PROPERTIES OF SELF-CONSOLIDATING CONCRETE CONTAINING EXPANDED SLATE LIGHTWEIGHT AGGREGATE

by

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Abstract

This thesis aimed to evaluate the performance of self-consolidating concrete using either lightweight fine expanded slate aggregate (LF) or lightweight coarse expanded slate aggregate (LC). The rheological and mechanical properties of the lightweight self-consolidating concrete (LWSCC) mixtures were evaluated, in addition to the impact resistance and the durability (including abrasion and salt scaling resistance). The variables in this study included the type of lightweight aggregate (LF and LC), lightweight aggregate volume, binder content (500 kg/m^3, 550 kg/m^3 and 600 kg/m^3), and types of concrete (LWSCC, normal weight self-consolidating concrete and lightweight vibrated concrete). The research program was divided into three stages. The first stage included optimization of LWSCC using expanded slate aggregate to obtain mixtures with minimum possible density (while achieving acceptable fresh properties) and mixtures having a target density of 2000 kg/m^3 with maximized compressive strength. The second stage included investigation on the mechanical properties and impact resistance, while the third stage covered the assessment of the durability of the optimized mixtures. The results showed higher flowability for the LWSCC mixtures when LF was used compared to LWSCC mixtures with LC. However, LWSCC mixtures with LF required more high range water reducer admixture to reach the acceptable level of flowability compared to LWSCC mixtures with LC. The results also revealed that LWSCC mixtures with LF had higher mechanical properties, impact resistance and abrasion resistance before and after the exposure to salt scaling compared to LWSCC mixtures with LC at the same density level. Additionally, the results showed that the stability of the LWSCC mixtures (using LC or LF) enhanced by increasing the binder content. Increasing the binder content also allowed for using more lightweight aggregate, thus resulting in lower density mixtures.

To the soul of my grandfather ***Mohamed ElEngawi***

To the soul of my grandmother ***Hanifa Mohamed***

To my parents ***Mansour Sadek*** *and* ***Howida ElEngawi***

To my brother ***Ahmed*** *and my sisters* ***Omnia*** *and* ***Israa***

To my uncles ***Ashraf****,* ***Adel****,* ***Hassan*** *and* ***Alaa***

For caring, support, encouragement, and sharing these years of hard work

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Disclaimer

It is to be noted that the published versions of each paper presented in Chapters 2, 3, and 4 have been slightly modified to satisfy the required thesis format

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List of Symbols, Nomenclature or Abbreviations

ASTM	is the American Society for Testing and Materials
LWC	is the Lightweight Concrete
SCC	is the Self-Consolidated Concrete
LWSCC	is the Lightweight Self-Consolidated Concrete
NWSCC	is the Normal Weight Self-Consolidating Concrete
HRWRA	is the High Range Water Reducer Admixtures
MK	is the Metakaolin
FA	is the Fly ash
NC	is the Normal Weight Coarse Aggregate
NF	is the Normal Weight Fine Aggregate
LC	is the Lightweight Coarse Aggregate
LF	is the Lightweight Fine Aggregate
W/B	is the Water to Binder Ratio
NS	is the No Visual Sign of Segregation
STS	is the Splitting Tensile Strength
FS	is the Flexural Strength
ME	is the Modulus of Elasticity
T_{50}	is the time to reach a diameter of 500 mm in the slump flow test
T_{50J}	is the time to reach a diameter of 500 mm in the J-ring test
N	is the number of drops

Co-Authorship Statement

I, Mohamed Mansour Sadek, 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. Mohamed K. Ismail). Described below is a detailed breakdown of the work facilitated by my team and me.

- Paper 1 in chapter 2: Sadek, M.M., Ismail, K. M. and Hassan, A.A.A., (2019). "Stability of Lightweight SCC Containing Coarse and Fine Expanded Slate Aggregates". Accepted in ACI materials journal October 2019.

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: Sadek, M.M., Ismail, K. M. and Hassan, A.A.A., "Impact Resistance and Mechanical Properties of Optimized SCC Developed with Coarse and Fine Lightweight Expanded Slate Aggregates", Submitted to ASCE journal of materials in civil engineering December 2019.

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

- Paper 3 in chapter 4: Sadek, M.M., and Hassan, A.A.A., "Abrasion and Scaling Resistance of SCC Containing Expanded Slate Aggregate", submitted to ACI materials journal November 2019.

I was the primary author, with a second author contributing to the idea, its formulation and development, and refinement of the presentation.

1. Introduction

1.1. Background and Overview

Concrete is a one of the main construction materials, alongside with steel and timber, owing to its durability, strength and economic benefits (Khaliq and Kodur, 2011). This construction material is mainly composed of aggregates (coarse and fine), cement and water. In the past decades, different types of concrete have been developed by adding to or replacing one or more of its main constituents with materials having better properties, creating a new type of concrete with unique characteristics. One of these types is the Lightweight concrete (LWC), which is generally developed by replacing the normal weight aggregate with lightweight aggregate (LWA). Since the aggregate possess the highest fraction of weight among other concrete mixture components (Bentur et al., 2001), the inclusion of LWA instead of the normal weight aggregate reduces the self-weight of concrete, which in turn deceases the overall structure's dead loads. This contributes to reducing cross sections and foundation loads (Haque et al., 2004), and then more economic designs can be achieved. Despite the fact that LWA is characterized by high porosity and relatively low strength, however, LWC provides a reasonably high strength/weight ratio as a result of the reduced density compared to conventional concrete. Additionally, LWC has higher thermal and sound insulation properties, compared to conventional concrete, because of its higher porosity (Ünal et al., 2007). In offshore structures, LWC has an advantage over conventional concrete as the structure weight is vital in designing such structures. The use of LWC significantly reduces the buoyancy forces which is a main factor in designing offshore and shallow marine structures (Hoff, 1996). Different structural application has been constructed using LWC such as precast concrete, prestressed concrete and long span bridge decks (Rossignolo et al., 2003, Melby et al., 1996).

Self-consolidating concrete (SCC) is a special type of concrete which characterized by the high flowability (Nik, and Omran, 2013). This type of concrete can spread and fill the formworks under its own weight without external mechanical vibration (Paultre et al., 2005). SCC significantly reduces the number of labors required for construction and their efforts as a result of its high flowability, thus reduces the total construction costs. In addition, using SCC increases the production rate which results in a reduced construction time (Naik, and Vyawahare, 2013). In order to achieve SCC, the concrete mixture should attain a minimum level of flowability, passing ability and viscosity. These levels were proposed by different standards such as the European Guidelines for Self-Compacting Concrete (2005). To achieve acceptable fresh properties of SCC, different procedures are typically considered such as (a) using optimized water-to-binder ratio (W/b), (b) increasing the volume of fine materials, (c) using different supplementary cementing materials (SCMs), and (d) using high range water reducer admixture (HRWRA) and modifying viscosity admixtures.

Lightweight self-consolidating concrete (LWSCC) is an innovative type of concrete which possess the advantages of LWC and SCC. This type of concrete has the sufficient flowability to fill the formwork without external mechanical vibration, along with the reduced own weight. Additionally, LWSCC provides a reduction in the total construction cost as a result of the low transportation and labour costs (Lachemi et al., 2009). However, the development of this type of concrete has several challenges. Firstly, the large difference in density between the LWA and the mortar can cause segregation of the concrete mixture (Andiç-Çakır, and Hızal, 2012). Secondly, the high absorption rate of the lightweight aggregate (compared to normal weight aggregate) due to its porous structure results in more absorption of the mixing water which negatively affects the flowability of the mixture (Juradin et al., 2012). Thirdly, the porous structure of the lightweight aggregate weakens the strength of the concrete, and accordingly negatively affects the mechanical properties. To overcome such challenges, SCMs play an important role in enhancing the performance of LWSCC. Several types of SCMs were found to enhance the flowability, particles suspension and strength of concrete mixture. For example, Metakaolin (MK) and Fly ash (FA) proved to enhance the performance of LWSCC mixtures (Ridgley et al., 2018). Using MK enhances the mixture viscosity and particles suspension (in addition to enhancing the mechanical properties) while using FA increases the flowability of the mixture.

The characteristics of LWSCC render it to be a strong candidate for multiple structural applications. Consequently, assessing the properties of such type of concrete became quietly needed. In some specific structures, concrete is vulnerable to dynamic loading, surface abrasion and scaling. For example, offshore structures are subjected to impact forces as a result of the collusion with waves, ice bergs and ships (Furnes, and Amdahl, 1980). The movement of gravel and sand in seabed also causes abrasion of the surface of concrete (Yen et al., 2007). In Arctic areas, concrete structures are exposed to cycles of freezing and thawing causing deterioration of the surface (Chidiac, and Panesar, 2008), therefore the assessment of scaling resistance of such concrete type is essential. Similarly, in bridges, concrete is subjected to dynamic loading and fatigue from trucks movements, while the friction between tires abrades the concrete surfaces (Huang et al., 1993). Therefore, the assessment of the impact, abrasion and scaling resistance of concrete is crucial.

Impact resistance of concrete is defined as the dynamic energy absorbed by the concrete (as per ACI 544). Several types of tests were used to estimate the impact resistance such as drop weight test (single or repeated), explosive test, and weighted pendulum Charpy type impact test. The impact resistance is estimated by either (a) counting the number of falls that cause failure (in the repeated impact test), (b) calculating the energy required to shatter a concrete specimen, or (c) the size of damage occurs at a concrete sample. The assessment of impact resistance of LWSCC is discussed in detail in chapter 3 using the repeated drop weight test on concrete cylinder and beam specimens, as this is considered the most common way to estimate the impact resistance of concrete.

