concrete mixtures.

Chapter 4 presents the conclusions and recommendations that were drawn from the overall investigation. And bring the recent finding based on experimental work. It also suggested related topics for further research of future works.

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Chapter 2: Impact Resistance and Mechanical Properties of Concrete under Cold Curing Conditions

2.1 Abstract

This study investigated the effect of different curing conditions on the mechanical properties and impact resistance of concrete developed with different mixture compositions. The studied parameters included coarse-to-fine aggregate (C/F) ratio (0.7 and 1.2), water-to-binder (w/b) ratio (0.4 and 0.55), type of supplementary cementing materials (SCMs) (metakaolin (MK) and silica fume (SLF)), and the addition of steel fibers (SFs). The studied mixtures were cured under different conditions, including added moisture at 23º C, air only at 23º C, air only at +5º C, and air only at -10º C. Curing concrete at +5º C showed significant reductions in the compressive strength, splitting tensile strength (STS), and impact resistance of 20%, 26%, and 25%, respectively, when compared to moisture curing at 23º C. These reductions increased by 39%, 42%, and 46%, respectively, when curing concrete at -10º C. The mechanical properties and impact resistance of mixtures developed with higher C/F ratio, higher w/b ratio, or mixtures with SFs or SCMs were more affected by the cold curing compared to the control mixture (with lower C/F ratio, higher w/b ratio, and no SFs or SCMs). The results also showed that cold temperature curing had a more pronounced negative effect on the impact resistance and STS compared to the compressive strength.

2.2 Introduction

Bridge piers and harbour platforms in Arctic regions are typically exposed to impact loading from ships and iceberg collisions. As a result, the strength and durability of such structures should be properly designed in order to withstand the applied loads. Concrete curing in Arctic regions is usually carried out in cold temperature and low humidity conditions. Therefore, it is necessary to evaluate the strength, and overall behaviour of concrete poured and cured under cold temperatures to prepare a convenient curing procedure for such structures in the construction management plan.

The curing of concrete is an important factor responsible for developing the desired strength of concrete mixtures. In order to achieve proper curing of concrete, a certain amount of water should be retained in the mixture to maintain the progress of the cement hydration. In addition, a minimum relative humidity of 80% and satisfactory curing temperature (18º C to 23º C) are required to achieve proper hydration for concrete mixtures. Curing concrete at low temperatures significantly affects the strength development and durability of concrete mixtures (Rubene & Vilnitis, 2017; Xie & Yan, 2018). The hydration process slows down as the temperature decreases, and so the development of early strength is negatively impacted when the curing temperature drops below 4º C (Kosmatka & Wilson, 2011; Kosmatka, Kerkhoff, & Panarese, 2002; Farzampour, 2017; ACI, 2010). The ACI Committee (2010), in their Cold Weather Concreting report, recommends proper cold weather curing when concrete is exposed to an average temperature of 5º C for at least three successive days. The committee also recommends protecting the fresh concrete against cold weather for at least the first 24 hours, or until it reaches a strength of at least 3.5 MPa, to prevent damaging the concrete at early ages due to freezing.

Several studies have investigated the effect of different curing conditions (including low-temperature curing) on the mechanical properties of concrete. All these studies have concluded noticeable reductions in strength and durability when concrete is cured in the air or at low temperatures. Al-alaily et al. (2017) studied the compressive strength and splitting tensile strength (STS) of conventional concrete under different curing techniques, including water curing at 23º C, air curing at 23º C, and air curing at 3-5º C for 28 days. Their results indicated that the highest compressive strength and STS were recorded for samples cured in water at 23º C, while the lowest results were observed for samples cured in the air at 3-5º C, which reached up to 37.7% reduction in the compressive strength. They also reported that samples cured in the air at 23º C showed a reduction in compressive strength and STS reached up to 30.2% and 27.7%, respectively, compared to samples cured in water at 23º C. Different mixture composition and/or mixture proportions can also significantly affect the strength and durability of concrete under different curing conditions. For example, the pozzolanic reactivity of supplementary cementing materials (SCMs), which are responsible for increasing the strength of the mixture, can be negatively affected by the cold temperature. Also, using a high water-to-cement ratio in the mixture can leave large water pockets in the paste, which can freeze under low temperatures and cause more cracks and higher reductions in the strength of concrete. Husem and Gozutok (2004) investigated the effect of low-temperature curing at -5º C, 0º C, 5º C, and 10º C on the compressive strength of normal-strength concrete and high-performance concrete mixtures. Their study showed that the compressive strength of normal-strength concrete was reduced by 79%, 62%, 44%, and 30% when samples were cured at -5º C, 0º C, 5º C, and 10º C, respectively, compared to samples cured in standard curing at 23 ± 2º C. Meanwhile, these reductions reached up to 63%, 33%, 26%, and 20%, respectively, for high-performance concrete.

The use of SCMs in concrete proved to enhance the mechanical properties, durability, impact resistance, and energy absorption (Abouhussien & Hassan, 2015; Ismail and Hassan, 2016; Blomberg, 2008). Metakaolin (MK), one of the SCMs with high pozzolanic reactivity, helps to modify the concrete micro-structure and enhance the overall concrete strength (Sadek, Ismail, & Hassan, 2020; Hassan, Lachemi, & Hossain, 2010; Nili & Zaheri, 2011). However, the effect of MK on the strength of concrete may be altered under different curing conditions; therefore, more investigation is needed in this area. Silica fume (SLF) is another type of SCM that has a high potential to enhance concrete strength and durability. The fine particles of SLF contribute to filling the voids in concrete mixtures, which reduces the concrete porosity and helps to develop denser concrete with higher strength (Monteiro, Branco, de Brito, & Neves, 2012; Massoud, Abou-Zeid, & Fahmy, 2003; Nili & Afroughsabet, 2010; Barluenga, Palomar, & Puentes, 2013). Despite the wide use of SLF in concrete mixtures, the behaviour of SLF concrete under different curing conditions still needs more investigation.

The mechanical properties and impact resistance of concrete structures can also be enhanced by adding fibers to the mixtures. Using fibers proved to generally enhance the tensile strength, impact resistance, and energy absorption of concrete (Zaki, AbdelAleem, Hassan, & Colbourne, 2019; AbdelAleem, Ismail, & Hassan, 2017; Altun & Aktaş, 2013;

Nia, Hedayatian, Nili, & Sabet, 2012). Under conventional curing conditions, steel fibers (SFs) are considered the most effective fibers to enhance the mechanical properties of concrete, particularly tensile strength, flexural toughness, and impact resistance (Nataraja, Nagaraj, & Basavaraja, 2005; Murali, Santhi, & Ganesh, 2016; Khaloo, Raisi, Hosseini, & Tahsiri, 2014). Ismail and Hassan (2017) studied the effect of using SFs on enhancing the mechanical properties and impact resistance under conventional curing conditions. Their results showed that using 0.35% SFs in rubberized self-consolidating concrete (SCC) mixture enhanced the compressive strength, STS, flexural strength, and impact resistance by 1%, 22.8%, 22.4%, and 150%, respectively, compared to the control mixture without fibers. On the other hand, there are few studies in the literature on the effect of SFs on impact resistance and concrete strength under different curing conditions. BAŞSÜRÜCÜ and Kazım (2019) studied the effect of different curing regimes on the compressive strength, STS, and flexural strength of concrete reinforced with SFs. Their results showed that changing the curing conditions from water to air curing decreased the compressive strength, STS, and flexural strength by 24.2%, 48%, and 16%, respectively, for mixtures without fibers, while these reductions reached 40.7%, 35.5%, and 18%, respectively, for mixtures with SFs, indicating the more pronounced effect of curing conditions for mixtures reinforced with SFs.

Using different coarse-to-fine aggregate ratios (C/F) and different water-to-binder ratios (w/b) also appeared to affect the concrete strength under normal curing conditions. Previous studies investigated different C/F and w/b ratios to determine the optimum percentage for each parameter in order to optimize the concrete strength under normal curing (Hassan &

Mayo, 2014; Ismail & Hassan, 2019; Hashemi, Shafigh, Karim, & Atis, 2018; Piasta & Zarzycki, 2017). However, there is a lack of studies that have investigated the effect of different C/F ratios and w/b ratios on the strength and impact resistance of concrete under different curing conditions, especially low temperature curing conditions.

This study investigated the effect of low temperature and different curing techniques on the mechanical properties and impact resistance of SCC mixtures developed with different mixture compositions. The different curing techniques included moisture curing at 23º C, air curing at 23º C, curing at +5º C, and curing at -10º C. The investigated mixtures were developed with different SCMs (MK and SLF), different C/F ratios, different w/b ratios, and the addition of SFs. The tested properties were compressive strength, STS, drop weight impact resistance and flexural impact resistance.

2.3 Research significance

During the winter season in cold regions, in situ cast concrete must be cured in cold temperatures, which, if not properly cured, can significantly affect the strength and durability of the structure. A review of the literature shows that there are a few studies that have investigated the effect of curing on the compressive strength of concrete. However, there are no available studies covering the effect of curing condition, especially curing in cold conditions, on the impact resistance of concrete. In addition, since the curing process is influenced by the mixture composition, it is important to understand the behaviour of concrete with different mixture compositions under different curing regimes and cold temperatures, as this information is absent from the literature. This investigation studied the effect of cold curing conditions on the impact resistance and mechanical properties of concrete mixtures developed with different mixture compositions. The authors believe that understanding the effect of curing conditions on the behaviour of concrete with different mixture compositions can help designers/engineers make the right decision regarding the proper curing plan in such weather conditions.

2.4 Experimental program

2.4.1 Materials

Canadian Portland cement (Type I), similar to ASTM C150 (2018), was used in all developed mixtures. MK and SLF, similar to ASTM C618 (2017) class N and ASTM C1240 (2014), respectively, were used as SCMs in the concrete mixtures. Table 2. 1 shows the chemical and physical properties of cementing materials. Crushed granite aggregates (10 mm maximum aggregate size) and natural sand were used as coarse and fine aggregates, respectively. Both aggregates have a specific gravity and absorption ratio of 2.6 and 1%, respectively. Figure 2. 1 shows the gradation curves for both coarse and fine aggregates. Single hook ends SFs 35 mm in length and with 65 aspect ratio were used in this investigation. The tensile strength, young's modulus, and specific gravity of SFs used were 1150 MPa, 210 GPa, and 7.85, respectively. A high-range water-reducing admixture similar to ASTM C494 (2016) with a specific gravity of 1.2, volatile weight of 62%, and pH of 9.5 was used to achieve the flowability requirements of the SCC mixtures.

Table 2. 1: Chemical and Physical properties of supplementary cementing materials used.

Chemical properties (%)	MK	SLF	Cement
SiO_2	51-53	90	19.64
Al_2O_3	42-44	0.4	5.48
Fe_2O_3	<2.2	0.4	2.38
CaO	<0.2	1.6	62.44
MgO	<0.1	-	2.48
Na_2O	<0.05	0.5	-
K_2O	<0.40	2.2	-
C_3S	-	-	52.34
C_2S	-	-	16.83
C_3A	-	-	10.50
C_4AF	-	-	7.24
L.O.I	0.95	0.57	2.05
Physical properties			
Specific gravity	2.56	2.2	3.15
Blaine fineness (m^2/kg)	1390	20000	410

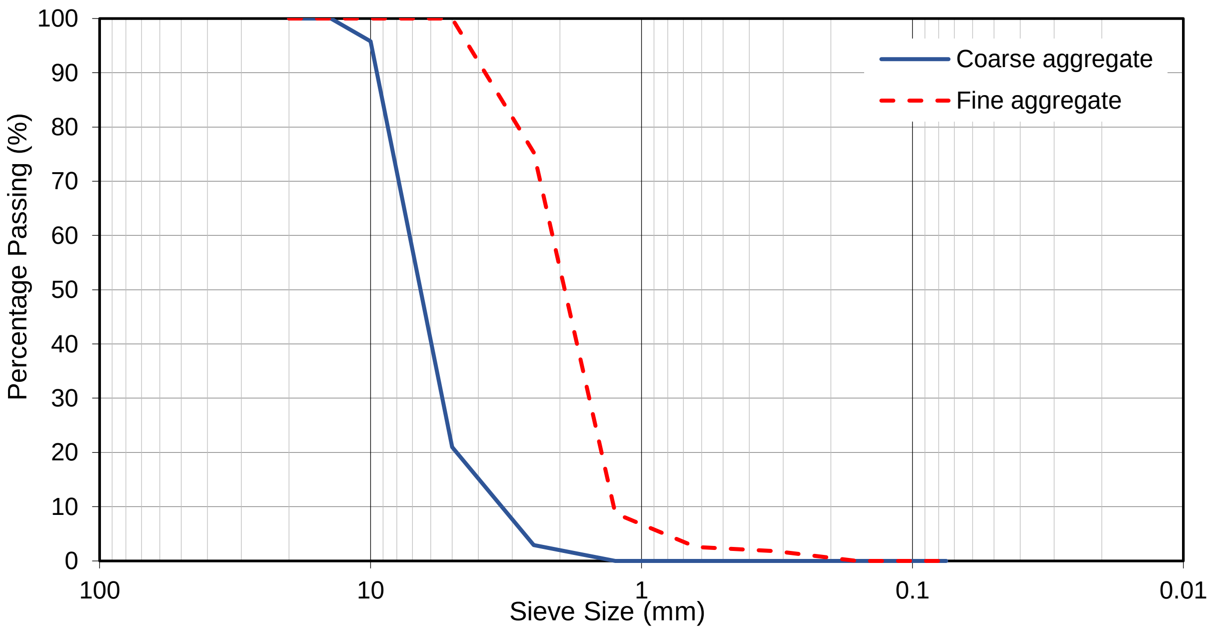


Figure 2. 1: Coarse and fine aggregate gradation curves.

2.4.2 Research program

This study was designed to evaluate the effect of different curing techniques on the mechanical properties and impact resistance of concrete mixtures developed with different mixture compositions. The studied mixtures included five SCC mixtures with different mixture proportions, one SCC mixture reinforced with SFs (SF-SCC), and one vibrated concrete mixture (VC). The developed SCC and SF-SCC mixtures were required to optimize the mixture viscosity in order to provide better particle suspension and reduce the risk of segregation with adequate mixture flowability. A preliminary trial mixture stage was performed to:

1) Determine the maximum C/F aggregate ratio and volume of MK, SLF, and SFs used in order to enhance the impact resistance and mechanical properties while achieving successful SCC mixtures (conferring to (EFNARC, 2005) guidelines) without overdosing the High-Range Water-Reducing Admixture (HRWRA).
2) Determine the minimum and maximum w/b ratios required to develop a successful SCC mixture without segregation and with minimal bleeding. The two ranges of w/b ratios (0.4 and 0.55) were required to investigate what effect the w/b ratio had on the behaviour of the mixtures under different curing regimes.

Out of the trial mixture stage, it was found that at least 500 kg/m^3 cement content and 0.4 w/b ratio were necessary to provide adequate flowability with no visual sign of segregation. In mixtures that incorporated SCMs, such as MK and SLF, 20% MK and 10% SLF were found to be the optimal percentages required to fulfill the requirements of the European Guidelines for SCC (EFNARC, 2005) in terms of flowability, passing ability, and segregation resistance. The trial mixtures also showed that 0.35% is the maximum percentage of SFs that could be added to develop successful SCC. Using a higher percentage of SFs (higher than 0.35%) significantly reduced the fresh properties of the developed mixtures. Also, based on the trial mixtures results, the maximum C/F aggregate ratio and w/b ratio that can be used to develop successful SCC were 1.2 and 0.55, respectively. Further increasing the C/F aggregate ratio (higher than 1.2) was found to significantly reduce the passing ability of the mixture while further increasing the w/b ratio (higher than 0.55) increased the risk of segregation. Table 2. 2 presents the proportions of all developed mixtures.