The abrasion of concrete is the wearing away or rubbing out the outer surface of concrete, while the scaling of concrete is the peeling of the surface mortar surrounding the aggregate as a result of the expansion of water particles when subjected to cycles of freezing and thawing (LI et al., 2006, Matalkah, and Soroushian, 2018). Several factors affect the abrasion and scaling resistance of concrete such as the mortar strength, type of aggregate used (LWA or normal weight aggregate), the coarse to fine aggregate ratio and the surface finishing. In addition, several findings have related the compressive strength to the abrasion resistance, in which increasing the compressive strength enhanced the abrasion resistance of concrete (Ibrahim et.al, 2017). In this thesis, the assessment of the abrasion resistance was performed according to the rotating cutter method (ASTM C944) and sandblasting method (ASTM C418), while the scaling resistance was assessed according to ASTM C672.

The LWA used in the development of SCC mixtures in this thesis were expanded slate LWA. This type of aggregate is considered to be a high strength lightweight aggregate as it was formed from volcanic ash. Expanded slate LWA has been utilized in the construction of several structural projects such as long-span bridges, post-tensioned high-rise buildings, and offshore oil platform.

1.2. Research Objective and Significance

The target of this study is to develop/optimize SCC mixtures using lightweight expanded slate aggregate (either coarse or fine aggregate), and investigate the mechanical properties, impact, abrasion and scaling resistance of the optimized mixtures. In addition to the developed LWSCC, lightweight vibrated concrete (LWVC) of the same aggregate type and normal weight SCC (NWSCC) mixtures were also developed to be compared with the LWSCC. A total of 24 concrete mixtures were developed (16 LWSCC mixtures, 6 LWVC mixtures and 2 NWC mixtures). The variables in this study included the type of concrete used (LWSCC, LWVC and NWSCC), volume of lightweight aggregate, type of lightweight aggregate (coarse LWA vs fine LWA), and the binder content.

Therefore, the main objectives of this study were as follows

1. Optimize SCC mixtures using either coarse or fine lightweight expanded slate aggregate
2. Investigate the impact resistance and the mechanical properties of the optimized LWSCC using expanded slate aggregate
3. Evaluate the abrasion and scaling resistance of the optimized mixtures
4. Compare the mechanical properties, impact resistance and abrasion resistance of the optimized LWSCC mixtures with their counterpart's mixtures of LWVC and NWSCC mixtures

The first objective was discussed in chapter 2, while the second and third objectives were discussed in chapters 3 and 4, respectively, and the fourth objective was discussed in chapters 3 and 4. This study aimed to fill the gaps of knowledge within the concrete research and development that incorporated lightweight expanded slate in the development of SCC to be further used in various structural applications.

1.3. Thesis Outline

This thesis consists of five chapters described as follows:

Chapter 1 includes background and an overview on LWSCC type, the scope of work and its significance.

Chapter 2 aims to study the stability of LWSCC mixtures using fine or course lightweight expanded slate aggregate.

Chapter 3 focuses on the impact resistance and the mechanical properties of the optimized SCC mixtures using fine or coarse expanded slate aggregate.

Chapter 4 demonstrate the abrasion and scaling resistance of the optimized SCC mixtures incorporating fine or coarse expanded slate aggregate.

Chapter 5 presents the conclusion, summary and recommendations out of this study.

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2. Stability of lightweight SCC containing coarse and fine expanded slate aggregates

2.1. Abstract

This study aimed to optimize the use of fine and coarse expanded slate lightweight aggregates in developing successful lightweight self-consolidating concrete (LWSCC) mixtures with densities ranging from 1850 kg/m^3 to 2000 kg/m^3 and strength of at least 50 MPa. All LWSCC mixtures were developed by replacing either the fine or coarse normal-weight aggregates with expanded slate aggregates. Two additional normal-weight self-consolidating concrete mixtures were developed for comparison. The results indicated that due to the challenge in achieving acceptable self-compactability, a minimum binder content of at least 500 kg/m^3 and a minimum w/b ratio of 0.4 were required to develop successful LWSCC with expanded slate. The use of metakaolin and fly ash were also found to be necessary to develop successful mixtures with optimized strength, flowability, and stability. The results also showed that LWSCC mixtures made with expanded slate fine aggregate required more high-range water-reducer admixture than mixtures made with expanded slate coarse aggregate. However, at a given density, mixtures developed with expanded slate fine aggregate generally exhibited better fresh properties in terms of flowability and passing ability, as well as higher strength compared to mixtures developed with expanded slate coarse aggregate.

2.2. Introduction

Lightweight concrete (LWC) is typically developed by either partially or totally replacing normal-weight aggregates with low-density aggregates (Dhir et al., 1984). The main advantage of using LWC is to decrease the self-weight of concrete structures that represent a significant portion of design loads (Balendran et al., 2002, Real et al. 2016). This helps to reduce the dimensions of structural elements and use lower volumes of concrete and steel reinforcements, thus offering significant savings in construction costs (Rossignolo and Agnesini, 2002, Ko and Choi 2013, Kim et al., 2012, Haque and Al-Khaiat, 1999). Despite the low density of LWC, this concrete can reach a relatively high level of strength, achieving more efficient strength-to-weight ratio (Sari and Pasamehmetoglu, 2005). Consequently, LWC has attracted significant attention in a wide range of construction projects. For example, in precast elements, using LWC effectively helps to reduce handling and transportation costs (Kayali, 2008). LWC was also employed in the construction of a significant number of bridges such as the San Francisco-Oakland Bay Suspension Bridge, Golden Gate Bridge, Tacoma Narrows Bridge, Napa River Bridge, and Parrots Ferry Road Bridge, resulting in a considerable reduction in their construction costs (Raithby, and Lydon, 1981). The acceptable durability properties of LWC extended its possible use to offshore structures. As an example, the Hibernia oil field gravity-based structure located offshore of Newfoundland, Canada, was constructed using concrete with a density of 2150 kg/m^3 developed by using lightweight coarse aggregate as a partial replacement for normal-weight coarse aggregate (Abouhussien et, 2015, Jiang et al., 2004).

Utilizing lightweight aggregates in the development of self-consolidating concrete (SCC) is considered a promising approach to developing an innovative type of concrete named lightweight self-consolidating concrete (LWSCC). This concrete type not only possesses the economic benefits of LWC but also has the superior rheological properties of SCC (Lachemi et al. 2009, Assaad, and Issa, 2017). Hence, LWSCC is characterized by a low density, has an excellent ability to flow easily through congested reinforcing areas, and fills complex formwork under its own weight without any external mechanical vibration (Aslani, 2013, Safiuddin et al., 2012, Rao et al., 2012). LWSCC was first used in Japan in 1992 to cast the main girder of a cable-stayed bridge (Okamura and Ouchi, 2003). And in the last few years, LWSCC has been widely used in several applications such as precast thin walls (Shi and Yang, 2005), precast panels supported by carbon fiber–reinforced polymer meshes as an internal reinforcement (Yao and Gerwick, 2006), precast stadium benches (Hubertova and Hela, 2007), and prestressed beams with spans reaching up to 20 meters (Papanicolaou and Kaffetzakis, 2011).

However, the development of SCC incorporating lightweight aggregate faces potential challenges. For example, the low density of lightweight aggregate induces particles to move toward the concrete surface during fresh state, thus increasing the risk of segregation (Lotfy et al., 2016, Karahan et al., 2016). Other studies also reported that the irregular shape of some types of lightweight aggregate such as expanded shale aggregate (Wua et al., 2009), lightweight slag aggregate (Abouhussien et al., 2015, Hassan et al., 2015), and rhyolitic origin lightweight aggregate (Granata, 2015) increased the blockage and interparticle friction, which negatively affected the flowability and passing ability of LWSCC mixtures. Another problem is that lightweight aggregates typically have a porous structure, which increases the tendency of particles to absorb water during mixing and thus reduces the mixture's workability. The high porosity of lightweight aggregate also weakens its strength compared to conventional aggregates, resulting in a decay of the compressive strength of concrete (Atmaca et al., 2017, Lo et al., 2007).

This study attempted to optimize the stability and strength of a number of SCC mixtures developed with either fine or coarse expanded slate aggregates. The studied parameters included different aggregate types, various coarse-to-fine aggregate ratios, and different binder contents. Additional normal-weight self-consolidating concrete (NWSCC) mixtures, developed with crushed granite fine and coarse aggregates, were cast for comparison. For all developed mixtures, the investigated properties included the high-range water-reducer admixture (HRWRA) demand, flowability, passing ability, segregation resistance, and compressive strength.

2.3. Research Significance

Despite the high quality and strength of expanded slate lightweight aggregate, a limited amount of research has evaluated the use of this aggregate in SCC, especially when different mixture compositions were used. In addition, the current literature has no sufficient information regarding the performance of lightweight expanded slate coarse aggregate compared to lightweight expanded slate fine aggregate. Therefore, this study attempted to optimize a number of successful SCC mixtures developed with each of fine and coarse expanded slate aggregates to highlight the advantage and disadvantage of each type when used in LWSCC mixtures. This can help designers/engineers decide which size of lightweight expanded slate aggregate to use in a specific application. All developed mixtures in this study ranged from 1850 kg/m^3 to 2000 kg/m^3 and had a minimum compressive strength of 50 MPa. Such mixtures can be classified as lightweight self-consolidating concrete (LWSCC) according to the Canadian code, combining the economic benefits of lightweight aggregate and the desirable properties of SCC. The authors believe that the results obtained from this investigation will effectively contribute to extending the possible use of SCC made with expanded slate aggregates in the construction industry.