The selection of the tested mixtures was based on the following:

1) Mixture 2 was compared to mixture 1 to study the effect of different curing techniques on the impact resistance and mechanical properties of concrete with different w/b ratios.

2) Mixture 3 was selected to study the effect of increasing coarse aggregate volume (C/F = 1.2 compared to 0.7 in mixture 1) on the impact resistance and mechanical properties under different curing techniques.

3) Mixture 4 and mixture 5 were developed with different SCMs (MK and SLF) to study the significance of using SCMs on enhancing the mechanical properties and impact resistance under different curing techniques.

4) Mixture 6 was developed with SFs to study the behaviour of fiber-reinforced concrete (compared to non-fibered concrete) under different curing conditions.

5) Mixture 7 is a VC mixture (with the same mixture composition as mixture 1, which is an SCC mixture) and was developed to compare the performances of SCC and VC under different curing techniques.

The mixture designation was chosen according to the type of concrete (SCC or VC), C/F ratio, w/b ratio, type of SCM, and the presence of fibers. For example, the SCC mixture with SLF as an SCM was labelled as SCC-SLF.

Table 2. 2: Mixture proportions of the developed mixtures.

#	Designation	Binder materials kg/m^3			Aggregate			w/b ratio	Water kg/m^3	Steel fibers kg/m^3	Dry density kg/m^3
		Cement	SF	MK	C/F ratio	Coarse kg/m^3	Fine kg/m^3				
M1	SCC	500	-	-	0.70	686.5	980.8	0.40	200	-	2367.3
M2	SCC-W/B	500	-	-	0.70	606.2	866.1	0.55	275	-	2172.3
M3	SCC-C/F	500	-	-	1.20	909.4	757.9	0.40	200	-	2367.3
M4	SCC-MK	400	-	100	0.70	678.7	969.6	0.40	200	-	2348.3
M5	SCC-SLF	450	50	-	0.70	679.2	970.3	0.40	200	-	2349.5
M6	SCC-SFs	500	-	-	0.70	686.2	980.2	0.40	200	27.5	2369.2
M7	VC	500	-	-	0.70	686.5	980.8	0.40	200	-	2367.3

2.4.3 Mixing, casting, and curing of the tested specimens

All dry materials, including binder materials (cement and SLF or MK) and aggregates (coarse and fine), were dry-mixed in a rotary mixer for 2.5 ± 0.5 minutes. Two-thirds of the required water was then added and re-mixed with the dry material for another minute.

The remaining water was mixed with the required dosage of HRWRA before being added to the mixer and re-mixed with the rest of the materials for another 2.5 ± 0.5 minutes. Once the target slump flow (700 ± 50 mm) was achieved for the SCC/SF-SCC mixtures, the rest of the fresh properties' tests were performed. All specimens were cured under four different curing conditions: moist curing (23º C) (C1); ambient air at room temperature curing (23º C) (C2); 5º C curing (C3); and -10º C curing (C4). The specimens cured in C1 curing condition were placed in a moist curing room with a controlled temperature of 23º C, while the specimens cured in C2 curing condition were kept at a room temperature of 23º C. On the other hand, the specimens cured in cold temperatures, C3 and C4, were placed in a cold room to monitor and maintain the specified temperatures (5º C and -10º C). All tested specimens in the different curing conditions were cured for 28 days before testing.

2.4.4 Mechanical properties and impact resistance tests

The compressive strength and STS were investigated in this study as per ASTM C39 (2020) and ASTM C496 (2017), respectively. For each curing condition, three identical cylinders with 100 mm diameter and 200 mm height were used to evaluate the compressive strength or STS of each mixture. Two impact resistance tests were carried out to evaluate the impact resistance of concrete under different curing techniques. The apparatus used to measure the impact resistance of samples and tested specimens after failure are shown in Figure 2.2.

- **Drop weight impact test**

In this test, for each curing condition, three cylindrical specimens with 150 mm diameter and 63.5 mm thickness were used to evaluate the impact resistance of concrete as per ACI committee 544 (1999). These specimens were cut from a concrete cylinder with 150 mm diameter and 300 mm height after removing the top and bottom surfaces of the cylinder using a diamond cutter. A drop weight of 4.45 kg was dropped from a height of 457 mm onto a steel ball with a diameter of 63.5 mm resting at the center of the top surface of the concrete specimen. The impact resistance of the tested specimen was evaluated by recording the number of drops required to cause failure (N).

- **Flexural impact test**

In this test, for each curing condition, three prisms (100 mm x 100 mm cross-section and 400 mm length) were used to evaluate the flexural impact resistance (Zaki R. A., AbdelAleem, Hassan, & Colbourne, 2021; Ismail & Hassan, 2016). A three-point loading pattern with a loading span of 350 mm was used, in which a 4.45 kg drop weight was dropped from a height of 150 mm onto a steel ball located at the midspan of the top surface of the concrete prism. The failure of SCC/VC prisms in this test was identified when the specimens broke into two halves. On the other hand, because SF-SCC specimens could not break into two halves, the failure of SF-SCC prisms was identified when a 5 mm maximum crack width was reached in the specimen.

In both tests the impact energy was calculated as follows:

$$IE = Nmgh \quad (2.1)$$

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

Figure 2. 2: Drop weight and flexural Impact tests setup (left), and tested samples in drop weight and flexural impact tests after failure (right).

2.5 Discussion of results

2.5.1 Effect of different curing conditions on the compressive strength and STS of the control mixture

Table 2. 3 and Figure 2. 3 show the compressive strength and STS of the control mixture (M1) under different curing conditions (C1-C4). From the table and figure, it can be seen that curing M1 samples in C1 (moisture curing condition) showed the highest compressive strength and STS compared to all other curing conditions. For example, curing M1 samples in C2, C3, and C4 curing conditions reduced the compressive strength by 11%, 20%, and 39%, respectively, compared to the C1 curing condition. In the meantime, the reduction in the STS reached up to 9%, 26%, and 42% when the samples cured in C2, C3, and C4 were compared to those cured in C1. This can be related to the exemplary condition of C1 in terms of controlled temperature and sufficient humidity compared to the other curing conditions. The availability of sufficient moisture in the case of C1 curing condition helped the hydration process to continue and avoided self-desiccation from occurring in the concrete mixture. On the other hand, the samples cured in C4 (-10º C) showed the lowest compressive strength and STS compared to the samples cured in all other curing conditions. For instance, curing M1 samples in C4 curing condition showed a reduction in the compressive strength of 39.2%, 31.9%, and 24.1% compared to C1, C2, and C3 curing conditions, respectively. Meanwhile, these reductions in STS reached 42.1%, 36.3%, and 22.2% when M1 samples cured in C4 curing condition were compared to their counterpart samples cured in C1, C2, and C3 curing conditions, respectively. Besides the fact that cold temperature significantly reduces the hydration process, curing samples in C4 curing

condition (-10º C) contributed to changing the water (that is available for hydration in concrete specimens) into ice, which also interrupts the hydration process and leads to a reduction in strength. Moreover, the formation of ice at -10º C in the concrete pores and cement aggregate interface zones encourages the cracks to initiate and propagate early in the cement matrix, especially around the aggregates. These cracks create internal stress and weaken the bond between coarse aggregates and surrounding mortar, which in turn significantly affects the concrete strength.

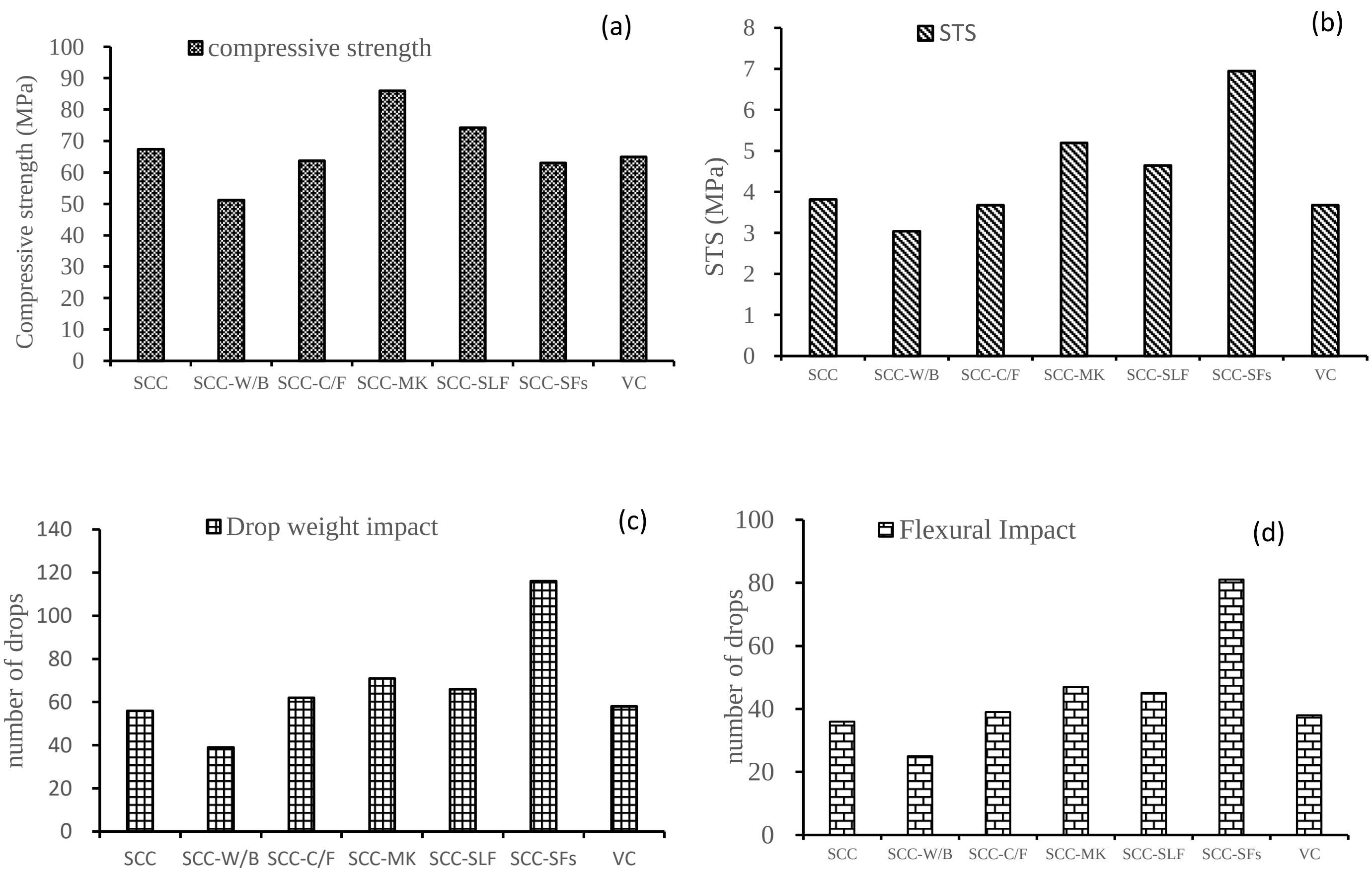


Figure 2. 3: (a) Compressive strength at moisture curing condition (C1); (b) STS at moisture curing condition (C1); (c) Drop weight impact results at moisture curing condition (C1); (d) flexural impact results at moisture curing condition (C1).

The results also showed that although air-curing concrete samples (C2) showed reduced compressive strength and STS compared to the moisture curing condition (C1), the compressive strength and STS of samples cured at C2 were significantly higher than those of samples cured at cold temperatures (C3 and C4). This indicates that the negative effect of temperature drop on the strength is higher than the negative effect when samples are cured in air instead of moisture curing. The reduced compressive strength and STS of C2 samples (air-cured) compared to C1 samples (moisture-cured) is related to the lower moisture content of C2 samples, which led to self-desiccation of the concrete mixture. Moreover, the reduced compressive strength and STS of C3 samples (cured at +5º C) is related to the slower hydration due to the temperature drop and the formation of internal cracks. In C3 samples, the difference between the cold temperature at the surface of the sample (+5º C) and the relatively higher temperature inside the core of the sample (due to the heat of hydration) creates a steep thermal gradient. This thermal gradient promotes the initiation and propagation of microcracks, especially at the interface between coarse aggregate and surrounding mortar, which results in reduced concrete strength.

Table 2. 3: Compressive Strength and STS for all tested mixtures at different Curing conditions (C1-C4).

Mixture #	Designation	compressive strength (MPa)				STS (MPa)			
		C1	C2	C3	C4	C1	C2	C3	C4
M1	SCC	67.40	60.25	54.00	41.00	3.82	3.47	2.84	2.21
M2	SCC-W/B	51.20	47.13	35.50	22.00	3.04	2.82	1.70	1.10
M3	SCC-C/F	63.70	54.72	49.00	35.00	3.68	3.00	2.35	1.75
M4	SCC-MK	86.00	70.00	60.00	43.00	5.20	4.39	3.00	2.35
M5	SCC-SLF	74.30	64.00	56.00	42.00	4.65	4.00	2.95	2.31
M6	SCC-SFs	63.00	55.70	51.00	38.00	6.95	6.10	4.22	3.10
M7	VC	65.00	59.00	54.00	40.00	3.68	3.30	2.62	2.00

2.5.2 Effect of different mixture compositions on the compressive strength and STS under different curing conditions

The results of compressive strength and STS of all developed mixtures under different curing conditions (C1-C4) are shown in Table 2. 3. The ratios between compressive strength at curing conditions C2, C3, and C4 and the compressive strength at C1 curing condition were calculated as shown in Eq. 2. 2.

$$\mathbf{C_{air} = \mathit{f}_c\ @\ C2 / \mathit{f}_c\ @\ C1,\ C_{+5} = \mathit{f}_c\ @\ C3 / \mathit{f}_c\ @\ C1,\ C_{-10} = \mathit{f}_c\ @\ C4 / \mathit{f}_c\ @\ C1} \qquad \mathbf{(2.\ 2)}$$

Where C_{air}, C_{+5}, C_{-10} are the compressive strength factors corresponding to curing conditions C2, C3, and C4, respectively, and f_c @ C is the compressive strength at a specified curing condition.

The ratios between STS at curing conditions C2, C3, and C4 and STS at curing condition C1 were calculated as shown in Eq. 2. 3.

$$\mathbf{S_{air} = STS\ @\ C2 / STS\ @\ C1,\ S_{+5} = STS\ @\ C3 / STS\ @\ C1,\ S_{-10} = STS\ @\ C4 / STS\ @\ C1} \qquad \mathbf{(2.\ 3)}$$

Where S_{air}, S_{+5}, S_{-10} are the STS factors corresponding to curing conditions C2, C3, and C4, respectively, and STS @ C is the STS at a specified curing condition.

Figure 2. 4 shows the values of C_{air}, C_{+5}, C_{-10}, S_{air}, S_{+5}, and S_{-10} for all tested mixtures. From the figure, it can be seen that the compressive strength and STS decreased (in all mixtures) when the concrete was cured in C2, C3, and C4 curing conditions compared to C1 curing condition. This decrease was confirmed by looking at the values of C_{air}, C_{+5}, C_{-10}, S_{air}, S_{+5},

and S_{-10}, which are less than 1 in all mixtures, and is related to the insufficient moisture content (C2 curing condition) and the cold curing temperature (C3 and C4) that slowed down the hydration process and the strength gains, as mentioned before.