2.4. Experimental Program

2.4.1. Materials

Table 2.1 shows the proportions of 16 LWSCC mixtures and 2 NWSCC mixtures.

- In all developed mixtures, Type GU Canadian Portland cement, metakaolin (MK), and fly ash (FA) (conforming to ASTM C150 Type I 2012, ASTM C618 class N 2012, ASTM C618 type F 2012, respectively) were used as binder materials.
- The normal-weight aggregates included crushed granite fine aggregate (designated as NF, referring to normal weight fine aggregate) and crushed granite coarse aggregate

(designated as NC, referring to normal weight coarse aggregate) with a specific gravity of 2.6 and absorption of 1%. The gradation curves of normal-weight aggregates are shown in Figure 2.1.

- The lightweight aggregates included expanded slate coarse aggregate (designated as LC, referring to lightweight coarse aggregate) and expanded slate fine aggregate (designated as LF, referring to lightweight fine aggregate) with a specific gravity of 1.53 and 1.8, respectively. The absorption of LC and LF was 7.1% and 10%, respectively. The gradation curves of lightweight aggregates are shown in Figure 2.1.
- The fresh properties of NWSCC and LWSCC mixtures were adjusted using a polycarboxylate-based HRWRA conforming to ASTM C494 with specific gravity, volatile weight, and pH of 1.2, 62%, and 9.5, respectively.

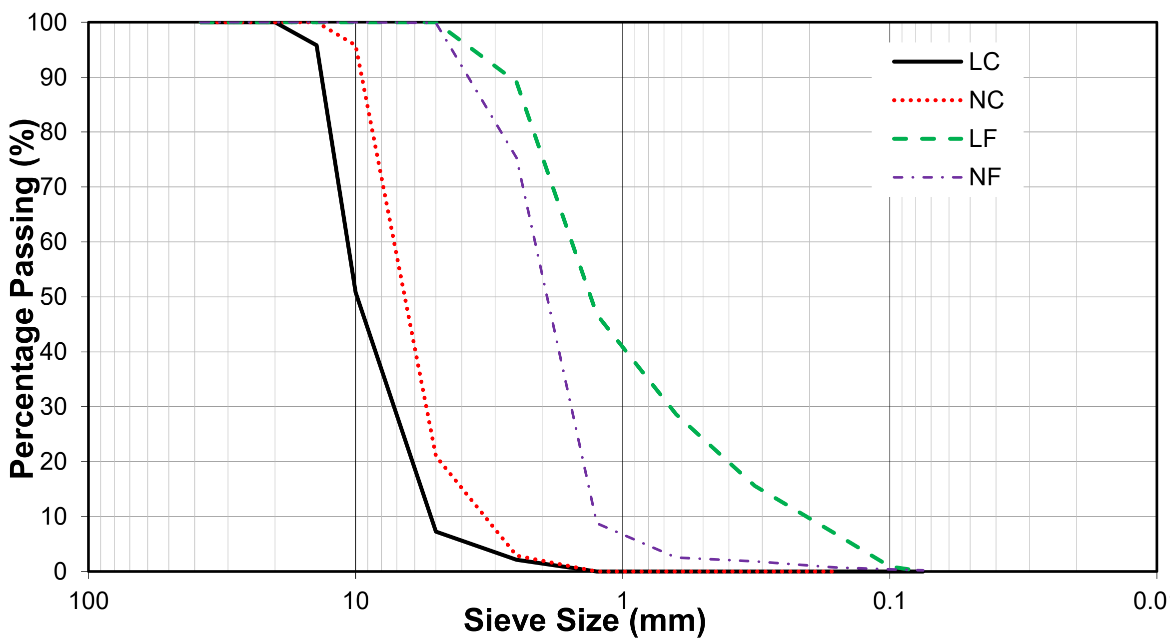


Figure 2.1 Gradation curves for fine and coarse normal-weight and lightweight aggregates

Table 2.1 Mixture proportions for all tested mixtures

Mix #	Designation	Cement kg/m^3	MK kg/m^3	FA kg/m^3	Coarse-to-fine aggregate ratio by weight	Aggregate: Normal-weight Aggregates		Aggregate: Lightweight Aggregates		Water kg/m^3	HRWR A L/m^3	Dry density kg/m^3
						NC kg/m^3	NF kg/m^3	LC kg/m^3	LF kg/m^3			
LC-LWSCC mixtures												
1	LC-SCC-500-0.5	250	100	150	0.50	-	869.4	434.7	-	200	4.20	2004
2	LC- SCC-500-0.8	250	100	150	0.80	-	681.6	545.2	-	200	3.60	1929
3	LC- SCC-550-0.48	275	110	165	0.48	-	831.1	398.9	-	220	4.00	1994
4	LC- SCC-550-1	275	110	165	1.00	-	559.0	559.0	-	220	3.53	1884
5	LC- SCC-550-1.1	275	110	165	1.10	-	525.9	578.5	-	220	3.60	1876
6	LC- SCC-600-0.44	300	120	180	0.44	-	806.6	354.9	-	240	3.59	2007
7	LC- SCC-600-1	300	120	180	1.00	-	522.3	522.3	-	240	3.31	1882
8	LC- SCC-600-1.25	300	120	180	1.25	-	451.2	564.0	-	240	3.06	1851
LF-LWSCC mixtures												
9	LF- SCC-500-0.9	250	100	150	0.90	617.3	-	-	685.9	200	4.53	1900
10	LF- SCC-500-1.25	250	100	150	1.25	746.0	-	-	596.8	200	4.20	1993
11	LF- SCC-550-0.7	275	110	165	0.70	492.5	-	-	703.7	220	4.40	1887
12	LF- SCC-550-1	275	110	165	1.00	617.3	-	-	617.3	220	4.06	1962
13	LF- SCC-550-1.44	275	110	165	1.44	748.0	-	-	526.8	220	3.80	2008
14	LF- SCC-600-0.6	300	120	180	0.60	413.7	-	-	689.6	240	4.00	1852
15	LF- SCC-600-1	300	120	180	1.00	576.7	-	-	576.7	240	3.73	1955
16	LF- SCC-600-1.67	300	120	180	1.67	755.9	-	-	452.6	240	3.53	1999
NWSCC mixture												
17	NW-SCC-550-0.8	275	110	165	0.80	670.7	838.3	-	-	220	5.80	2270
18	NW-SCC-550-1	275	110	165	1.00	754.5	754.5	-	-	220	5.50	2261

2.4.2. Concrete Mixtures

This study aimed to optimize a number of successful LWSCC mixtures developed with density ranging from 1850 kg/m^3 to 2000 kg/m^3 using various combinations of normal-weight and lightweight aggregates. The main challenges in developing such mixtures are the low density and high porosity of lightweight aggregates, which result in high risk of segregation, high water absorption, and reduction of the overall concrete strength. For this reason, the authors conducted a preliminary trial mix stage in order to determine the optimal mixture proportions that could be used to develop LWSCC mixtures having 700 ± 50 mm slump flow diameter with no visual sign of segregation and reasonable strengths. To achieve those aspects, different techniques were conducted as follows:

(a) A preliminary preparation was conducted to achieve saturated surface dry condition for the lightweight aggregates prior to mixing to avoid absorbing any part of the mixture's water.

(b) An effective ternary material system was used in order to improve the mixture's viscosity and increase the particle suspension in order to reduce the risk of segregation.

(c) High binder content, relatively low water-to-binder (w/b) ratio, and high pozzolanic supplementary cementing materials were used in order to alleviate the low strength of lightweight aggregate and achieve a composite with a reasonable strength and improved flowability and particle suspension.

The investigated parameters in the trial mix stage included the volume of lightweight aggregates in the mixture (to target the minimum mixture density), the w/b ratio (to target the minimum possible w/b ratio), and the use of different types and contents of supplementary cementing materials (to target the optimum strength, flowability, and viscosity of the mixture). From the trial mix stage, it was found that:

- A minimum binder content of 500 kg/m^3 and a minimum w/b ratio of 0.4 were required to develop LWSCC mixtures with a slump flow diameter of 700 ± 50 mm without overdosing the HRWRA and with no visual sign of segregation.
- A ternary binder system consisting of 50% cement, 30% FA, and 20% MK was necessary to optimize the mixture's viscosity, in which MK improved the particle suspension and reduced the risk of segregation, while FA offered sufficient flowability at reasonable HRWRA demand.
- At a binder content of 500 kg/m^3, it was possible to develop a minimum possible density LC-LWSCC mixture when an LC/NF ratio of 0.8 was used. Further increase in the LC/NF ratio resulted in high friction between aggregate particles, thus significantly reducing the flowability and passing ability of mixtures. Increasing the binder content resulted in improved flowability of mixtures, which in turn allowed higher LC/NF ratios to be used successfully. When 550 kg/m^3 and 600 kg/m^3 binder were used, the maximum LC/NF ratio that could be used reached up to 1.1 and 1.25, respectively. This allowed for further reduction in the mixture density, reaching up to 1851 kg/m^3 when 600 kg/m^3 binder content was used (containing 50% cement, 20% MK, and 30% FA).
- At binder content of 500 kg/m^3, the lowest possible mixture density was reached at NC/LF ratio of 0.9. It was hard to use a NC/LF ratio of less than 0.9 as the risk of segregation was obviously increased. The use of higher binder content increased the viscosity and enhanced the stability and particle suspension of the mixture; this allowed for higher content of LF to be used safely. Using binder content of 550 kg/m^3 and 600 kg/m^3 allowed for NC/LF ratio of up to 0.7 and 0.6, respectively, to be used in the mixture, obtaining a density of up to 1852 kg/m^3 with 600 kg/m^3 binder content.