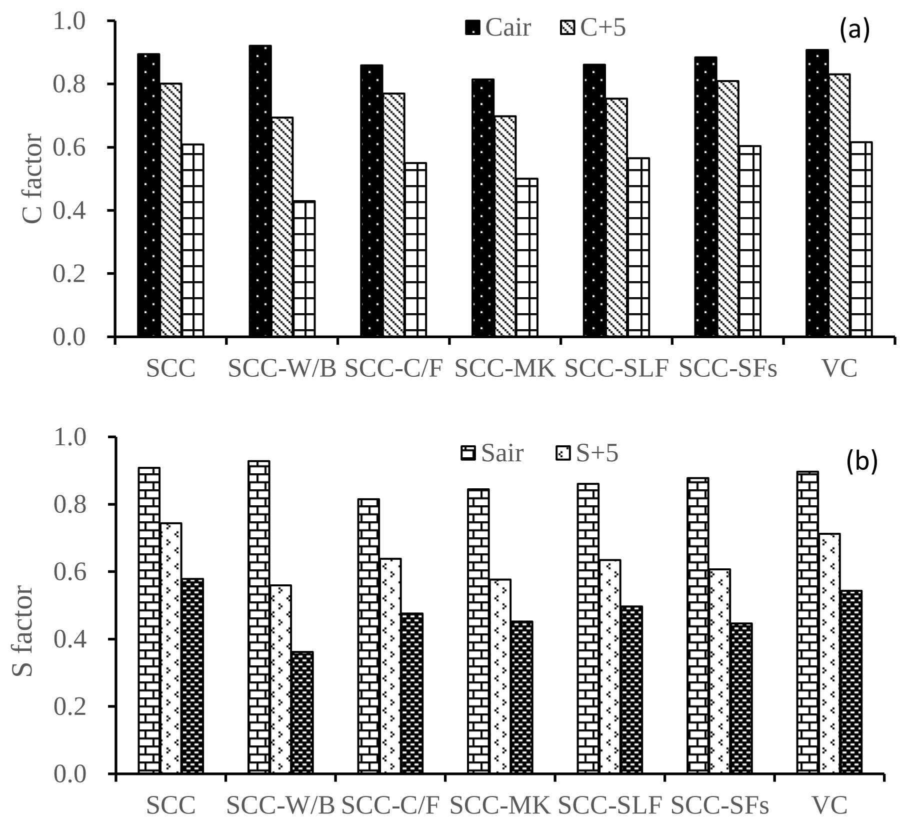


Figure 2. 4: (a) C factor for different curing conditions (air curing at 23º C, +5º C, and -10º C) for all tested mixtures; (b) S factor for different curing conditions (air curing at 23º C, +5º C, and -10º C) for all tested mixtures.

- **Effect of C/F ratio**

The values of C_{air}, C_{+5}, C_{-10}, S_{air}, S_{+5}, and S_{-10} for mixtures with different C/F aggregate ratios are presented in Figure 2. 4. The figure shows that the negative effect of the cold curing on the compressive strength and STS was more pronounced in the mixture with higher C/F aggregate ratio (M3 compared to M1). M3, with 1.2 C/F aggregate ratio, showed C_{+5} and C_{-10} values of 0.77 and 0.55, respectively, while these values were 0.8 and 0.61, respectively, in the control mixture (M1) with 0.7 C/F ratio. Similarly, S_{+5} and S_{-10} appeared to be lower for M3 with 1.2 C/F ratio, which reached 0.64 and 0.48, respectively, compared to the control mixture (M1) with values of 0.74 and 0.58, respectively. This can be related to the higher volume/size of the mortar-coarse aggregate interface zone in the higher C/F ratio mixture (M3 compared to M1). The mortar-coarse aggregate interface zone, considered the weakest zone in the concrete matrix, usually has less cement concentration and relatively higher water content compared to the rest of the concrete matrix (Zaki, AbdelAleem, Hassan, & Colbourne, 2019). Mixtures with a higher C/F ratio have larger volume/thickness of mortar-coarse aggregate interface zone, which increases the chance of developing more microcracks around coarse aggregate (due to ice formation as in the -10º C curing or due to the steep thermal gradient in the +5º C curing). This, in turn, contributed to decreasing the bond between aggregate and surrounding mortar, reducing the concrete strength. It should also be noted that the effect of different curing conditions appeared to be more pronounced in the STS results compared to compressive strength results. This can be related to the fact that the STS is more affected by the development of microcracks inside concrete mixtures compared to compressive strength.

- **Effect of SFs**

The results also highlighted the effect of adding SFs to concrete mixtures under different curing conditions. From Figure 2. 4, it can be seen that mixtures reinforced with SFs showed comparable compressive strength results at different curing conditions (C1-C4). For example, by comparing the results of C_{air}, C_{+5}, and C_{-10} for the mixture with SFs (M6) to their counterparts for the control mixture (M1), it can be noticed that the difference did not exceed 3%. On the other hand, despite the significant enhancement in the STS for the moisture curing condition when SFs were used, this enhancement reduced considerably when concrete samples were cured in cold curing temperature for the mixture reinforced with SFs. For instance, adding SFs to the control mixture increased the STS by 81.9% under moisture curing condition, while this enhancement reached up to 48.6% and 40.2% when the mixture with SFs was cured in +5º C and -10º C, respectively (M6 compared to M1). The lower enhancement for the mixture with SFs compared to the control mixture when cured in +5º C and -10º C may be attributed to the lower bond and grip effect of the concrete matrix around the SFs. In fact, curing concrete at cold temperatures slows down the hydration process, which reduces the amount of hydration products that grow around the fibers (BAŞSÜRÜCÜ & TÜRK, 2019; Madandoust, Kazemi, Talebi, & Brito, 2019). This, in turn, weakened the bond between SFs and the concrete matrix, which reduced the bridging mechanism effect and hence decreased the STS. In addition, the steep thermal gradient that occurs in the +5º C curing condition and the formation of ice in of the -10º C curing condition contributed to developing microcracks, which reduced the bond between SFs and the concrete matrix and in turn decreased the STS.

- **Effect of w/b ratio**

Figure 2. 4 shows the effect of different curing conditions on the compressive strength and STS of mixtures developed with different w/b ratios. From the figure, it can be observed that the compressive strength results for the mixture with higher w/b ratio are more negatively affected by the cold temperature curing compared to the results of the mixture with lower w/b ratio. For example, the mixture with higher w/b ratio (0.55) exhibited C_{+5} and C_{-10} values of 0.69 and 0.43, respectively, while the control mixture with lower w/b ratio showed values of 0.8 and 0.61, respectively (M2 compared to M1). Similarly, the STS results of the mixture with high w/b ratio appeared to be more influenced by the cold temperature curing compared to the mixture with low w/b ratio. By comparing S_{+5} and S_{-10} for mixture M2 (high w/b ratio) to their counterparts for mixture M1(low w/b ratio), it can be seen that S_{+5} and S_{-10} decreased by 25% and 37%, respectively, when the w/b ratio increased from 0.4 to 0.55. This can be attributed to the reduced hydration activity at cold temperature (+5º C), which leaves a relatively larger amount of mixing water (that was not used for hydration) in the matrix. And in mixtures with high w/b ratio (cured at +5º C), the amount of free water left in the matrix would be higher than in mixtures with low w/b ratio. This high amount of unused water for hydration would further reduce the strength of the mixture. In addition, under freezing temperature curing such as -10º C, the excess water stored in the capillary pores can turn into ice with larger volume, which induces an internal pressure on the concrete matrix. This pressure led to the initiation of cracks in the concrete matrix, which reduced the concrete strength. The results also showed that at C2 curing condition (air curing), the mixture with high w/b ratio showed less reduction in compressive

strength and STS compared to the mixture with lower w/b ratio (opposite to the case of C3 and C4). For example, the mixture with high w/b ratio showed C_{air} and S_{air} of 0.92 and 0.93, respectively, while these values reached 0.89 and 0.91, respectively, in the mixture with lower w/b ratio. This can be related to the higher amount of water available for hydration in the mixture with higher w/b ratio, which allows the hydration process to continue and limits the self-desiccation of the concrete mixture.

- **Effect of SCMs**

The effect of SCMs on enhancing the strength was less in cold curing temperatures (C3 and C4) compared to moisture curing (C1). For example, using MK increased the compressive strength by 27.6% when concrete was cured in moisture curing condition (C1), while this enhancement was only 11.1% and 4.8% at C3 and C4 curing conditions, respectively (M4 compared to M1, see Table 2. 3). Similar behaviour for SCMs was also observed in the STS results. This can be related to the lower amount of hydration products available to react with MK at cold temperature curing. MK, as an SCM, reacts with the calcium hydroxide produced from the cement hydration (pozzolanic reaction) to form more cementitious products and increase the strength of the matrix. And since the cold temperature curing led to a reduction in the hydration reaction (reduction in the amount of calcium hydroxide), the hydration between MK and the available amount of calcium hydroxide (pozzolanic reaction) was significantly reduced. It should be noted that, despite the limited effect of SCMs (MK or SLF) on the strength at cold curing, using SCMs still showed better enhancement of the strength compared to mixtures without SCMs, even up to +5º C curing (M4 and M5 compared to M1 at C3).

By comparing the VC mixture to the SCC mixture, it can be seen that the compressive strength and STS results are comparable for both mixtures in all curing conditions (C1-C4).

2.6 Effect of different curing conditions on the impact resistance of the control mixture

When concrete samples are subjected to impact loading, there are two main components that can resist the applied loads. The first component is the coarse aggregate used in the mixture; using high-strength coarse aggregate helps to enhance the strength and impact resistance of concrete, as reported by several researchers (Pham & Hao, 2017; Hassan & Mayo, 2014; Zhang, Shim, Lu, & Chew, 2005). The second component that affects the impact resistance of concrete is the strength of cement mortar and between the coarse aggregates and mortar (AbdelAleem, Ismail, & Hassan, 2017; Ismail & Hassan, 2020). Table 2. 4 shows the number of drops required to cause failure for cylinders subjected to drop weight impact loading and prisms subjected to flexural impact loads. From the table, it can be seen that samples of M1 cured at C1 curing condition required the highest number of drops to cause failure compared to all other curing conditions (C2, C3, and C4) in either drop weight impact or flexural impact tests. For example, curing samples at C2, C3, and C4 curing conditions exhibited reductions of 12%, 25%, and 46%, respectively, in the number of drops for drop weight impact test compared to the C1 curing condition. These reductions reached up to 11%, 28%, and 50% when samples of the flexural impact test cured at C2, C3, and C4 were compared to their counterparts cured at C1. By comparing the results of impact resistance to the results of compressive strength at cold curing conditions, it can be noticed that the negative effect of cold temperature curing seemed to be more pronounced in the impact resistance results compared to the compressive strength results. The results also indicated that curing samples under -10º C (C4) showed significantly lower impact resistance compared to all other curing conditions. For example, samples of M1 in drop weight impact that were cured at C4 curing condition showed a reduction in the number of drops, reaching up to 46%, 39%, and 29% compared to C1, C2, and C3 curing conditions, respectively. This can be related to the weakened cement matrix and the reduced bond between the aggregate and cement mortar due to the ice formed in the capillary voids of concrete when concrete was cured at subzero temperatures, as mentioned before.

Table 2. 4: Drop weight impact and flexural impact results for all tested mixtures at different Curing conditions (C1-C4).

Mixture #	Designation	N. of drops for Drop weight impact				N. of drops for Flexural impact			
		C1	C2	C3	C4	C1	C2	C3	C4
M1	SCC	56	49	42	30	36	32	26	18
M2	SCC-W/B	39	35	24	15	25	23	14	8
M3	SCC-C/F	62	50	41	28	39	31	25	16
M4	SCC-MK	71	61	46	28	47	42	29	16
M5	SCC-SLF	66	54	46	31	45	38	30	19
M6	SCC-SFs	116	104	70	49	81	73	48	28
M7	VC	58	50	44	29	38	35	28	20

2.6.1 Effect of different mixture compositions on drop weight impact and flexural impact resistance under different curing conditions

The ratios between the number of drops required to cause failure (for both drop weight impact and flexural impact) at different curing conditions (C2, C3, and C4) and the comparable number of drops at moisture curing condition (C1) were calculated using Eqs. 2. 4 and 2. 5:

$$\mathbf{I_{cair} = N_c\ @\ C2 / N_c\ @\ C1,\ I_{c+5} = N_c\ @\ C3 / N_c\ @\ C1,\ I_{c-10} = N_c\ @\ C4 / N_c\ @\ C1} \quad \textbf{(2. 4)}$$

$$\mathbf{I_{pair} = N_p\ @\ C2 / N_p\ @\ C1,\ I_{p+5} = N_p\ @\ C3 / N_p\ @\ C1,\ I_{p-10} = N_p\ @\ C4 / N_p\ @\ C1} \quad \textbf{(2. 5)}$$

Where I_{cair}, I_{c+5}, and I_{c-10} are the drop weight impact factors corresponding to curing conditions C2, C3, and C4, respectively, and N_c is the number of drops that caused failure in the drop weight test.

I_{pair}, I_{p+5}, and I_{p-10} are the flexural impact factors corresponding to curing conditions C2, C3, and C4, respectively, and N_p is the number of drops that caused failure in the flexural impact test.

- **Effect of C/F ratio**

Figure 2. 5 presents the values of I_{cair}, I_{c+5}, I_{c-10}, I_{pair}, I_{p+5}, and I_{p-10} for mixtures with different C/F aggregate ratios. It can be seen that increasing the C/F aggregate ratio from 0.7 to 1.2 in the C1 curing condition exhibited a slightly higher number of drops in both drop weight impact and flexural impact resistance tests. This indicates a slightly higher impact

resistance for the mixture with 1.2 C/F ratio compared to that with 0.7 C/F ratio at C1 curing condition. This is because increasing the C/F ratio increased the amount of coarse aggregates in the concrete mixture, which increased the probability of impact loads hitting the sample at the location of coarse aggregate. And, since the coarse aggregate used in this study has a higher impact resistance compared to cement mortar (crushed granite coarse aggregate), the overall impact resistance of samples with higher C/F ratio are expected to be enhanced. Despite both mixtures with different C/F ratios showing a reduced impact resistance when cured in cold temperature compared to moisture curing, this reduction appeared to be more pronounced in the mixture with higher C/F ratio compared to the mixture with lower C/F ratio. For example, the mixture with 1.2 C/F ratio exhibited I_{C+5} and I_{C-10} values of 0.66 and 0.45, respectively, while these values reached up to 0.75 and 0.54, respectively, in the mixture with 0.7 C/F ratio. This can be attributed to the higher reduction in the compressive strength and STS of mixtures with high C/F ratio compared to mixtures with lower C/F ratio, when cured in cold temperature curing (Figure 2. 5).

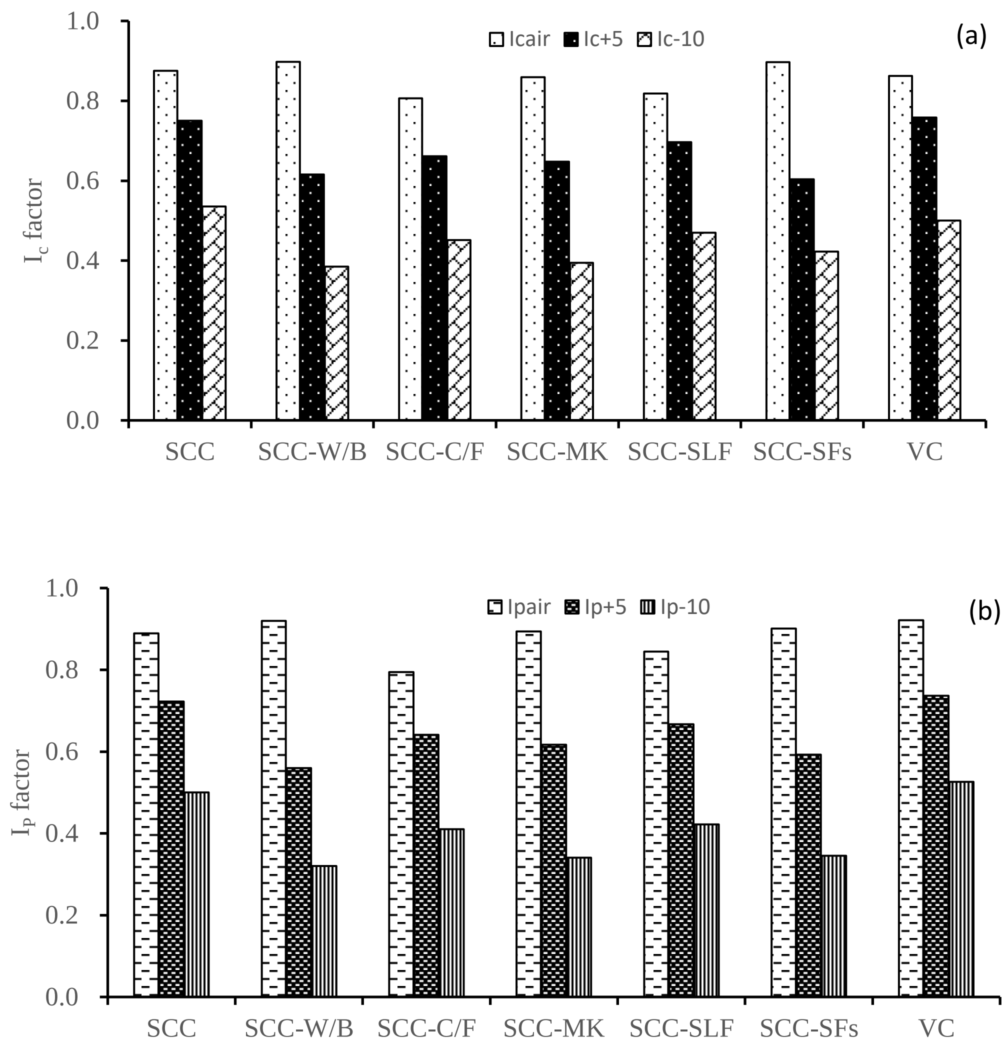


Figure 2. 5: (a) I_c factor for drop weight impact test for different curing conditions (air curing at 23º C, +5º C, and -10º C); (b) I_P factor for flexural impact test for different curing conditions (air curing at 23º C, +5º C, and -10º C).

- **Effect of SFs**

Figure 2. 5 also shows the effect of different curing conditions on the impact resistance of fiber-reinforced concrete. As expected, for moisture curing conditions (C1), the results indicated that adding SFs significantly enhanced the impact resistance of concrete

compared to the control mixture without fibers. This is related to how fiber restricts the cracks and transfers stress across the cracked section, which enhances the tensile strength of concrete and, in turn, improves the impact resistance. Since the flexural impact is more affected by the tensile strength of concrete compared to drop weight impact, the effect of SFs appeared to be more pronounced on the results of flexural impact compared to the results of drop weight impact. By comparing the effect of cold temperature curing to moisture curing (C3 and C4 compared to C1), it can be seen that the impact resistance of the mixture with fibers (M6) was more negatively affected by cold temperature curing compared to the mixture without fibers (M1). However, mixture reinforced with SFs still showed a higher impact resistance in both drop weight impact and flexural impact compared to the control mixture without SFs. For example, the number of drops in the drop weight impact test for fiber-reinforced concrete (M6) exhibited 1.67 and 1.63-times higher values in C3 and C4 curing conditions, respectively, compared to the control mixture without fibers (M1). These values reached up to 1.85 and 1.56 times higher in C3 and C4 curing conditions, respectively, when comparing flexural impact results of M6 to M1.

- **Effect of w/b ratio**

For mixtures developed with different w/b ratios, the results indicated that under moisture curing condition the impact resistance results of the mixture with higher w/b ratio were significantly lower than the mixture with lower w/b ratio (M2 compared to M1), as expected. For example, the mixture with 0.55 w/b ratio showed a reduction in the number of drops for drop weight impact and flexural impact of 30% and 31%, respectively, compared to the mixture with 0.4 w/b ratio at moisture curing condition. The results also revealed that using high w/b ratio exhibited a higher reduction in the impact resistance at cold curing temperatures (C3 and C4) compared to the mixture with lower w/b ratio. For instance, increasing the w/b ratio from 0.4 to 0.55 reduced the I_{c+5} and I_{c+10} by 18% and 29.6%, respectively, indicating a higher reduction in the impact resistance for mixtures with higher w/b ratio when cured under cold curing temperature. This higher reduction in the impact resistance under cold curing temperature for mixture with high w/b ratio may be related to the further weakening of cement mortar and aggregate mortar interface when the mixture with high w/b ratio was cured at cold curing temperature. Mixtures with high w/b ratio have a higher possibility of forming ice in the capillary pores under cold curing temperature, which increases the ice pressure on the cement mortar, forming microcracks and in turn reducing the mortar strength. It should be noted that the results of flexural impact under cold temperature curing were more affected by the increase in w/b ratio compared to the results of drop weight impact test. For example, when the w/b ratio increased from 0.4 to 0.55, the reduction in I_{c-10} reached up to 29.6% in drop weight impact results, while this reduction reached up to 36% in flexural impact results.

- **Effect of SCMs**

Adding SCMs such as MK or SLF enhanced the impact resistance of concrete samples cured in moisture curing conditions. For example, adding MK to the concrete mixture (M4) increased the number of drops required to cause failure in drop weight impact test and flexural impact test by 26.8% and 30.6%, respectively, compared to the control mixture

(M1). Meanwhile, these increases reached up to 17.9% and 25%, respectively, when the mixture with SLF (M5) was compared to the control mixture (M1). On the other hand, at cold curing condition (C3 and C4), mixtures with SCMs showed higher reductions in the impact resistance compared to mixtures without SCMs. For example, in the mixture with MK, the I_{c+5} and I_{c-10} were 0.65 and 0.39, respectively, while these factors were 0.75 and 0.54, respectively, in the control mixture (without MK). Similar behaviour was also observed in the flexural impact results when cold temperature curing was compared to moisture curing. The further reduction in impact resistance for mixtures with SCMs in cold curing conditions may be related to the same reasons discussed earlier in the compressive strength and STS section. Despite the limited effect of SCMs on enhancing the impact resistance at cold curing, using SCMs still provided some enhancements on the impact resistance, even at +5º C curing temperature (C3 curing) (Table 2. 3). The results of this investigation also indicated that VC mixtures showed comparable behaviour to SCC mixtures in both drop weight impact and flexural impact results.

Figures 2.6 and 2.7 represent the failure pattern of tested specimens under the drop weight and flexural impact test, respectively. It can be seen in Figure 2.6 that the control mixture (M1) is suddenly broken into two halves under the effect of 56 hits in the ACI drop weight impact test. Meanwhile, M4 with SCMs was able to sustain a significant number of drops before the first crack. The Figure 2.6 also shows that the mixture with SFs cracked after sustaining a significant number of hits but didn’t break into two halves. In addition, by looking at Figure 2.7, It can be observed that the crack failure pattern is changed from several cracks in the control mixture (M1) with a single crack for mixture with SFs (M6) or mixture with SCMs(M4) under C1. Also. it can be seen that adding SFs or SCMs reduced the crack number and crack widths compared with the control mixture without SFs or SCMs. However, Changing the curing condition from C1 to C4 altered the crack pattern (for the same mixture) from a single crack to multiple cracks in M4 and M6. A similar crack pattern can be observed for the mixture with a higher C/F ratio compared to the control mixture (M1) with a lower C/F ratio.

M1

M4

M6

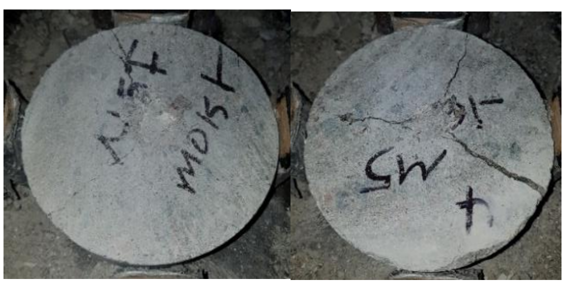
Figure 2. 6: Tested speciement under drop weight impact test after failure

M1 (moisture curing, -10ºC curing)

M2 (moisture curing, -10ºC curing)

M3 (moisture curing, -10ºC curing)

M4 (moisture curing, -10ºC curing)



M6 (moisture curing, -10ºC curing)

M7 (moisture curing, -10ºC curing)

Figure 2. 7: Tested specimens under flexural impact test after failure

2.7 Conclusions

This study investigated the effect of different curing conditions on the mechanical properties and impact resistance of concrete mixtures developed with different mixture compositions. The studied parameters were different C/F ratio (0.7 and 1.2), different w/b ratio (0.4 and 0.55), different SCMs (MK and SLF), and the addition of fibers. The following conclusions can be drawn:

1) Curing concrete at +5º C showed a significant reduction in the compressive strength and STS of up to 20% and 26%, respectively, for the control mixture when compared to moisture curing at 23º C. Meanwhile, curing concrete at -10º C exhibited the worst reduction in the compressive strength and STS, reaching up to 39% and 42%, respectively, for the control mixture when compared to moisture curing at 23º C.
2) The reduction in STS due to curing in cold temperatures appeared to be more pronounced than the reduction in compressive strength. This can be related to the fact that the STS of concrete is more affected by the microcracks initiated (due to steep thermal gradient and ice formation in concrete pores) when concrete samples were cured in cold temperature curing.
3) The effect of cold temperature curing appeared to be more pronounced on the compressive strength, STS, and impact resistance of mixtures with higher C/F ratio or higher w/b ratio, in which higher reductions in the mechanical properties and impact resistance were observed in such mixtures compared to the control mixture (with lower C/F and w/b ratios), when cured in cold temperature curing.
4) Despite the significant enhancement in STS of mixtures reinforced with SFs compared to the control mixture at moisture curing condition, this enhancement reduced significantly when concrete was cured in cold temperature curing. In the meantime, mixture reinforced with SFs showed comparable compressive strength results at different curing conditions (C1-C4).
5) Curing concrete at cold temperatures significantly reduced the positive effect of SCMs (MK and SLF) on enhancing the compressive strength and STS of concrete.

For example, using MK enhanced the compressive strength of the control mixture by 27.6% at moisture curing condition, while this enhancement reached up to 4.8% at -10º C curing condition.

6) The negative effect of cold temperature curing appeared to be more pronounced on the impact resistance and STS results compared to compressive strength results. The reduction in impact resistance and STS reached 46% and 42% when the control samples were cured at -10º C compared to moisture curing, while this reduction reached 39% in compressive strength.
7) The impact resistance of mixtures with SFs/MK/SLF was more negatively affected by cold temperature curing compared to the control mixture (without SFs/MK/SLF), in which a lower value of I_{C+5}, I_{C-10}, I_{p+5}, and I_{P-10} were observed in mixtures with SFs/MK/SLF compared to the control mixture. However, some enhancements in impact resistance were observed in mixtures with SFs/MK/SLF compared to the control mixture even at +5º C curing condition (C3).

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Chapter 3: Abrasion Resistance of Concrete with Different Mixture Compositions at Cold Curing Temperatures

3.1 Abstract

This study aimed to investigate the effect of different curing conditions/temperatures on the compressive strength, flexural strength (FS), modulus of elasticity (ME), and abrasion resistance of concrete developed with different mixture compositions. The studied parameters included different water-to-binder (w/b) ratios (0.4 and 0.55), different coarse-to-fine (C/F) aggregate ratios (0.7 and 1.2), addition of steel fibers (SFs), and different supplementary cementing materials (SCMs) (metakaolin (MK) and silica fume (SLF)). The developed mixtures were cured at four different curing conditions: moisture curing condition (C1), air curing condition (C2), +5º C curing condition (C3), and -10º C curing condition (C4). The results indicated that the effect of curing concrete samples under cold curing conditions was more pronounced on FS results compared to all other mechanical properties results, in which the FS reduced by 23% and 41% at +5º C and -10º C curing conditions, respectively, compared to at moisture curing condition. Despite the considerable enhancement in the mechanical properties and abrasion resistance when SFs or SCMs were used in the mixtures, cold curing of mixtures with SCMs or SFs significantly reduced this enhancement. Moreover, cold curing mixtures with SFs showed lower abrasion resistance, even less than mixtures without SFs. The results also revealed that the

negative effect of cold curing in some tested mixtures was more pronounced in the rotating cutter abrasion test compared to sandblasting abrasion test.

3.2 Introduction

Concrete is primarily designed to withstand structural loads, but it should also contend with the cycle of environmental forces. The most severe environmental loading may include wetting and drying cycles, extreme cold temperatures, and other forms of natural attack such as abrasive loads in harsh environments. For example, lighthouses and bridge piers in cold regions may become exposed to abrasive loads of sand, rocks, gravel, and ice flow in addition to impact loads from the collision of icebergs and ships. Abrasion resistance of structures can be greatly influenced by changing the curing condition. In fact, appropriate curing condition plays an important role in improving the durability and strength gain, which can directly affect the abrasion resistance of concrete.

Curing of concrete is defined as providing adequate moisture and favorable temperature that allows concrete to achieve the desired strength and durability. Changing the curing condition may significantly affect the mechanical properties of concrete. Specifically, cold weather can considerably reduce the final strength of concrete, if the protection of fresh concrete against freezing is not properly followed ACI-306R-88. Past studies reported that to achieve a proper hydration for concrete mixture, a minimum relative humidity of 80% and average curing temperature of 18º C to 23º C are required (ACI, 2010; Wilson & Kosmatka, 2011). This is in addition to preserving a certain amount of water in the mixture to maintain the cement hydration's progress. If the temperature of fresh concrete mixtures drops below zero, not only will the hydration process be delayed but the mixing water inside the mixture may freeze, causing internal cracks. These cracks can weaken the bond between the aggregates and surrounding paste, and, in turn, significantly reduce the overall strength of the concrete. Therefore, a special preparation for curing should always be considered when mixtures are cured in low temperatures in order to achieve proper strength gains.