In total, 18 mixtures were developed in this study as follows (see Table 2.1):

a) Mixtures 1-8 were developed as LC-LWSCC in order to investigate the effect of using different contents of LC on the fresh and mechanical properties of SCC. Mixtures 1, 3, and 6 had the upper density limit in this investigation (2000 kg/m^3), while mixtures 2, 5, and 8 had the minimum possible density. Mixtures 4 and 7 were also included to evaluate the effect of increasing the binder content on the fresh properties and strength of LC-LWSCC.
b) Mixtures 9-16 were developed as LF-LWSCC in order to evaluate the influence of using various contents of LF on the fresh and mechanical properties of SCC. Mixtures 10, 13, and 16 had a target density of 2000 kg/m^3, while mixtures 9, 11, and 14 had the minimum possible density. Mixture 12 and 15 were used to investigate the influence of increasing the binder content on the fresh properties and strength of LF-LWSCC mixtures.
c) Mixtures 4 and 7 were also designed to be compared with mixtures 12 and 15, respectively, in order to evaluate the use of LC compared to LF in LWSCC mixtures at a given mixture's density.
d) Mixtures 17 and 18 were developed as normal-weight SCC (NWSCC) for comparison with their counterpart LWSCC mixtures developed with either LC or LF (mixtures 4 and 12). These two mixtures were designed to evaluate the fresh properties of SCC developed with expanded slate aggregates compared to the fresh propertied of SCC developed with a similar volume of normal-weight aggregates.

All the mixtures were designated by the type of replacement (LC for LC-LWSCC and LF for LF-LWSCC), type of concrete (SCC), binder content, and coarse-to-fine aggregate ratio. For example, a mixture with LC, 500 kg/m^3 binder content, and 0.5 coarse-to-fine aggregate ratio was designated as LC-SCC-500-0.5. The NWSCC mixture was designated as NW-SCC-550-1, referring to the use of normal-weight fine and coarse aggregates, 550 kg/m^3 binder content, and 1.0 coarse-to-fine aggregate ratio.

2.4.3. Preparation, Mixing, Sample Casting, and Conditioning Procedures

Owing to the high-water absorption of lightweight expanded slate aggregates, both the LC and LF were placed in a saturated surface dry condition before mixing. Therefore, the LC and LF were immersed in water for a period of 24 ± 4 h at room temperature. Then, both aggregates were removed from the water and spread over a large absorbent mat until all visible films of water were eliminated.

Next, all materials including cement, MK, FA, fine and coarse aggregates were dry-mixed for 2.5 ± 0.5 minutes using a rotary mixer. Two-thirds of the required amount of water was then added and re-mixed for 2.5 ± 0.5 minutes. The remaining one-third of water was mixed first with the required dosage of HRWRA and then added to the mixer and re-mixed for another 2.5 ± 0.5 minutes. Upon achieving the target slump flow (700 ± 50 mm) in LWSCC and NWSCC mixtures, the fresh properties tests were carried out. Also, cylindrical specimens with 100 mm diameter and 200 mm height were cast to evaluate the compressive strength of the developed mixtures. All concrete cylinders were moist cured in a controlled room temperature of 25 ± 1.5°C for 28 days before testing.

2.4.4. Fresh and Mechanical Properties Tests

The fresh properties of NWSCC and LWSCC mixtures were evaluated using L-box, J-ring, slump flow, and V-funnel tests. The slump flow, J-ring, and V-funnel tests were performed to assess the flowability of the developed mixtures. On the other hand, the L-box test and the difference between the slump flow diameter and J-ring diameter were used to evaluate the passing ability of the developed mixtures. The slump flow, V-funnel, and L-box tests were performed according to

EFNARC 2002, while the J-ring test was conducted as per procedures given by ASTM C1621 2009 b. The stability of lightweight aggregates (either LC or LF) was investigated using two methods: (a) a visual inspection for a splitted hardened concrete cylinder (see Figure 2.2a), and (b) evaluating the variation in density throughout the height of cast specimens (see Figure 2.2b). The compressive strength of the developed mixtures was tested as per ASTM C39 2011 using 100 mm diameter x 200 mm high cylinders. The results obtained from the fresh and mechanical properties are shown in Tables 2.2 and 2.3.

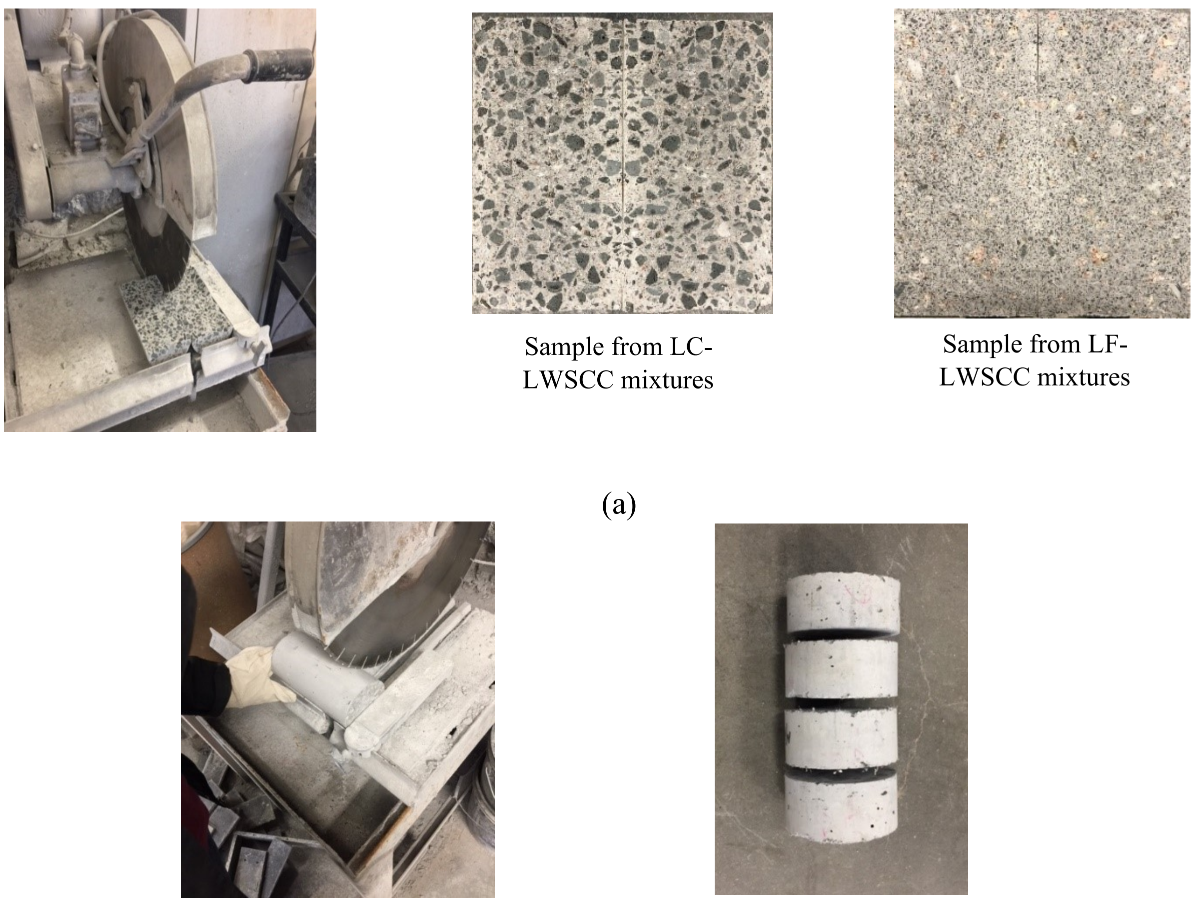


Figure 2.2 Evaluation of the distribution of lightweight aggregate in hardened concrete and the stability of LWSCC mixtures: a) splitting hardened concrete cylinders, b) dividing hardened concrete cylinders into four segments.