In severe environments, surface abrasion of concrete can be one of the most critical types of deterioration. It is a form of natural attack resulting from several cycles of scraping/wearing away of materials from the concrete surface. Offshore concrete structures, for example, especially those in Arctic regions, may be exposed to aggressive abrasion attacks. The continuous rubbing effect of moving ice sheets against the concrete surface can cause wearing of the concrete cover and disintegration of aggregate particles at the surface, leading to a significant reduction in concrete strength (Ridgley, Abouhussien, Hassan, & Colbourne, 2019; Sonebi & Khayat, 2001). Past studies suggested several measures to improve the abrasion resistance of concrete, including optimizing the water content (i.e., reducing the water-to-binder ratio), using more durable aggregates, optimizing the coarse-to-fine aggregate ratio, using supplementary cementing materials, and/or adding fibers to the concrete mixture (Papenfus, 2003; Shurpali, Edwards, Kernes, Lange, & Barkan, 2017).

The resistance of concrete to abrasion is highly dependent on the stiffness of concrete (hardness of the paste and aggregate combined) and the bond between the aggregate and cement paste (Papenfus, 2003; Ismail, Hassan, & Lachemi, 2019). More specifically, the hardness and volume of coarse aggregates in the mixtures play a crucial role in improving the abrasion resistance of concrete (Papenfus, 2003; Ismail & Hassan, 2019; Kilic, et al., 2008). For example, Laplante et al. (1991) found that concrete made with granite coarse aggregates had the highest abrasion resistance among other tested concrete mixtures containing limestone and dolomite aggregates. Other studies also concluded that increasing the coarse-to-fine (C/F) aggregate ratio increased the abrasion resistance of concrete (Ismail & Hassan, 2019; Zaki, AbdelAleem, Hassan, & Colbourne, 2019; Adewuy, Sulaiman, & Akinyele, 2017). Although there are sufficient available studies in the literature that investigated the effect of coarse aggregate on the abrasion resistance of concrete, very limited research included the effect of different curing conditions in their investigation.

Using supplementary cementing materials (SCMs) such as metakaolin (MK) and silica fume (SLF) has proven to be another factor that can considerably improve the abrasion resistance of concrete under normal curing condition (Rashad, 2013; Ismail & Hassan, 2016). The pozzolanic reactivity of SCMs enhances the surface abrasion resistance of concrete by increasing the strength of the mortar and its bonding with aggregate particles (Ismail, Hassan, & Lachemi, 2019). Ismail and Hassan (2019) reported that using 8% SLF and 20% MK enhanced the abrasion resistance of concrete by 11.5% and 21.4%, respectively, compared with the control mixture. Despite the beneficial effect of adding MK and SLF to improve the abrasion resistance and mechanical properties of concrete under conventional curing conditions, the abrasion resistance of concrete containing SLF and MK under different curing conditions (especially under low temperatures) still needs further investigation, as the pozzolanic reactivity of such SCMs can be significantly affected by low temperature.

Another critical parameter that appeared to considerably affect abrasion resistance and mechanical properties is the addition of fibers to concrete mixtures (Ismail & Hassan, 2017; Nia, Hedayatian, Nili, & Sabet, 2012). Fibers act as anchors for the surrounding concrete, which prevents particles dislodging from the surface (Shurpali, Edwards, Kernes, Lange, & Barkan, 2017). By reviewing the related studies, it can be observed that steel fibers (SFs) and polypropylene fibers are the two common types of fibers that were regularly used to enhance the mechanical properties and abrasion resistance of concrete. However, SFs appeared to be more effective than polypropylene fibers (Zaki, AbdelAleem, Hassan, & Colbourne, 2019; Shurpali, Edwards, Kernes, Lange, & Barkan, 2017). Using SFs proved to be more useful in a harsh environment (such as cold regions) than polypropylene fibers due to the low glass transition temperature of the polypropylene fibers, making them more vulnerable to cold temperatures (Zaki R. A., AbdelAleem, Hassan, & Colbourne, 2021). Previous studies indicated that adding SFs in concrete significantly affected the cracking behaviour, flexural strength, and abrasion resistance of concrete under conventional curing conditions (Afroughsabet, Biolzi, & Ozbakkaloglu, 2017; Olivito & Zuccarello, 2010; Khaloo, Raisi, Hosseini, & Tahsiri, 2014). For instance, Ismail and Hassan (2016) found that using 0.35% SFs in a rubberized SCC mixture enhanced the flexural strength by 22.4% compared to the control mixture without fibers. Shurpali et al. (2017) found that using 0.5% SFs enhanced the abrasion resistance of concrete by 41%. Few studies investigated the effect of fibers on abrasion resistance under different curing conditions. Poor curing can affect the bond between fibers and cement paste, which may reduce the positive effect of fibers on improving the abrasion and mechanical properties of concrete.

Optimizing the water content is a crucial parameter that considerably affects the strength development and abrasion resistance of concrete. This is mainly due to the direct effect of the water-to-binder (w/b) ratio on the bond strength between mortar and aggregates. Increasing the w/b ratio increases the pore sizes in the mixture, reducing the compressive strength and abrasion resistance of concrete. Increasing the water content in the mixture can be even more critical when curing concrete at freezing conditions. The excess water in the pore structure of the fresh mixture can freeze under subzero temperatures, causing internal cracks and further reduction in the strength and durability of the mixture. Even though several studies investigated the effect of w/b ratio on the mechanical properties and abrasion resistance of concrete under normal curing conditions, limited studies have investigated that effect under different curing conditions, especially at low temperatures.

Therefore, this study was conducted to investigate the effect of low temperatures and different curing methods on the mechanical properties and abrasion resistance of mixtures developed with different mixture compositions. Four different curing methods were applied: moisture curing at +23º C, air curing at +23º C, curing at +5º C, and curing at -10º C. The investigated mixtures were developed with different SCMs (MK and SLF), different C/F aggregate ratios, different w/b ratios, and the addition of SFs. The tested properties were compressive strength, flexural strength, modulus of elasticity, and rotating cutter and sandblasting abrasion tests.

3.3 Research Significance

Investigating abrasion resistance is an important aspect of the long-term performance evaluation of concrete. Despite the fact that several studies examined the mechanical properties of concrete under normal curing conditions, limited research has been conducted to investigate the effect of different curing conditions on the performance of concrete, especially the abrasion resistance. In addition, there are no available studies that included different mixture compositions in the evaluation of the abrasion resistance under cold curing conditions. Concrete in Arctic regions may be exposed to cold temperature at early ages if not cured properly. However, the information regarding the resulted mechanical properties and abrasion resistance of concrete exposed to cold curing is missing from the literature.

This study aimed to fill this knowledge gap and discover the effect of different curing conditions and temperatures on the abrasion resistance of concrete. In addition, this study thoroughly investigated the significant influence of using different mixture compositions on abrasion resistance and mechanical properties of concrete under different curing conditions. The authors believe that this study will immensely help to improve the abrasion resistance of concrete and give a better understanding of the role of curing in influencing the mechanical properties and abrasion resistance.

3.4 Experimental Study

3.4.1 Materials

In this study, type I General Use Canadian Portland cement, similar to ASTM C150 (2018) was used. Two types of supplementary cementing materials were used in this study: MK similar to ASTM C618 (2017) class N and SLF similar to ASTM C1240 (2014). Natural sand and crushed granite aggregates (10 mm (0.39 in.) maximum aggregate size) were used as the fine and coarse aggregates, respectively. Both aggregates had a specific gravity and absorption ratio of 2.6 and 1%, respectively. Single 35 mm (1.37 in.) hooked-end SFs with 65 aspect ratios were used to develop the fiber-reinforced SCC mixture. The modulus of elasticity, specific gravity, and tensile strength of SFs were 210 GPa (30450 ksi), 7.85, and 1150 MPa (166.75 ksi), respectively. A high-range water-reducing admixture (HRWRA) similar to ASTM C494 (2016), with a specific gravity of 1.2, pH of 9.5, and volatile weight of 62%, was added to the concrete mixture in order to achieve the flowability requirements of the SCC mixtures. Figure 3. 1 shows the gradation curves for both coarse and fine aggregates. Table 3. 1 represents the chemical and physical properties of cement and SCMs (SLF and MK) used in this study.

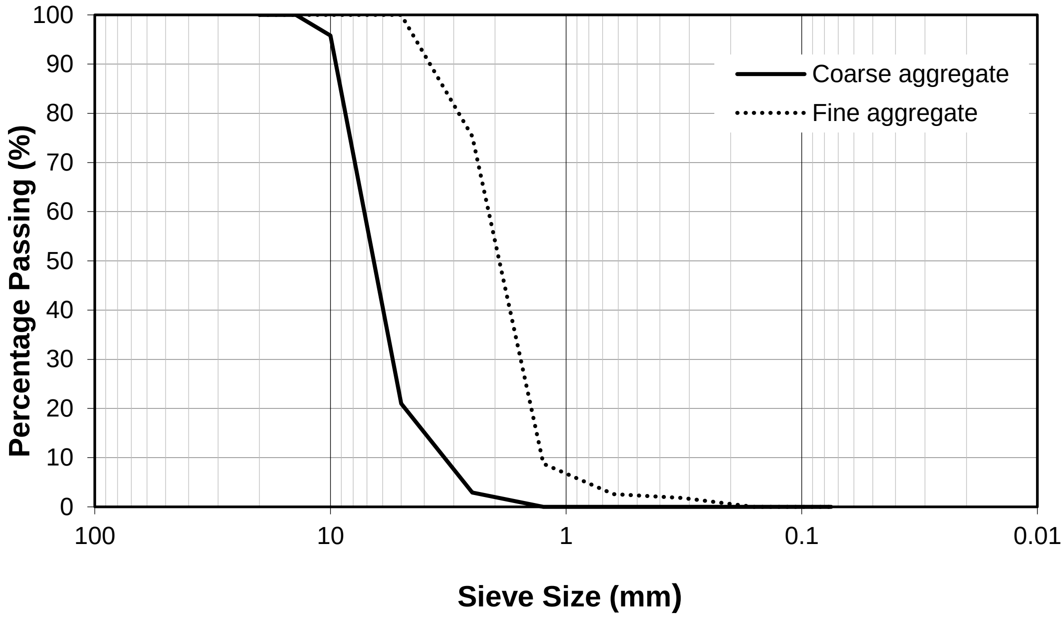


Figure 3. 1: Coarse and fine aggregate gradation curves.
(1 mm = 0.039 in)

Table 3. 1 : Chemical and physical properties of supplementary cementing materials.

Chemical properties (%)	Cement	SLF	MK
SiO_2	19.64	90	51-53
Al_2O_3	5.48	0.4	42-44
Fe_2O_3	2.38	0.4	<2.2
CaO	62.44	1.6	<0.2
MgO	2.48	-	<0.1
Na_2O	-	0.5	<0.05
K_2O	-	2.2	<0.40
C_3S	52.34	-	-
C_2S	16.83	-	-
C_3A	10.50	-	-
C_4AF	7.24	-	-
L.O.I	2.05	0.57	0.95
Physical properties			
Specific gravity	3.15	2.2	2.56
Blaine fineness (m^2/kg)	410	20000	1390

Note: $m^2/kg = 4.85\ ft^2/Ib$

3.4.2 Research program

The aim of this study was to evaluate the effect of using different curing techniques on the abrasion resistance and mechanical properties (compressive strength, flexural strength, and modulus of elasticity) of concrete developed with different mixture compositions. The investigated mixtures included five SCC mixtures, one SCC mixture reinforced with SFs (SF-SCC), and one vibrated concrete mixture (VC). Several trial mixtures were preliminarily conducted to optimize the flowability and stability of the tested SCC mixtures (see Table 3.3). The preliminary trial mixture stage was performed to achieve the following:

a) Determine the maximum and minimum range of C/F aggregate ratios needed to achieve acceptable SCC mixtures. This range was used to study the effect of C/F aggregate ratio on the mechanical properties and abrasion resistance of the tested mixtures under different curing conditions. In this investigation, 0.7 and 1.2 C/F aggregate ratios were found to be safe to develop successful SCC mixtures with acceptable flowability and stability, as per EFNARC (2005) guidelines.

b) Determine the minimum and maximum range of w/b ratios required to develop successful SCC mixtures with minimal bleeding and without segregation of particles. This range was used to study how the w/b ratio affected the mechanical properties and abrasion resistance of the tested mixtures under different curing conditions. In this investigation, HRWRA was used with different dosages in each mixture until a slump flow of 750 ± 50 was achieved. The investigation found that a minimum w/b ratio of 0.4 was needed to achieve the acceptable flowability of SCC mixtures, without overloading the HRWRA. Also, 0.55 was found to be the maximum w/b ratio that can be used safely to develop SCC mixtures with sufficient stability and no signs of segregation.

c) Optimize the volume of MK, SLF, and SFs needed in order to develop successful SCC mixtures with enhanced abrasion resistance and mechanical properties.

The trial mixture stage concluded that a minimum of 500 kg/m^3 cement content was necessary to achieve adequate flowability and no signs of segregation. In mixtures that incorporated SCMs (MK and SLF), 20% MK and 10% SLF were found to be the optimal percentages to achieve optimized mixtures with maximized strength and stability. The trial mixtures also concluded that 0.35% was the maximum percentage of SFs that could be added to develop successful SCC. Using a higher percentage of SFs (higher than 0.35%) appeared to significantly reduce the fresh properties of the developed mixtures. Table 3. 2 presents the proportions of all developed mixtures.

Table 3.2: Mixture proportions of the developed mixtures.

#	Designation	Binder materials kg/m^3			w/b ratio	Water kg/m^3	Aggregate			Steel fibers kg/m^3	Dry density kg/m^3
		Cement	SLF	MK			C/F ratio	Coarse kg/m^3	Fine kg/m^3		
M1	SCC	500	-	-	0.40	200	0.70	686.5	980.8	-	2367.3
M2	SCC-W/B	500	-	-	0.55	275	0.70	606.2	866.1	-	2172.3
M3	SCC-C/F	500	-	-	0.40	200	1.20	909.4	757.9	-	2367.3
M4	SCC-MK	400	-	100	0.40	200	0.70	678.7	969.6	-	2348.3
M5	SCC-SLF	450	50	-	0.40	200	0.70	679.2	970.3	-	2349.5
M6	SCC-SFs	500	-	-	0.40	200	0.70	686.2	980.2	27.5	2369.2
M7	VC	500	-	-	0.40	200	0.70	686.5	980.8	-	2367.3

Note: MK = metakaolin; SLF = silica fume; and 1 kg/m^3 = 0.06243 lb/ft^3

The approach of selecting the tested mixtures was based on the following:

1. Mixture 1 was selected as a reference mixture.
2. Mixture 2 (with higher w/b ratio) and Mixture 3 (with higher C/F aggregate ratio) were designed to study the effect of curing on the abrasion resistance and mechanical properties of mixtures with different w/b ratios and mixtures with different C/F aggregate ratios, respectively.
3. Mixture 4 and Mixture 5 contained MK and SLF, respectively. These mixtures were designed to study the importance of using SCMs to improve the mechanical properties and abrasion resistance under different curing techniques (compared with the reference mixture without SCMs).
4. Mixture 6 was designed to investigate the behaviour of fiber-reinforced concrete (including 0.35% SFs) compared to non-fibered concrete (Mixture 1) under different curing conditions.
5. Mixture 7 was developed as a VC mixture (with similar mixture composition to Mixture 1) to compare the performance of VC to SCC under the different curing techniques.

The designation of mixtures was based on the type of concrete (SCC or VC), C/F aggregate ratio, w/b ratio, SCM type (MK or SLF), and the presence of SFs. For instance, the SCC mixture with SLF as SCMs was labelled as SCC-SLF (Mixture 5). Also, the SCC mixture with SFs was labelled as SCC-SFs (Mixture 6), as shown in Table 3. 2. Fresh properties results of all tested mixtures are shown in Table 3. 3.

Table 3. 3: Fresh properties results of all tested mixtures.

Mix #	Mixture	T50 (sec)	T50J (sec)	V-funnel (sec)	L-box	Slump–J-ring diameters	SR%
1	SCC	2.1	2.85	8.0	0.89	14	3.56
2	SCC-W/B	3.8	4.5	15	0.75	75	8.5
3	SCC-C/F	3.15	3.9	9.5	0.76	60	6.5
4	SCC-MK	3.5	4.25	9.9	0.92	10	2.6
5	SCC-SLF	2.4	3.1	8.3	0.85	20	3.0
6	SCC-SFs	2.9	3.6	9.0	0.8	30	3.9

3.4.3 Sample preparation

All the materials, including aggregates and binders (cement and SLF or MK), were dry-mixed for 2.5 minutes, then two-thirds of the required water was added and remixed for another minute. The required dosage of HRWRA was added to the remaining amount of water, then mixed with the materials for another 2.5 ± 0.5 minutes. When the slump flow for SCC mixtures was reached (700 ± 50 mm), the rest of the fresh properties tests were conducted. The specimens were cured under four different curing techniques, including moist curing condition (C1), air curing condition at ambient air room temperature (C2), 5^{o} C temperature curing condition (C3), and -10^{o} C curing condition (C4). The specimens cured in C1 were kept in a moist curing room with a controlled temperature of 23 ± 1^{o} C for 28 days, while the specimens cured in C2 were stored at a room temperature of 23 ± 1^{o} C for 28 days. On the other hand, the specimens cured in cold temperatures (C3 and C4) were kept in a cold room to control and maintain the specified temperatures ($+5^{o}$ C and -10^{o} C for C3 and C4, respectively) for 28 days.

The mechanical properties investigated in this study included compressive strength, modulus of elasticity, and flexural strength as per ASTM C39 (2020), ASTM C469 (2014), and ASTM C78 (2016), respectively. For each of the four curing conditions, three identical cylinders (200 mm (7.87 in.) high with a 100 mm (3.93 in.) diameter) were used to measure the compressive strength and modulus of elasticity. Prisms measuring 100 x 100 x 400 mm (3.93 x 3.93 x 15.72 in.) were tested in four-point loading to measure the flexural strength of the studied specimens.

3.4.4 Abrasion resistance tests

The tested samples of the abrasion resistance were prepared by cutting three 100 mm cubes from the 100 x 100 x 400 mm (3.93 x 3.93 x 15.72 in.) prism ASTM C944 (2012). The abrasion resistance was measured using two different tests: rotating cutter and sandblasting abrasion tests (see Figure 3. 2). Details of the two abrasion tests are as follows:

- **Rotating cutter test**

This test was used to measure the surface abrasion resistance of samples as per ASTM C944 (2012). The test simulates the abrasion of concrete subjected to abrasive forces, such as heavy traffic on highways and concrete bridges. In this test, three 100 mm cubic samples from each mixture were tested by using a rotating-cutter drill press. At the first step, the samples were weighed to the nearest 0.1 g and then securely fastened in the rotating-cutter drill press. The surface of each sample was subjected to a 4-minute cycle of abrasion with a constant applied load of 98 N. The abrasion test was performed for three rounds with a total abrasion time of 12 minutes. After finishing the test, the surfaces of samples were air-blown clean and then weighed again to the nearest 0.1 g. The average mass loss of the samples was measured by subtracting the final weight of the sample from its original weight.

(a)

(b)

Figure 3. 2: (a) Sandblasting and rotating cutter tests setup; (b) tested samples in sandblasting and rotating cutter tests.

- **Sandblasting abrasion test**

This test was conducted to measure the surface abrasion resistance as per ASTM C418 (2012). This method is designed to simulate the abrasive load of waterborne and moving traffic on the concrete surface. In this test, the sample was initially weighed to the nearest 0.1 g and then placed in the sandblast cabinet perpendicular to the nozzle with a distance of 75 ± 2.5 mm. The surface of the tested samples was then subjected to a blast using air-driven silica sand for a duration of 1 minute on nine different spots, on the concrete surface. The sandblasting results in cavitation of the concrete surface. After the test, the sample was weighed again to the nearest 0.1 g, and the mass loss was calculated. The difference between the initial weight of the concrete and after sandblasting shows the abrasion resistance of concrete specimens in the sandblasting method.

3.5 Discussion of Results

3.5.1 Effect of different curing conditions on the mechanical properties of the control mixture

Table 3. 4 shows the effect of different curing conditions on the compressive strength, FS, and modulus of elasticity of the control mixture. From the table, it can be observed that curing the control mixture (M1) in cold curing conditions (C3 or C4) considerably reduced the compressive strength, modulus of elasticity, and FS compared to samples cured at moisture curing condition (C1). For example, samples cured at C3 curing condition showed a reduction in the compressive strength, FS, and modulus of elasticity of up to 20%, 23%, and 14%, respectively, compared to C1 curing condition. Meanwhile, these ratios increased to 39%, 41%, and 32%, when C4 curing condition was used. The reduction in the mechanical properties of samples cured at cold curing conditions (C3 and C4) may be

related to the deficiency in the cement matrix's hydration process that resulted from curing samples at cold curing conditions. In addition, at subzero curing temperature (similar to C4) the water stored in capillary pores (required for hydration) changes into ice, which expands and induces a pressure on the concrete matrix. This pressure promotes the initiation of micro-cracks in the cement matrix, which can considerably affect the concrete strength.

From the results, it can also be noted that the FS was more affected by the cold curing compared to the other mechanical properties, while the modulus of elasticity appeared to be insignificantly affected by the cold curing temperature. This can be attributed to the fact that the FS is more sensitive to the initiation of micro-cracks in the concrete matrix that resulted from cold temperature curing.

Table 3. 2: Compressive strength, FS, and ME for all tested mixtures at different curing conditions (C1-C4).

#	Designation	Compressive strength (MPa)				FS (MPa)				ME(GPa)			
		C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
M1	SCC	67.40	60.25	54.00	41.00	7.80	7.20	6.00	4.60	29.40	27.60	25.23	20.00
M2	SCC-W/B	51.20	47.13	35.50	22.00	5.70	5.55	3.60	2.20	23.21	22.24	17.08	11.38
M3	SCC-C/F	63.70	54.72	49.00	35.00	6.80	6.00	4.75	3.60	27.14	24.71	22.12	16.43
M4	SCC-MK	86.00	70.00	60.00	43.00	10.20	8.46	6.85	4.90	37.00	31.70	27.80	20.70
M5	SCC-SLF	74.30	64.00	56.00	42.00	8.95	7.85	6.35	4.75	33.10	30.14	26.70	20.00
M6	SCC-SFs	63.00	55.70	51.00	38.00	9.35	8.40	6.60	4.80	30.40	28.54	25.31	19.85
M7	VC	65.00	59.00	54.00	40.00	7.20	6.60	5.25	4.30	29.00	28.04	25.14	19.33

1 MPa = 0.145 Ksi; 1GPa = 145 Ksi

Figure 3. 3 shows a comparison between the experimental flexural strength and theoretical flexural strength calculated based on Canadian Standard Code CSA (CSA-A23.1, 2019), and Eurocode-EC2 (EN-1992-1-1. Eurocode 2, 2005).

As per EC2:

$$\mathbf{FS = 0.3\, {f'_c}^{2/3}} \quad \textbf{(MPa)}$$

As per CSA:

$$\mathbf{FS = 0.6\, \sqrt{f'c}} \quad \textbf{(MPa)}$$

Where FS is the flexural strength, and f'_c is the compressive strength.

From the figure, it can be observed that the design codes (CSA and EC2) underestimated the flexural strength of the control mixture at all studied curing conditions. This can be clearly observed by looking at the ratios between FS^{theo}/ FS^{exp}, in which all ratios are calculated by CSA (CSA-A23.1, 2019) and EC2 (EN-1992-1-1. Eurocode 2, 2005) are less than 1. The results also indicated that the underestimation of design codes for FS^{theo} appeared to be higher in C1 curing condition compared to cold curing conditions (C3 and C4). For example, the FS^{theo}/ FS^{exp} ratio of the control mixture showed values of 0.63 and 0.64 for CSA (CSA-A23.1, 2019) and EC2 (EN-1992-1-1. Eurocode 2, 2005), respectively, at C1 curing condition, while these ratios reached up to 0.84 and 0.78 for CSA (CSA-A23.1, 2019) and EC2 (EN-1992-1-1. Eurocode 2, 2005), respectively, at C4 curing condition. The lower underestimation of the design codes for FS at cold curing conditions may be related to the fact that changing the curing condition from moisture curing to cold curing conditions showed a higher rate of reduction in the FS^{exp} than that of FS^{theo}. The FS^{theo} is calculated based on the compressive strength to the power of 1/2 or 2/3 (CSA and EC2, respectively), which have a lower reduction rate when the curing condition changed from moisture to cold curing conditions. Therefore, changing the curing condition from C1 to C3 and C4 showed a lower reduction rate for FS^{theo} compared to FS^{exp}. This, in turn, exhibited a higher FS^{theo}/ FS^{exp} ratio (lower underestimation) for samples cured in cold curing conditions.

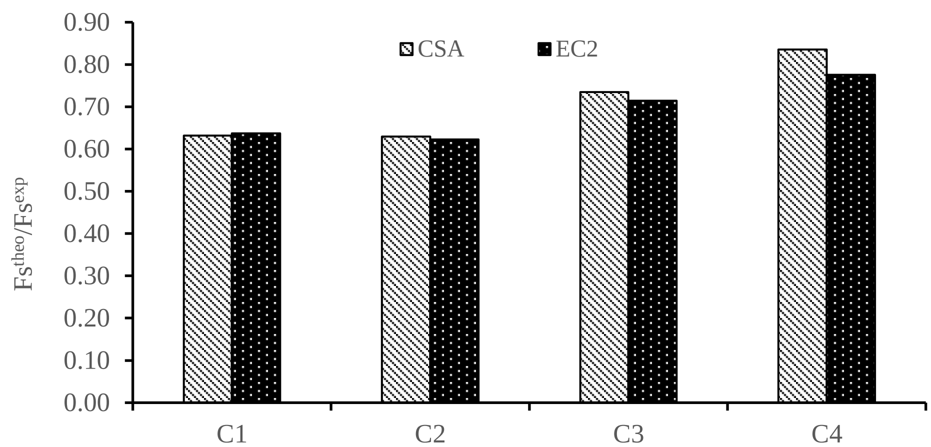


Figure 3. 3: Theoretical-to-experimental FS ratios for control mixture at all different curing conditions.

3.5.2 Effect of different mixture compositions on the mechanical properties of concrete under different curing conditions

- **Effect of C/F aggregate ratio**

Figure 3. 4 shows the mechanical properties results of mixtures developed with different C/F aggregate ratios at different curing conditions. From the figure, it can be seen that at

moisture curing (C1), increasing the C/F aggregate ratio from 0.7 (M1) to 1.2 (M3) reduced the compressive strength, FS, and ME by 5%, 13%, and 8%, respectively. This can be related to the increased volume of aggregate-mortar interface in mixture with higher C/F aggregate ratio. This aggregate-mortar interface is considered the weakest part in the matrix and greatly affects the strength of concrete. On the other hand, at cold curing conditions (C3 and C4), increasing the C/F aggregate ratio from 0.7 to 1.2 (M3 compared to M1) showed higher reductions in the mechanical properties compared to the moisture curing (C1). For example, increasing the C/F aggregate ratio from 0.7 (M1) to 1.2 (M3) reduced the compressive strength, FS, and ME by 15%, 22%, and 18%, respectively, at C4 curing condition, compared to 5%, 13%, and 8% observed at C1 curing condition. The higher reduction in mechanical properties of M3 at cold curing conditions compared to M1 may be attributed to the higher volumes of the aggregate-mortar interface in mixture with a higher C/F aggregate ratio. The aggregate-mortar interface is exposed to either a) internal pressure induced by the formation of ice (at C4 curing condition) or b) steep thermal gradient (difference in temperature between the outer surface and the core of the sample) developed at C3 curing condition. This internal pressure/steep thermal gradient encourages more cracks to initiate around the coarse aggregate, reducing the bond strength between aggregate and surrounding mortar, which in turn reduces the concrete strength.

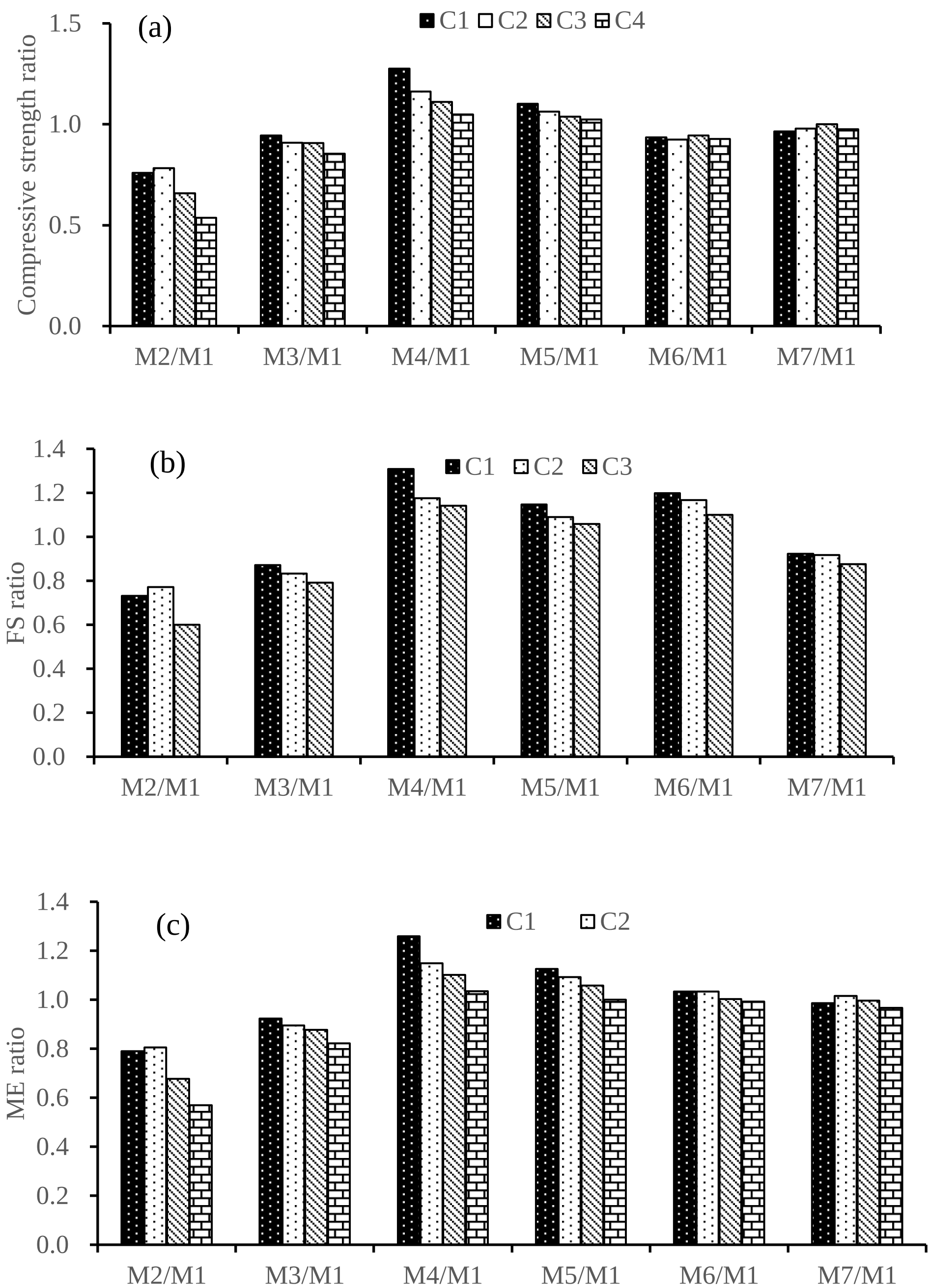


Figure 3.4: (a) Ratios between compressive strength at different curing conditions; (b) ratios between FS at different curing conditions; (c) ratios between ME at different curing conditions.