Table 2.2 Fresh and mechanical properties for all tested mixtures

Mix #	Designation	Slump T_{50} (sec)	J-ring T_{50J} (sec)	V-funnel (sec)	Slump diameter - J-ring diameter (mm)	L-box H2/H1	Air %	f'_c MPa	Segregation resistance
LC-LWSCC mixtures									
1	LC-SCC-500-0.5	2.18	3.20	12.0	44	0.88	3.3	55.7	NS
2	LC- SCC-500-0.8	2.58	4.20	17.6	78	0.80	3.4	50.5	NS
3	LC- SCC-550-0.48	1.95	2.80	10.6	38	0.90	3.0	57.2	NS
4	LC- SCC-550-1	2.34	3.65	14.7	55	0.84	3.5	52.9	NS
5	LC- SCC-550-1.1	2.52	4.15	17.2	74	0.81	3.5	50.0	NS
6	LC- SCC-600-0.44	1.70	2.15	7.50	33	0.93	3.2	59.3	NS
7	LC- SCC-600-1	2.07	2.90	10.7	46	0.88	3.3	57.5	NS
8	LC- SCC-600-1.25	2.50	3.90	16.7	73	0.81	3.4	51.5	NS
LF-LWSCC mixtures									
9	LF- SCC-500-0.9	2.20	3.40	12.5	50	0.87	3.4	51.8	NS
10	LF- SCC-500-1.25	2.44	4.10	16.1	70	0.82	3.6	56.0	NS
11	LF- SCC-550-0.7	1.80	2.40	8.90	34	0.91	3.6	55.5	NS
12	LF- SCC-550-1	1.95	2.80	10.85	44	0.89	3.7	56.2	NS
13	LF- SCC-550-1.44	2.36	3.70	15.25	57	0.84	3.3	59.8	NS
14	LF- SCC-600-0.6	1.60	1.90	6.70	27	0.95	3.2	56.4	NS
15	LF- SCC-600-1	1.78	2.25	8.20	34	0.92	3.4	59.6	NS
16	LF- SCC-600-1.67	2.41	3.30	15.40	65	0.83	3.8	60.5	NS
NWSCC mixture									
17	NW-SCC-550-0.8	1.81	2.58	9.29	30	0.96	2.6	73.9	-
18	NW-SCC-550-1	2.20	3.13	12.70	49	0.86	3.4	71.2	-

Table 2.3 Relative dry density of the LWSCC mixtures along the concrete cylinders' heights

Mixture number	Designation	Unit Weight Ratios			
		Bottom segment	Middle segments 1	Middle segments 2	Top segment
LC-LWSCC					
1	LC-SCC-500-0.5	1.018	0.995	0.991	0.998
2	LC- SCC-500-0.8	1.012	1.000	0.998	0.990
3	LC- SCC-550-0.48	1.020	1.014	1.002	0.988
4	LC- SCC-550-1	1.012	0.99	0.994	0.989
5	LC- SCC-550-1.1	1.029	0.996	0.998	0.990
6	LC- SCC-600-0.44	1.007	0.998	0.999	0.992
7	LC- SCC-600-1	1.011	0.997	0.996	0.988
8	LC- SCC-600-1.25	1.02	1.009	0.999	0.989
LF-LWSCC					
9	LF- SCC-500-0.9	1.017	0.999	0.998	0.978
10	LF- SCC-500-1.25	1.004	0.997	1.003	0.986
11	LF- SCC-550-0.7	1.020	1.002	0.997	0.990
12	LF- SCC-550-1	1.000	0.997	0.996	0.981
13	LF- SCC-550-1.44	1.010	1.005	1.006	0.999
14	LF- SCC-600-0.6	1.023	1.000	0.998	0.992
15	LF- SCC-600-1	1.017	1.006	0.999	0.991
16	LF- SCC-600-1.67	1.009	0.999	0.997	0.985

2.5. Discussion of Results

2.5.1. LC-LWSCC and LF-LWSCC Mixtures

2.5.1.1. HRWRA Demand

For each mixture, the HRWRA was used to achieve a target level of flowability specified by a slump flow diameter of 700 ± 50 mm. Table 2.1 shows the HRWRA amount consumed by all developed mixtures. Figure 2.3 also shows the correlation between the dry density and the HRWRA demand for all developed mixtures. In LC-LWSCC mixtures, the reduction in the mixture's density due to increasing the content of LC was accompanied by a decrease in the

HRWRA demand, as seen in Figure 2.3. This can be attributed to the reduction in the total surface area of aggregate as a result of decreasing the amount of fine aggregate; therefore, less HRWRA was required to reach the desired flowability. For example, with binder content of 500 kg/m^3, the amount of HRWRA decreased by 11.8% when the mixture's density decreased from 1990 kg/m^3 to 1930 kg/m^3 (a reduction of 60 kg/m^3). On the other hand, the HRWRA demand was found to be increased in the LF-LWSCC mixtures; the mixture's density decreased due to the increased content of LF, which in turn increased the total surface area of aggregates. With binder content of 500 kg/m^3, decreasing the mixture's density from 1990 kg/m^3 to 1930 kg/m^3 increased the demand of HRWRA by 5.2% (see Figure 2.3).

The results also indicated that at a comparable mixture density, developing LWSCC with LC required a lower amount of HRWRA than that required by LWSCC with LF. For example, mixture 8 compared to mixture 14 (at density of around 1850 kg/m^3) shows that the LC-LWSCC mixture consumed around 3.06 l/m^3, which is 23.5% less than the amount consumed by the LF-LWSCC mixture.

From Figure 2.3, it can also be seen that the HRWRA demand decreased as the binder content increased. In mixtures with comparable density, increasing the binder content from 550 kg/m^3 to 600 kg/m^3 reduced the HRWRA demand by 6.2% in the LC-LWSCC mixtures (mixture 4 compared to mixture 7) and by 8.1% in the LF-LWSCC mixtures (mixture 12 compared to mixture 15). This could be related to increasing the fine materials in the mixture, which decreased the interparticle friction and then reduced the amount of HRWRA required to achieve the target flowability.

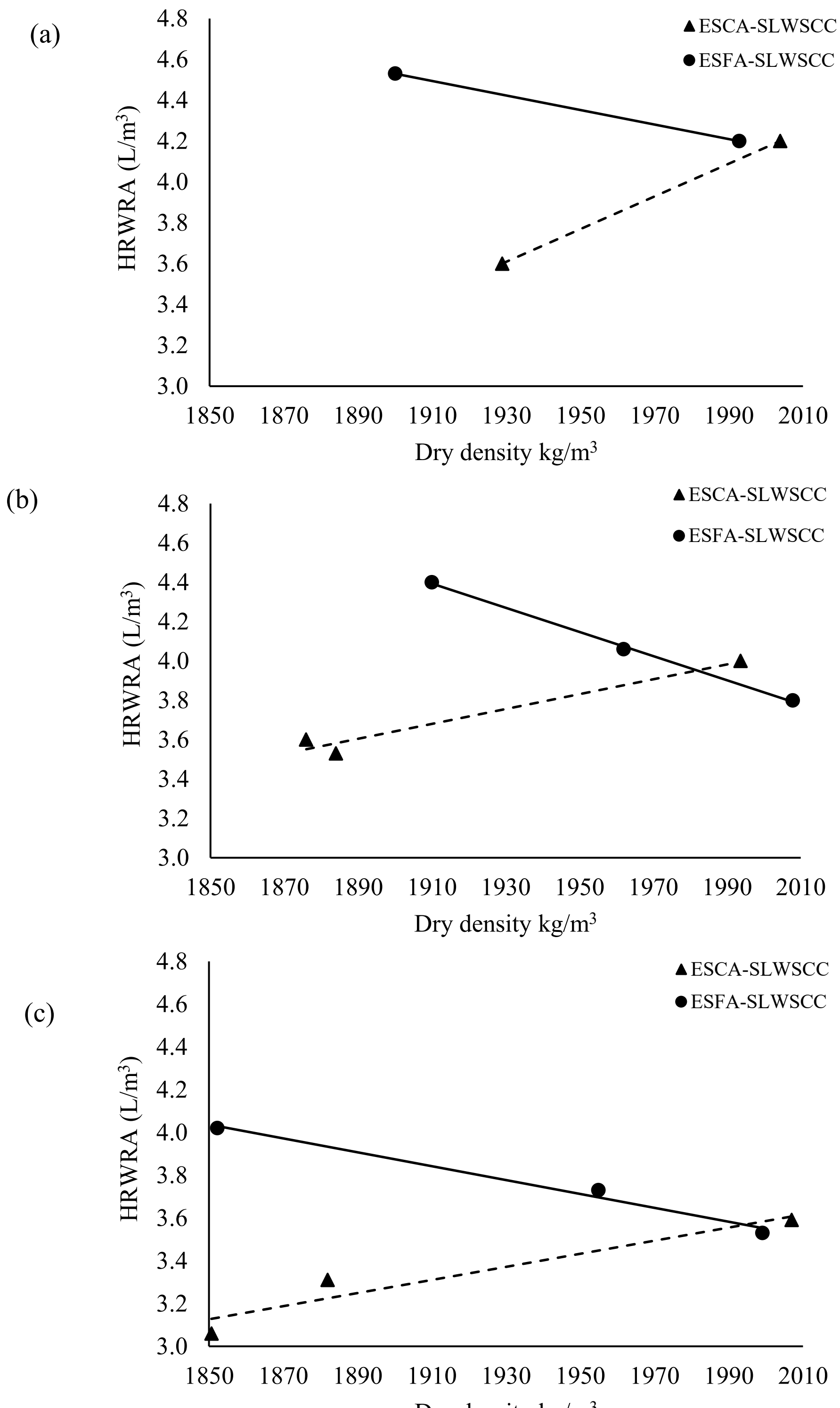


Figure 2.3 HRWRA demand - dry density relationships of LWSCC mixtures: a) at binder content 500 kg/m^3, b) at binder content 550 kg/m^3, c) at binder content 600 kg/m^3

2.5.1.2. Flowability

Table 2.2 and Figure 2.4 show the results of T_{50}, T_{50J}, and V-funnel times, which are used to evaluate the flowability of the developed mixtures. As seen in LWSCC mixtures, at a given binder content, increasing the volume of LC (decreasing the mixture density) exhibited higher T_{50}, T_{50J}, and V-funnel times, indicating a reduction in the flowability. For example, in LC-LWSCC mixtures with 500 kg/m^3, the T_{50}, T_{50J}, and V-funnel times increased by 18.3%, 31.3%, and 46.6%, respectively, when the LC/NF ratio increased from 0.5 to 0.8 (mixtures 1-2). Such results could be attributed to the fact that increasing the content of coarse aggregate resulted in higher interparticle friction, which in turn reduced the flowability of mixtures. The results also indicated that the effect of increasing the coarse aggregate content on decaying the flowability was more pronounced in the J-ring and V-funnel tests compared to the slump flow test. This is directly related to the nature of the tests: in the slump flow test, the mixture freely spread without facing obstructions, while in the J-ring and V-funnel tests, the mixture passed through limited openings (i.e., the spaces between the steel bars of the J-ring device or the opening of the V-funnel apparatus). Therefore, the possible collision and blocking due to increased coarse aggregate particles can contribute to increasing the flow time in the J-ring and V-funnel tests, more so than in the slump flow test.

On the other hand, increasing the volume of LF in LF-LWSCC mixtures reduced the T_{50}, T_{50J}, and V-funnel time, indicating an enhancement of the mixture's flowability. Mixtures 9-10 reveal that decreasing the NC/LF ratio from 1.25 to 0.9 reduced the T_{50}, T_{50J}, and V-funnel times by 9.8%, 17.1%, and 22.4%, respectively.

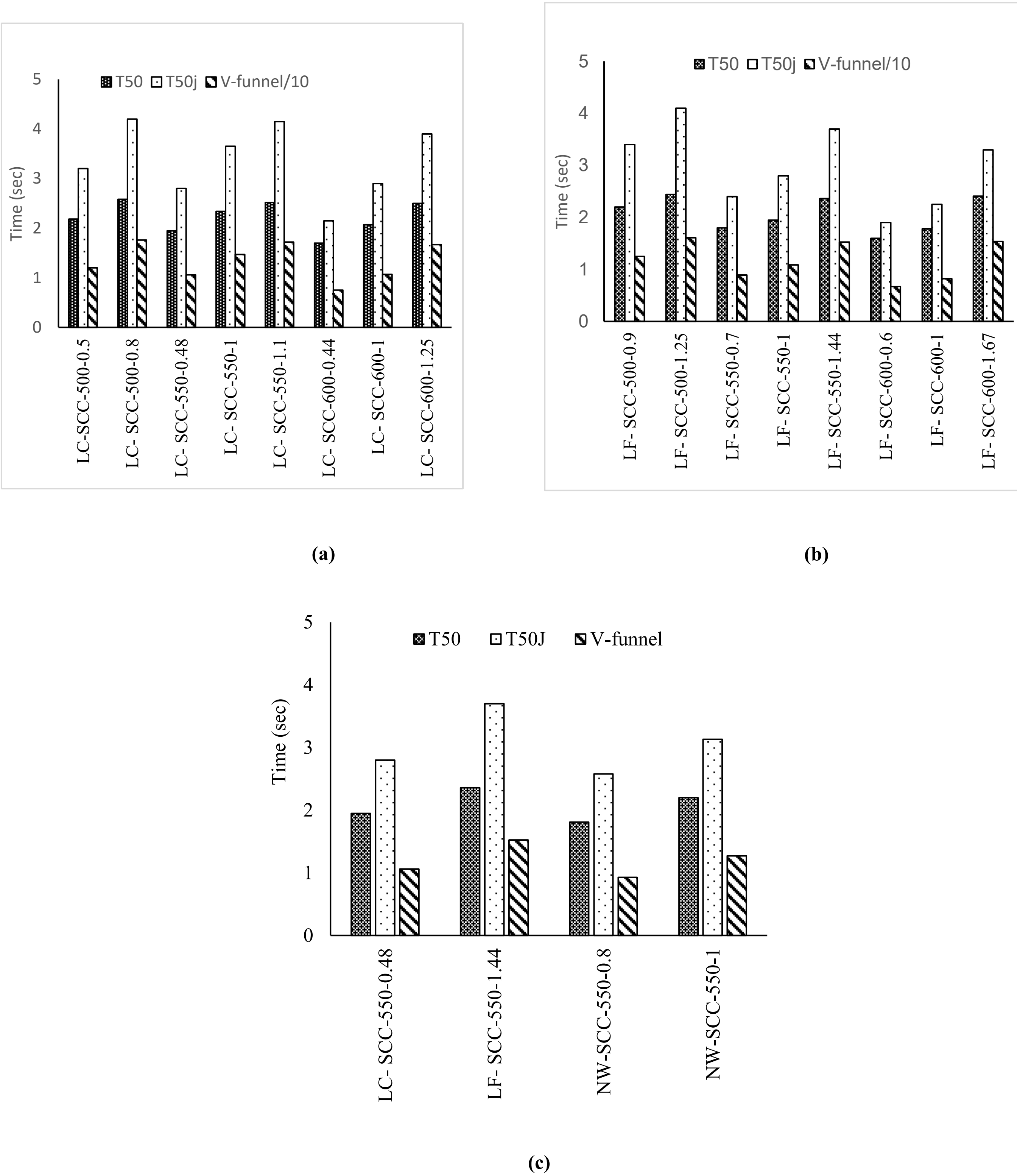


Figure 2.4 Flowability of the tested mixtures: a) LC-LWSCC mixtures, b) LF-LWSCC mixtures, c) LC-LWSCC vs. LF-LWSCC vs. NWSCC

The results also indicated that the LF-LWSCC mixture exhibited higher flowability compared to the LC-LWSCC mixture at comparable density. For example, as seen in mixture 14 compared to mixture 8 (at density of around 1850 kg/m^3), the T_{50}, T_{50J}, and V-funnel times of LF-LWSCC mixture were 36%, 51.3%, and 59.9% less than that of LC-LWSCC mixture, as seen in Table 2.2 and Figure 2.4.

The flowability of LC- and LF-LWSCC mixtures increased as the binder content increased, as shown in Table 2.2 and Figure 2.4. This can be seen in LC-LWSCC mixtures by comparing mixture 4 to 7 (mixtures with comparable density), in which at LC/NF ratio of 1.0, increasing the binder content from 550 to 600 kg/m^3 decreased the T_{50}, T_{50J}, and V-funnel times by 11.5%, 20.5%, and 27.2%, respectively. In LF-LWSCC mixtures with NC/LF ratio of 1.0 (mixture 12 compared to mixture 15), these reductions reached up to 8.7%, 19.6%, and 24.4% in the T_{50}, T_{50J}, and V-funnel times, respectively, when binder content increased from 550 to 600 kg/m^3. Increasing the binder content increased the volume of mortar in the mixture, which helped to lubricate the particles' surface and reduce interparticle friction. This contributed to improving the ability of mixtures to carry coarse aggregate particles and offers smoother flow, reaching higher flowability.

2.5.1.3. Passing ability

Table 2.2and Figure 2.5 show the difference between slump flow and J-ring diameters, as well as the L-box ratios, which were used to assess the passing ability of all developed mixtures. From the results, it can be seen that increasing the volume of LC in LC-LWSCC mixtures generally exhibited higher blockage behind steel rebars of either the J-ring or L-box devices, which decayed the passing ability. With 500 kg/m^3 binder content, changing the LC/NF ratio from 0.5 to 0.8 (mixtures 1-2) increased the difference between the slump flow and J-ring diameters from 44 mm to 78 mm, while the L-box ratio decreased from 0.88 to 0.8. On the other hand, in LF-LWSCC mixtures, when the volume of LF increased the passing ability increased. In mixtures 9-10, decreasing the NC/LF ratio from 1.25 to 0.9, the L-box ratio increased from 0.82 to 0.87 and the difference between slump flow diameter and J-ring diameter decreased from 70 mm to 50 mm. The results also showed that at comparable density, the LF-LWSCC mixture was found to have higher passing ability compared to the LC-LWSCC mixture. This can be seen by comparing, for example, mixture 14 to mixture 8 (at density of around 1850 kg/m^3), in which the LF-LWSCC (mixture 14) had higher L-box ratio and lower difference between slump flow diameter and J-ring diameter by 17.3% and 63% compared to the LC-LWSCC mixture (mixture 8).

The results in Table 2.2 and Figure 2.5 also indicated that increasing the binder content appeared to improve the passing ability of LC-LWSCC mixtures. Increasing the binder content from 550 to 600 kg/m^3 (mixture 4 vs. mixture 7) decreased the difference between the slump flow and J-ring diameters from 55 mm to 46 mm and increased the L-box ratio from 0.84 to 0.88. For the same increase in the binder content in LF-LWSCC mixtures (mixture 12 vs. mixture 15), the L-box ratio increased from 0.89 to 0.92 and the difference between slump flow and J-ring diameters reduced from 44 mm to 34 mm. This could be related to the fact that increasing the binder content increased the volume of mortar and decreased the content of aggregates, which allowed for better particle distribution and lower blockage between coarse aggregate particles at limited openings.