- **Effect of w/b ratio**

The mechanical properties results of mixtures developed with different w/b ratios are presented in Figure 3. 4. From the figure, it can be noticed that increasing the w/b ratio generally reduced the compressive strength, FS, and ME of concrete at all studied curing conditions. However, the reduction in mechanical properties due to the increase in w/b ratio appeared to be more significant when samples were cured at cold curing conditions (C3 and C4) compared to moisture curing condition (C1). For example, increasing the w/b ratio from 0.4 to 0.55 decreased the compressive strength, FS, and ME by 24%, 27%, and 21%, respectively, at C1 curing condition, while these ratios reached up to 34%, 40%, and 32%, respectively, at C3 curing condition. Similarly, at C4 curing condition, the compressive strength, FS, and ME were reduced by 46%, 52%, and 43%, respectively, when the w/b ratio was increased from 0.4 to 0.55. The significant reduction in mechanical properties of mixture with high w/b ratio at -10º C may be related to the freezing of the excess water (that was unused for hydration) in the capillary pores, which induces a pressure on the concrete matrix. This pressure led to the initiation of cracks that weaken the cement mortar and bond strength between aggregate and mortar, significantly decreasing the concrete strength. In addition, curing concrete mixtures at +5º C contributed to depressing the hydration activity (Farzampour, 2017; Kosmatka & Wilson, 2011), especially in the mixture with higher w/b ratio (M2) compared to the mixture with lower w/b ratio (M1). Unlike the higher reduction in the mechanical properties of M2 compared to M1 at cold curing conditions (C3 and C4), the mixture with higher w/b ratio (M2) showed a lower reduction in mechanical properties compared to the mixture with lower w/b ratio (M1) at air curing condition (C2). For example, by comparing the FS results of M2 to M1, it can be seen that the FS decreased by 40% and 52% when samples were cured at C3 and C4, respectively, while this reduction reached up to 23% at C2 curing condition. This can be explained by the higher amount of water (at M2) available to help the hydration process continue and thus avoid the self-desiccation of the concrete mixture at air curing condition.

- **Effect of SFs**

By looking at mixture reinforced with SFs, it can be seen that using SFs showed comparable compressive strength and ME results to those of the control mixture without fibers (M6 compared to M1) at the four different curing conditions (C1-C4), see Figure 3. 4. On the other hand, by comparing the FS results of the mixture reinforced with SFs (M6) to the control mixture without SFs (M1), it can be seen that adding SFs exhibited a significant increase in the FS results of M6, reaching up to 1.2 times the FS of M1 at C1 curing condition. This can be related to the effect of SFs in transferring the stress across the cracked section, which enhanced the FS of the concrete matrix reinforced with SFs. In the meantime, the enhancement in the FS that resulted from using SFs appeared to be lower when samples of M6 were cured at cold curing conditions compared to C1 curing condition. For example, using SFs in M6 enhanced the FS by 20% at C1 curing condition, while this ratio reached up to 10% and 4% at C3 and C4, respectively, compared to the control mixture without SFs (M1). The lower enhancement in FS under cold curing conditions may be related to the lower bond strength between SFs and the surrounding matrix under cold curing conditions. As mentioned before, curing samples at C3 and C4 curing conditions led to a deficiency in the hydration process (Farzampour, 2017; BAŞSÜRÜCÜ & TÜRK, 2019), which reduced the amount of hydration products that can fill the voids around the SFs. In fact, curing concrete at cold temperatures can decrease the amount of hydration products. Therefore, empty spaces around the fiber cannot properly fill with hydration products, which decreases the fiber-matrix bond. This, in turn, contributed to weakening the bond strength of SFs and reduced the effect of SFs on enhancing the FS of concrete. Moreover, the bond between SFs and surrounding mortar were also negatively affected by the micro-cracks initiated in the concrete matrix around SFs due to the steep thermal gradient that resulted from curing concrete at +5º C (C3).

- **Effect of SCMs**

Using SCMs in concrete mixtures showed a significant enhancement in the mechanical properties of concrete at C1 curing condition. For example, adding MK to the concrete mixture (M4) increased the compressive strength, FS, and ME by 28%, 31%, and 26%, respectively, compared to the control mixture without MK (M1) at C1 curing condition. Similarly, the enhancement in the compressive strength, FS, and ME reached up to 10%, 15%, and 13%, respectively, when the mixture with SLF (M5) was compared to the control mixture (M1) at C1 curing condition. This can be related to the high pozzolanic reactivity and filling effect of SCMs, which contributed to enhancing the pore structure and provided a denser cement matrix. On the other hand, curing concrete at cold temperature contributed to a decay in the effect of SCMs on enhancing mechanical properties of concrete compared to the moisture curing condition. However, mixtures with SCMs still showed a slight enhancement in mechanical properties compared to the control mixture when cured at +5º C. For example, at +5º C, the mixture with MK showed a slightly higher compressive strength, FS, and ME that reached up to 1.11, 1.14, and 1.1 times compared to those of the control mixture (M4 compared to M1). Similar behaviour was observed for the mixture developed with SLF (M5 compared to M1). The lower enhancement of mixtures with SCMs at cold curing conditions may be related to the fact that the hydration process slows down at cold curing conditions, resulting in a lower amount of calcium hydroxide (which is produced after cement hydration). The SCMs react with calcium hydroxide to produce cementitious product that is responsible for strength gain (pozzolanic reaction). Since curing at cold temperatures significantly reduced the amount of calcium hydroxide, the reaction between SCMs and calcium hydroxide is significantly reduced, which then negatively affects the strength of the concrete.

The results also indicated that the results of all the mechanical properties for the VC mixture were comparable to those of its counterpart SCC mixture (M7 compared to M1).

3.5.3 Effect of different curing conditions on abrasion resistance of the control mixture

The abrasion resistance of concrete is usually affected by the strength and hardness of coarse aggregate used in the mixture and the strength and hardness of cement mortar. In addition, the bond strength between the coarse aggregate and surrounding mortar plays an important role in the abrasion resistance of concrete. As the bond strength between coarse aggregate and surrounding mortar increases, the possibility of pulling the coarse aggregate out of the concrete surface under the action of abrasion force decreases. Table 3. 5 shows the mass loss obtained from the rotating cutter and sandblasting tests for all tested mixtures under different curing conditions. From the table, it can be seen that for the control mixture (M1) samples, the rotating cutter test showed a higher mass loss compared to the sandblasting test at all curing conditions (C1-C4). This may be related to the higher surface area affected by the abrasion force in the rotating cutter test compared to the sandblasting test. However, since each of the abrasion tests is simulating a special case of surface abrasion, the difference in mass loss between the rotating cutter test and the sandblasting test was expected. The rotating cutter test represents the abrasion of highway and concrete bridges under the effect of traffic load, while the sandblasting test represents the abrasion of concrete surfaces under waterborne action. The results also indicated that samples cured under moisture curing condition (C1) showed the highest abrasion resistance in both rotating cutter and sandblasting tests compared to all other curing conditions. Similar behaviour was observed in the sandblasting test results. On the other hand, curing the M1 samples in cold curing temperature (C3 and C4 curing conditions) exhibited a significant increase in the mass loss in both rotating cutter and sandblasting tests compared to C1 curing condition. This indicates a lower abrasion resistance for samples cured in cold curing conditions compared to samples cured in moisture curing conditions. For example, curing samples of M1 at C3 and C4 curing condition showed increases in the mass loss of rotating cutter test, reaching up to 1.28 and 1.41 times, respectively, compared to the mass loss of their counterpart samples cured in C1 curing condition. These increases reached up to 1.35 and 1.51 times when samples of the sandblasting test cured at C3 and C4 were compared to their counterparts cured at C1. The higher mass loss (lower abrasion resistance) of samples cured at cold curing condition may be related to the reduction in the strength of cement mortar and mortar-aggregate bond strength when samples were cured at cold curing condition. Curing concrete in cold curing conditions negatively affected the hydration process, which resulted in a weakened cement matrix and reduced the bond between aggregate and cement mortar. This, in turn, contributed to the easy removal of the aggregate and hydrated cement particles from the concrete surface under the action of abrasion force, increasing the mass loss and hence reducing the abrasion resistance of concrete.

Table 3. 3: Rotating cutter mass loss and sandblasting mass loss for all tested mixtures at different curing conditions (C1-C4).

Mixture #	**Designation**	**Rotating cutter mass loss (gm)**				**Sandblasting mass loss (gm)**			
		C1	**C2**	**C3**	**C4**	**C1**	**C2**	**C3**	**C4**
M1	SCC	7.10	8.00	9.10	10.00	5.50	6.40	7.40	8.30
M2	SCC-W/B	9.40	10.30	13.00	15.40	7.60	8.50	11.10	13.60
M3	SCC-C/F	6.00	7.15	9.00	11.70	4.40	5.40	7.40	10.30
M4	SCC-MK	5.40	6.20	7.60	9.00	4.00	4.85	6.00	7.30
M5	SCC-SLF	6.10	7.00	8.30	9.80	4.50	5.50	6.60	7.90
M6	SCC-SFs	5.90	6.90	8.60	11.00	4.30	5.20	6.50	7.90
M7	VC	7.50	8.60	9.70	10.80	6.00	7.15	8.20	9.30

1 gm = 0.0022 Ib.

3.5.4 Effect of different mixture compositions on abrasion resistance of concrete under different curing conditions

- **Effect of C/F aggregate ratio**

Figure 3.5 shows the ratio between the mass loss of the mixture with 1.2 C/F aggregate ratio (M3) and the mass loss of the control mixture with 0.7 C/F aggregate ratio (M1) for both rotating cutter and sandblasting tests, respectively, at different curing conditions (C1-C4). From the figure, it can be seen that at C1 curing condition, increasing the volume of coarse aggregate from 0.7 (M1) to 1.2 (M3) reduced the mass loss in both rotating cutter and sandblasting tests by 15% and 20%, respectively. This can be attributed to the higher volume of coarse aggregate in the mixture with higher C/F aggregate ratio, which increased the probability of exposing the coarse aggregate to abrasion force rather than cement matrix. In this study, since the coarse aggregates used were crushed granite, which has a high strength and hardness compared to cement mortar, the overall hardness of concrete surface against abrasion force was expected to enhance in the mixture with higher C/F aggregate ratio. At C2 curing condition, the mixture with higher C/F aggregate ratio also showed a lower mass loss compared to the mixture with lower C/F aggregate ratio, but with a slightly higher mass loss compared to samples cured at C1 curing condition. On the contrary, at cold curing conditions (C3 and C4), increasing the C/F aggregate ratio to 1.2 showed either a comparable mass loss (at C3 curing condition) or higher mass loss (at C4 curing condition) compared to the control mixture with 0.7 C/F aggregate ratio. For example, increasing the C/F aggregate ratio from 0.7 to 1.2 increased the mass loss by 17% and 24% in the rotating cutter and sandblasting tests, respectively, at C4 curing condition.

The higher mass loss (lower abrasion resistance) of the mixture with higher C/F aggregate ratio at cold curing conditions compared to the mixture with lower C/F aggregate ratio may be related to the weaker aggregate-mortar interface under cold curing conditions. Curing concrete under cold curing conditions, especially at subzero (C4), contributed to weakening the bond between aggregate and surrounding mortar due to the initiation of micro-cracks at the aggregate-cement interface. And since the mixture with higher C/F aggregate ratio had a higher volume of the aggregate-cement interface, the chance of pulling out the aggregate under the action of abrasion force was higher under cold curing conditions, leading to a higher mass loss and lower abrasion resistance.

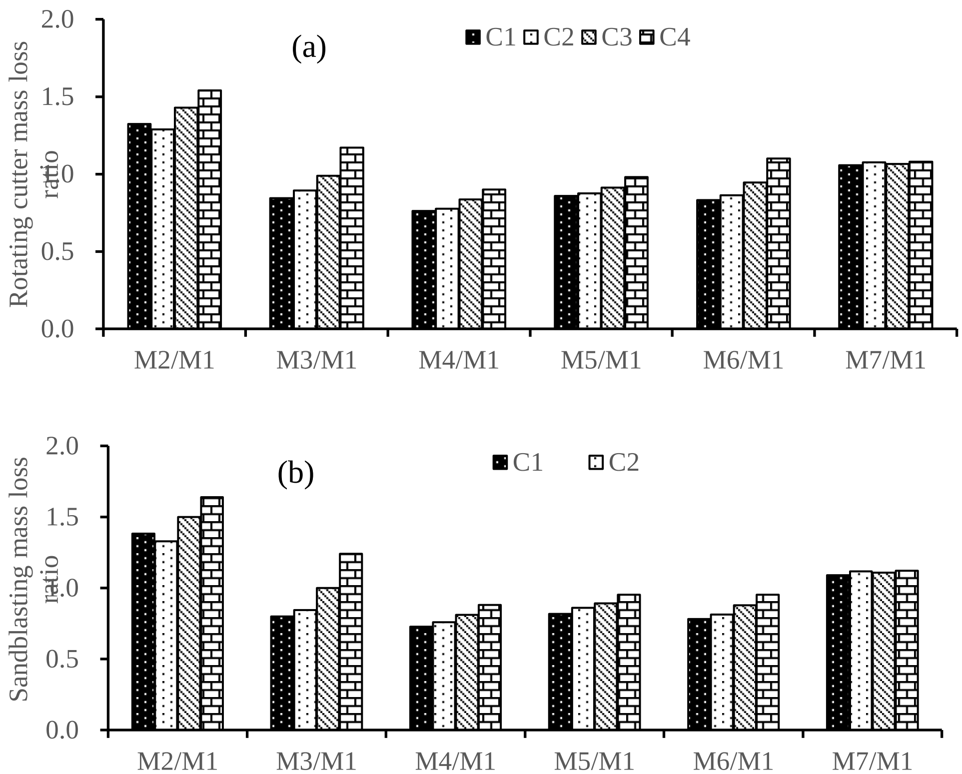


Figure 3.5: (a) Mass loss ratios for rotating cutter test at different curing conditions; (b) mass loss ratios for sandblasting test at different curing conditions.