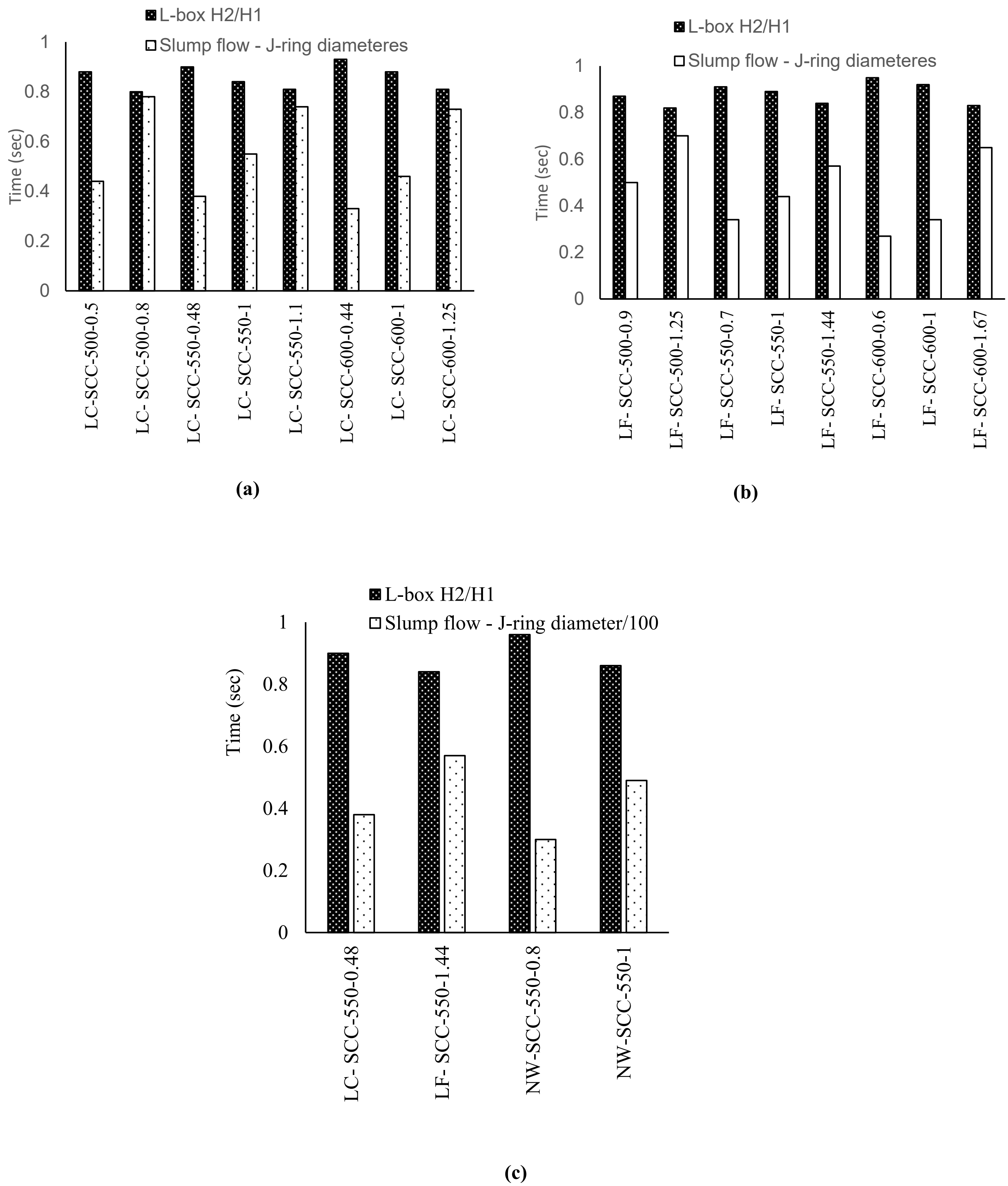


Figure 2.5 Passing ability of tested mixtures: a) LC-LWSCC mixtures, b) LF-LWSCC mixtures, c) LC-LWSCC vs. LF-LWSCC vs. NWSCC

2.5.1.4. Segregation resistance

Owing to the low density of LC and LF, both aggregates had a high tendency to segregate during fresh state. Therefore, evaluating the segregation resistance is a key factor in the development of LC- and LF-LWSCC mixtures. Two methods were used to assess the segregation resistance of the produced mixtures. The first method involved splitting a 100 mm diameter x 200 mm high cylinder and examining the distribution of the aggregate along the cylinder (Figure 2.2a). As shown in Table 2.2, both LC- and LF-LWSCC mixtures had good particle distribution along the cylinder height with no visual sign of segregation (denoted by NS). The good distribution of aggregate indicates that the ternary material system successfully achieved adequate viscosity, which enhanced the particle suspension and reduced the risk of segregation.

The second method of segregation assessment involved cutting a concrete cylinder with a height of 200 mm into four equal segments (disks) for each mixture (Figure 2.2b). The segregation resistance was assessed by calculating the density of each segment relative to the dry density of its corresponding mixture in order to determine the variation in aggregate distribution along the specimen height. Table 2.3 shows the relative densities calculated for each mixture segment. As seen in the table, the maximum difference between the relative density of top and bottom segments was about 3.9% (less than 5%), which indicates that all developed mixtures had an acceptable level of stability.

2.5.1.5. Consistence classification of LC- and LF-LWSCC mixtures

The European Guidelines for Self-Compacting Concrete proposed different classes for flowability and viscosity of SCC in order to evaluate the suitability of a mixture for a given application. The flowability classes are proposed based on slump flow diameter including three classes: SF1 (550-

650 mm), SF2 (660-750 mm), and SF3 (760-850 mm). Meanwhile, the viscosity classes are proposed based on the T_{50} and V-funnel times, including two classes: VS1/VF1 ($T_{50} \leq 2$ seconds and V-funnel flow time ≤ 8 seconds) and VS2/VF2 ($T_{50} > 2$ seconds and V-funnel flow time ranging from 9 to 25 seconds). According to these categories, mixtures 6, 11, 14, and 15 can be classified as SF2/VS1/VF1, which are characterized by a superior self-leveling and a good filling ability even with congested reinforcement.[32] Meanwhile, the other developed LWSCC mixtures had a $T_{50} > 2$ seconds and/or V-funnel flow time ranging from 9 to 25 seconds, which can be classified as SF2/VS2/VF2. According to the European Guidelines, this class is more likely to exhibit thixotropic effects, which may help to improve segregation resistance and limit the formwork pressure. However, both classes are suitable for many applications such as slabs, columns, piles, walls, and ramps.

As per the European Guidelines for Self-Compacting Concrete, all developed LWSCC mixtures can be classified as PA2 class (L-box ratio ≥ 0.80), which is suitable for structural elements with a gap between reinforcement rebars between 60 mm and 80 mm.

2.5.1.6. Compressive strength

The results of the 28-day compressive strength of all LC- and LF-LWSCC mixtures are shown in Table 2.2 and Figure 2.6. In LC-LWSCC mixtures, when the dry density reduced by a maximum of 7.8% (as a result of increasing the LC content), the compressive strength decreased by a maximum of 13%. By looking at mixtures 6-8, increasing the LC/NF ratio from 0.44 to 1.25 (a reduction of 156 kg/m^3 in the dry density) reduced the compressive strength from 59.3 MPa to 51.5 MPa. On the other hand, in LF-LWSCC mixtures, when the dry density reduced by a maximum of 7.4% (due to increasing the content of LF), the compressive strength decreased by a maximum of 6.8%. This was observed in mixtures 14-16. When the NC/LF ratio decreased from

1.67 to 0.6 (a reduction of 147 kg/m^3 in the dry density), the compressive strength decreased from 60.5 MPa to 56.4 MPa.

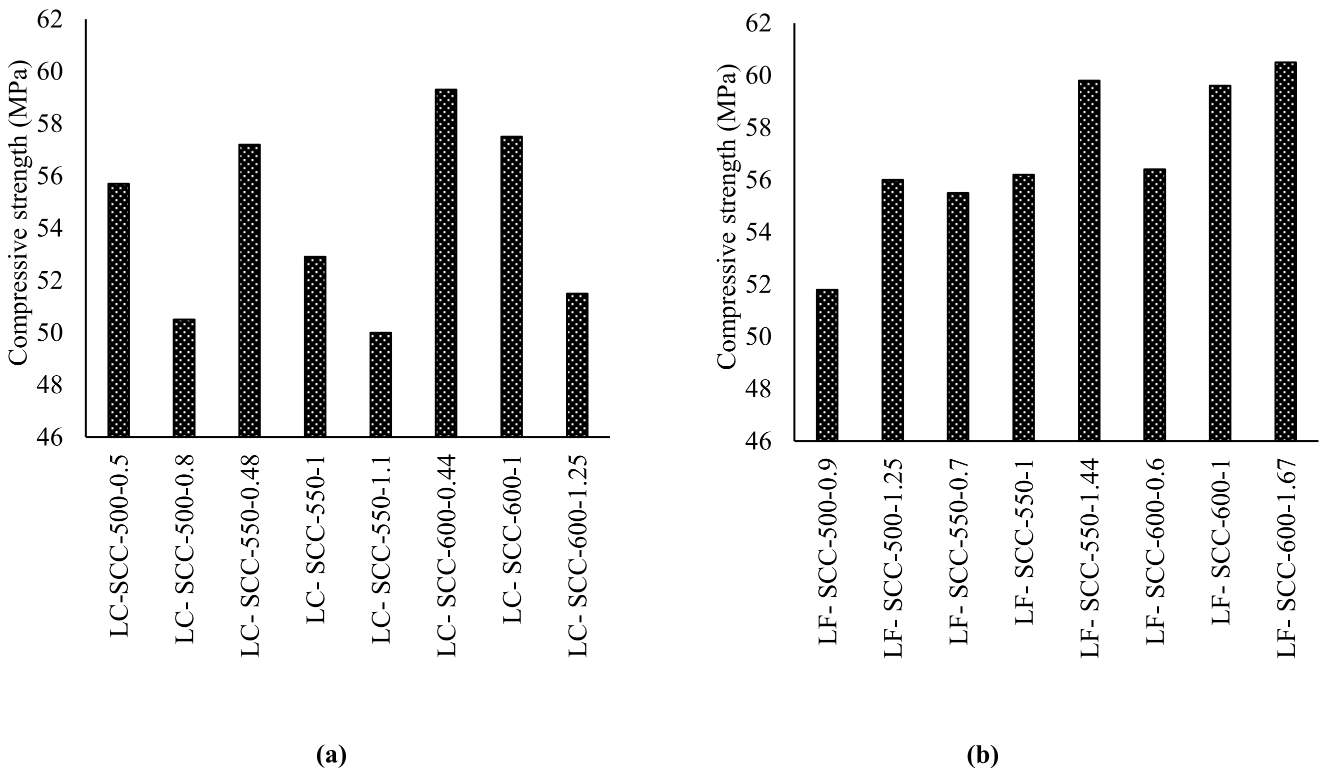
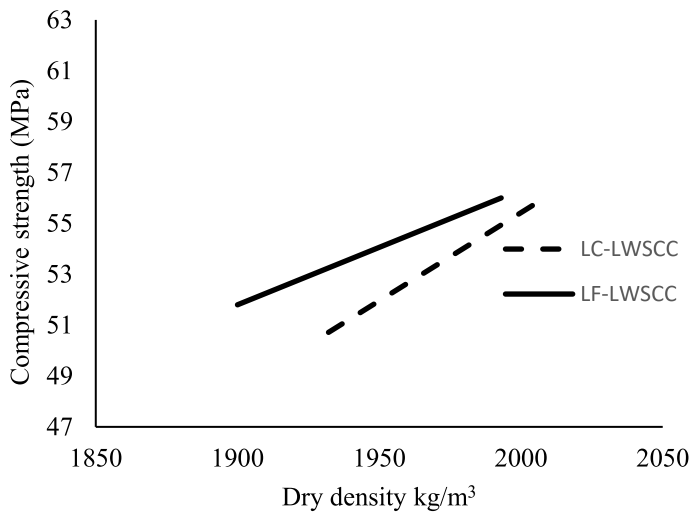