- **Effect of w/b ratio**

For mixtures developed with different w/b ratios, the abrasion results indicated that at C1 curing condition the mixture with higher w/b ratio exhibited a significant lower abrasion resistance compared to mixture with lower w/b ratio (M2 compared to M1). This was expected since increasing the w/b ratio contributed to weakening the cement mortar strength and mortar-aggregate interface, which led to an easily pulling out of particles from the concrete surface under the action of abrasion force. By comparing the reductions in the abrasion resistance at cold curing conditions (C3 and C4) and moisture curing condition (C1) due to increasing the w/b ratio, it can be observed that increasing the w/b ratio from 0.4 to 0.55 showed a higher reduction in the abrasion resistance under C3 and C4 compared to C1. For example, increasing the w/b ratio from 0.4 to 0.55 increased the mass loss of rotating cutter test at C1 curing condition by 32%, while this percentage reached up to 43% and 54% at C3 and C4, respectively, indicating higher reduction in the abrasion resistance at cold curing conditions. The increased reduction in the abrasion resistance under cold curing conditions for mixture with higher w/b ratio may be related to the further weakening of cement mortar and mortar-aggregate interface when mixture with higher w/b ratio were cured at cold curing conditions. Mixture with higher w/b ratio experienced higher volume of micro-cracks in cement mortar and at mortar-aggregate interface when cured at cold curing conditions. This can be due to the excess amount of water in concrete capillary pores (at C4), which developed due to pressure on the cement mortar when water turned to ice, initiating micro-cracks and, in turn, reducing the mortar strength.

- **Effect of SFs**

Figure 3. 5 shows the ratio between the mass loss of mixture developed with SFs (M6) and mass loss of the control mixture without SFs (M1) for both rotating cutter and sandblasting tests, respectively, under different curing conditions (C1-C4). From the figure, it can be seen that at moisture curing condition, adding SFs reduced the mass loss for both rotating cutter and sandblasting tests compared to mixture without fibers, indicating a higher abrasion resistance for mixture reinforced with SFs. For example, using SFs in M6 reduced the mass loss for rotating cutter and sandblasting tests by 17% and 22%, respectively, compared to the control mixture (M1) without SFs at C1 curing condition. This can be related to the effect of fibers in tying the concrete matrix together and reducing the scattering of concrete particles under the effect of abrasion force. By comparing the effect of cold curing (C3 and C4) to moisture curing (C1) condition, it can be observed that mixture with SFs was more affected by cold curing (higher than mixture without SFs). For example, unlike the enhanced abrasion resistance in the SFs mixture at C1 curing condition, the mixture with SFs showed lower abrasion resistance at C4 compared to the mixture without SFs (control mixture, M1). This can be attributed to the negative effect of cold curing condition on the bond between SFs and concrete matrix. This, in turn, allowed the SFs and concrete particles to be easily pulled out of the concrete surface under the action of rotating cutter abrasion, which increased the mass loss of mixture reinforced with SFs.

By comparing the sandblasting test to the rotating cutter test, it can be observed that the effect of cold curing condition was more pronounced in rotating cutter test results for the mixture with SFs. This can be observed by comparing M6 (with SFs) to M1 (without SFs), in which higher mass loss in the rotating cutter test was observed compared to the sandblasting test at C3 curing condition (Figure 3. 4). This result indicates that the mixture with SFs was less affected by the cold curing temperature when exposed to sandblasting abrasion test compared to rotating cutter test. This can be related to the fact that the negative effect of cold curing temperature on reducing the bond between SFs and surrounding mortar was more pronounced on the abrasion resistance when a larger area of concrete surface was subjected to abrasion force. Therefore, since the surface area subjected to abrasion in the sandblasting test was much smaller than that in the rotating cutter test, the results of the sandblasting abrasion test were less affected by the cold curing conditions (compared to the rotating cutter test).

- **Effect of SCMs**

Using SCMs in concrete mixtures generally enhances the abrasion resistance of concrete when cured in moisture curing conditions. For instance, using MK in concrete mixture (M4) decreased the mass loss in the rotating cutter and sandblasting tests by 24% and 27%, respectively, compared to the control mixture (M1), indicating higher abrasion resistance of M4. In the meantime, these reductions in mass loss reached up to 14% and 18%, respectively, when mixture with SLF (M5) was compared to the control mixture (M1). This can be attributed to the high pozzolanic reactivity of SCMs in strengthening the cement matrix and enhancing the hardness of the concrete surface, which in turn enhanced the abrasion resistance of concrete when cured at C1 curing conditions. On the contrary, mixtures developed with SCMs showed a lower enhancement in the abrasion resistance when cured in cold curing conditions (C3 and C4) compared to moisture curing condition. For example, the reduction in mass loss in rotating cutter test of M4 (mixture with MK) compared to M1 (control mixture) reduced from 24% in C1 to 16% in C3 and 10% in C4. Meanwhile, the reduction in mass loss for sandblasting test of M4 compared to M1 reached up to 27% in C1, 19% in C3, and 12% in C4. This indicates a lower abrasion resistance for the mixture with MK at C3 and C4 compared to C1. Similar results were observed in the mixture with SLF at cold curing conditions. The lower enhancement in the abrasion resistance of mixtures with SCMs under cold curing conditions can be related to the effect of cold weather in retarding the hydration process, as discussed under the mechanical properties section.

Figures 2. 5 and 2. 6 show the surface damage and the mass loss under sandblasting and rotating cutter abrasion tests, respectively, for all tested mixtures in 4 different curing conditions. By looking at the mass loss (surface damage) of all tested mixtures, it can be noticed that the mixture cured at C4 conditions experienced higher mass loss (both rotating cutter and sandblasting results) in all seven-mixture compared with mixtures curing at C1 condition. Moreover, adding SCMs or SFs to the control mixture reduced the rotating cutter and sandblasting mass loss, which resulted in higher abrasion resistance in M4 and M6 compared with the control mixture (M1) under C1 curing condition. In addition, increasing the C/F ratio from 0.7 (M1) to 1.2 (M3) reduced the rotating cutter and sandblasting mass loss under C1 curing condition. Meanwhile, increasing the W/B ratio from 0.4 (M1) to 0.55 (M2) increased the mass loss (rotating cutter and sandblasting) under C1.

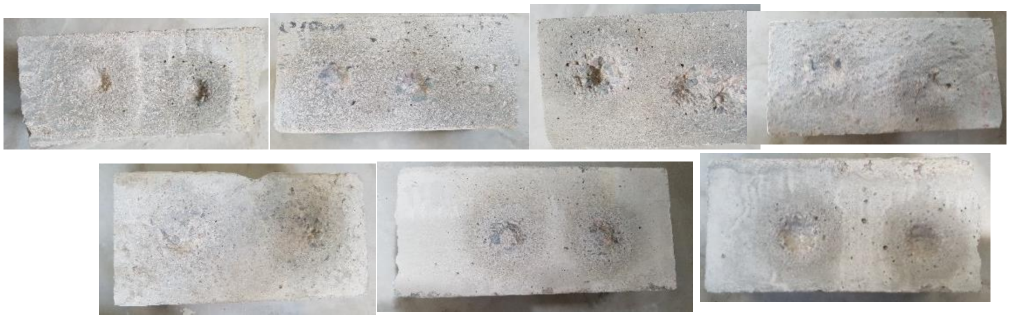
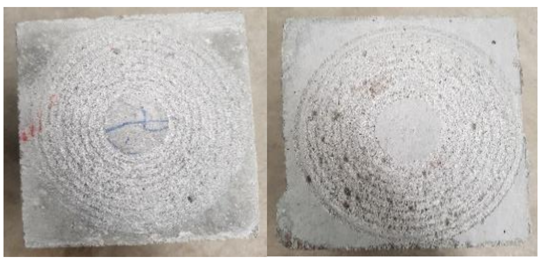
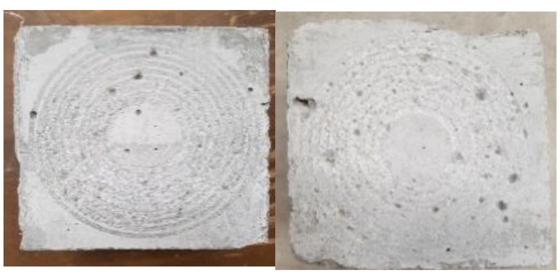


Figure 3. 6: Tested specimens after sandblasting abrasion test



M1 (moisture curing, -10ºC curing)

M2 (moisture curing, -10ºC curing)



M3 (moisture curing, -10ºC curing)

M4 (moisture curing, -10ºC curing)

M6 (moisture curing, -10ºC curing)

M7 (moisture curing, -10ºC curing)

Figure 3. 7: Tested specimens after rotating cutter abrasion test

3.6 Conclusion

The compressive strength, FS, ME, and abrasion resistance of concrete mixtures developed with different mixture compositions at different curing conditions were investigated. The studied parameters were different w/b ratios (0.4 and 0.55), different SCMs (MK and SLF), different C/F aggregate ratios (0.7 and 1.2), and the addition of SFs. From the results, the following conclusions can be drawn:

1) The FS results appeared to be the most affected results by the cold curing conditions compared to all other mechanical properties, in which the FS reduced by 23% and 41% at +5º C and -10º C curing conditions, respectively, compared to moisture curing condition. On the other hand, the ME showed the least affected results by the cold curing conditions, in which the ME reduced by 14% and 32% at +5º C and -10º C curing conditions, respectively, compared to moisture curing condition.
2) The prediction of FS results based on the compressive strength proposed by design codes gave conservative results for FS at all studied curing conditions. Higher conservative results were observed at moisture curing condition compared to cold curing condition.
3) The reductions in the compressive strength, FS, and ME of concrete mixtures due to increasing the C/F aggregate ratio or w/b ratio were more significant when samples were cured at cold curing conditions compared to moisture curing condition.
4) Unlike the significant enhancement in the mechanical properties at the moisture curing condition due to the addition of SFs or SCMs, at cold curing conditions, this

enhancement remarkably decayed due to the deficiency in hydration process. However, using SFs/SCMs still showed some enhancement of the mechanical properties at +5º C.

5) Increasing the C/F aggregate ratio in the mixture increased the abrasion resistance at the moisture curing condition. However, when cold curing was utilized (-10º C), lower abrasion resistance was observed in mixtures with higher C/F aggregate ratio (compared to mixture with lower C/F aggregate ratio). This can be related to the weaker bond between the aggregate particles and surrounding mortar under cold curing condition, which increases the chance of particles being pulled out under abrasion action.

6) Adding SFs enhanced the abrasion resistance in the rotating cutter test at moisture curing conditions. However, at cold curing conditions, mixture reinforced with SFs showed slightly lower abrasion resistance at -10º C curing condition (10% higher mass loss) compared to mixture without SFs. In addition, the negative effect of cold curing in mixture with SFs was more pronounced in the rotating cutter test results compared to sandblasting test results.

7) A significant enhancement in the abrasion resistance was observed when using SCMs at moisture curing condition. However, when SCMs were used at cold curing conditions (C3 or C4), lower enhancement in the abrasion resistance was observed. The enhancement in the rotating cutter abrasion resistance of mixture with MK, as an example, reached up to 24% at C1, 16% at C3, and 10% at C4 compared to the control mixture without MK.

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Chapter 4: Summary and recommendation

4.1. Summary

The individual studies conducted for this project are described in-depth in previous chapters. This study was separated into two parts to show the results in a straightforward manner. Chapter 2 focuses on the role of changing curing conditions on impact resistance, compressive strength, and STS of seven different mixtures. And Chapter 3 investigates the effect of applying four different curing conditions on the abrasion resistance and mechanical properties of series of the concrete mixture.

This study was based on experimental programs, which included developing various concrete mixtures, conducting mechanical properties tests, and implementing drop weight and flexural impact tests to assess impact resistance of samples. In addition, rotating cutter and sandblasting tests were conducted to evaluate the abrasion resistance of samples. The following conclusions can be drawn from this study:

1) Curing concrete at +5º C showed a significant reduction in the compressive strength and STS of up to 20% and 26%, respectively, for the control mixture when compared to moisture curing at 23º C. Meanwhile, curing concrete at -10º C exhibited the worst reduction in the compressive strength and STS, reaching up to 39% and 42%, respectively, for the control mixture when compared to moisture curing at 23º C.

2) The reduction in STS and FS due to curing in cold temperatures appeared to be more pronounced than the reduction in compressive strength. This can be related to the fact that the STS and FS of concrete are more affected by the microcracks initiated (due to steep thermal gradient and ice formation in concrete pores) when concrete samples were cured in cold temperature curing. On the other hand, the ME showed the least affected results by the cold curing conditions, in which the ME reduced by 14% and 32% at +5º C and -10º C curing conditions, respectively, compared to moisture curing condition.
3) The effect of cold temperature curing appeared to be more pronounced on the mechanical properties and impact resistance of mixtures with a higher C/F ratio or higher w/b ratio, in which higher reductions in the mechanical properties and impact resistance were observed in such mixtures compared to the control mixture (with lower C/F and w/b ratios), when cured in cold temperature curing.
4) Despite the significant enhancement in STS and FS of mixtures reinforced with SFs compared to the control mixture at moisture curing condition, this enhancement reduced significantly when concrete was cured in cold temperature curing. In the meantime, the mixture reinforced with SFs showed comparable compressive strength results to the control mixture at any curing conditions (C1-C4).
5) Unlike the significant enhancement in the mechanical properties at the moisture curing condition due to the addition of SFs or SCMs, at cold curing conditions, this enhancement remarkably decayed due to the deficiency in the hydration process. However, using SFs/SCMs still showed some enhancements on the mechanical properties at +5º C. For example, using MK enhanced the compressive strength of

the control mixture by 27.6% at moisture curing condition, while this enhancement reached up to 4.8% at -10º C curing condition.

6) The prediction of FS results based on the compressive strength proposed by design codes gave conservative results for FS at all studied curing conditions. Higher conservative results were observed at moisture curing condition compared to cold curing condition.

7) The impact resistance of mixtures with SFs/MK/SLF was more negatively affected by cold temperature curing compared to the control mixture (without SFs/MK/SLF). However, some enhancements in impact resistance were observed in mixtures with SFs/MK/SLF compared to the control mixture even at +5º C curing condition (C3).

8) Increasing the C/F aggregate ratio in the mixture increased the abrasion resistance at the moisture curing condition. However, when cold curing was utilized (-10ºC), lower abrasion resistance was observed in mixtures with a higher C/F aggregate ratio (compared to the mixture with a lower C/F aggregate ratio). This can be related to the weaker bond between the aggregate particles and surrounding mortar under cold curing condition, which increases the chance of particles being pulled out under abrasion action.

9) Adding SFs enhanced the abrasion resistance in the rotating cutter test at moisture curing conditions. However, at cold curing conditions, mixture reinforced with SFs showed slightly lower abrasion resistance at -10º C curing condition (10% higher mass loss) compared to the mixture without SFs. In addition, the negative effect of

cold curing in mixture with SFs was more pronounced in the rotating cutter test results compared to sandblasting test results.

4.2 Limitation of research

It is worth noting that while for this study, several samples for each mixture were tested to assess mechanical properties, abrasion, and impact resistance under four different curing conditions, it is recommended that more samples be tested to validate results that were achieved in this study.

In addition, this study was conducted before and during dealing with Covid-19 that impacted the speed of the work. Memorial University labs were closed for more than a year. Therefore, access to samples and apparatus was restricted during some parts of this study that affected the speed of the work.

4.3 Recommendation for future research

1. Using various types of fibers (such as double hook SFs or propylene) to develop SCC mixtures at cold curing conditions and assess the mechanical properties, impact and abrasion resistance of such concrete mixtures.
2. Implement other tests to evaluate the impact resistance of SCC, such as the Charpy impact test, to confirm the results in this investigation.

3. Develop SCC mixture at different curing conditions, including high temperature with various mixture compositions, to examine the effect of hot curing conditions on impact and abrasion resistance of SCC.

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