Figure 2.6 28-days compressive strength of the tested mixtures: a) LC-LWSCC mixtures, b) LF-LWSCC mixtures

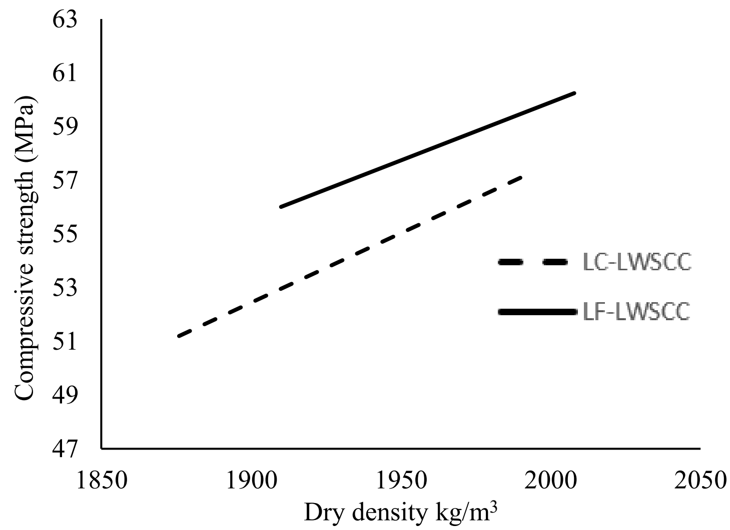
As seen in Figure 2.7, regardless of the binder content, the LC-LWSCC mixtures generally exhibited a higher reduction in the compressive strength when the content of lightweight aggregate was increased compared to the LF-LWSCC mixtures (at a given reduction in the dry density). This is also clear from Figure 2.7, which shows an increase in the slope of the line representing LC-LWSCC compared to that of LF-LWSCC in all binder contents. The lower reduction in the compressive strength with higher content of lightweight aggregate in mixtures with LF compared to mixtures with LC may be attributed to the higher internal pores in LC compared to LF, which is also clear from the difference between their specific gravities (1.53 for LC compared to 1.8 for

LF). These internal pores can cause more reduction in the compressive strength, with increased LC compared to increased LF, with relatively stronger structure.

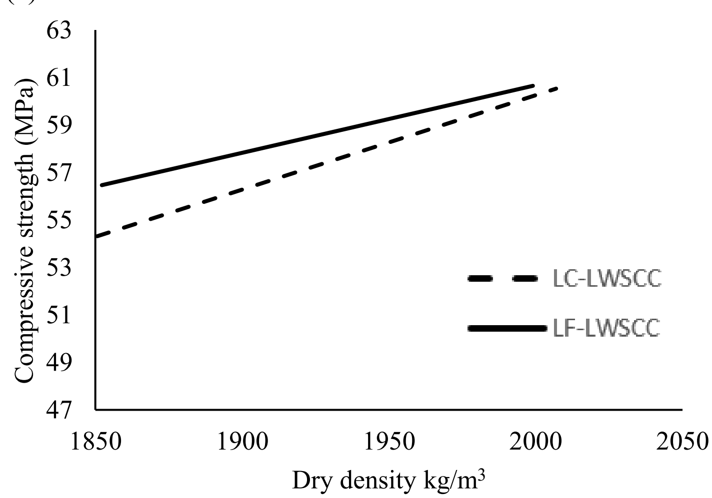
Figure 2.7 also shows that increasing the binder content from 500 kg/m^3 to 600 kg/m^3 was found to noticeably decrease the reduction in the compressive strength (as a result of incorporating either LC or LF) at a given dry density. This is also clear from Figure 2.7, which shows that the distance between the two lines of both LC and LF mixtures is reduced when the mixture density decreases.



(a)



(b)



(c)

Figure 2.7 Strength-density relationships of LWSCC mixtures: a) at binder content 500 kg/m^3, b) at binder content 550 kg/m^3, c) at binder content 600 kg/m^3

2.5.2. Fresh Properties of LWSCC Mixtures Compared to NWSCC Mixtures

Table 2.2 and Figures 2.4-2.5 show the flowability and passing ability results of LWSCC mixtures compared to NWSCC at similar aggregate volume. From the results, it can be seen that the LC-LWSCC mixture exhibited lower flowability compared to the NWSCC. This was clear from the T_{50}, T_{50J}, and V-funnel times results, which showed higher values by 7.7%, 8.5%, and 14.1%, respectively, compared to those for NWSCC (mixture 3 compared to mixture 17). Such results may be attributed to the difference in weight between LC and NC. Since SCC consolidates mainly under its own weight, increasing the self-weight of the mixture can greatly help to increase the self-compactability and flowability of the mixture. For the same reason, the LC-LWSCC showed lower passing ability compared to NWSCC, in which the L-box of the LC-LWSCC was 6.7% lower and the difference between the slump flow and J-ring diameters was 26.7% higher compared to the NWSCC mixture (mixture 3 compared to mixture 17).

Similarly, the LF-LWSCC exhibited lower flowability and passing ability compared to that of the NWSCC (mixture 13 compared to mixture 18). The T_{50}, T_{50J}, and V-funnel times of LF-LWSCC were higher than those of the NWSCC by 7.3%, 18.2%, and 20.1%, respectively. The L-box ratio of the LF-LWSCC was slightly lower (by 2.3%) than the NWSCC, while the difference between the slump flow and J-ring diameters of the LF-LWSCC was 16.3% lower than that of the NWSCC.

2.6. Conclusion

This study investigated the maximum possible use of either LC or LF in the development of LWSCC mixtures. In total, 16 LWSCC mixtures were produced using different coarse-to-fine aggregate ratios and various binder contents. Additional NWSCC mixtures were cast for comparison. Based on the fresh properties, stability, and strength results of the developed mixtures, the following conclusions can be drawn:

1. Using a w/b ratio of at least 0.4 and a minimum binder content of 500 kg/m^3 were found to be necessary to develop LWSCC with either LC or LF having acceptable self-compactability properties. Also, using a ternary material system by replacing 50% of cement with 20% MK and 30% FA greatly helped to develop a mixture with a balanced/optimized viscosity, in which MK improved the particle suspension and reduced the risk of segregation, while FA offered sufficient flowability at reasonable HRWRA demand.
2. Developing LWSCC with LC required less HRWRA demand compared to LF to reach a certain level of flowability. For example, at a density of around 1850 kg/m^3, the LC-LWSCC consumed 23.9% less HRWRA than the LF-LWSCC. Increasing the binder content, however, was found to generally decrease the HRWRA demand. For example, at comparable density, increasing the binder content from 550 kg/m^3 to 600 kg/m^3 reduced the HRWRA demand by 6.2% in the LC-LWSCC mixtures and by 8.1% in the LF-LWSCC mixtures.
3. A maximum LC/NF ratio of 0.8 can be used in the development of minimum density LC-LWSCC with 500 kg/m^3 binder content. Exceeding this value led to a significant reduction in the passing ability and stability of the mixtures. Meanwhile, at the same binder content (500 kg/m^3), the minimum density of LF-LWSCC was achieved at a minimum NC/LF ratio of 0.9. Further exceeding this amount of LF was not possible due to the high risk of segregation in the mixture.
4. Increasing the binder content from 500 kg/m^3 to 600 kg/m^3 noticeably improved the flowability, passing ability, stability, and strength of LWSCC, which allowed for higher amounts of lightweight aggregates to be used safely, achieving mixtures with further

reduction in the dry density (while maintaining acceptable self-compactability properties, especially passing ability and segregation resistance). For example, at 600 kg/m^3 binder content, it was possible to reach a minimum density of 1851 kg/m^3 in LC-LWSCC compared to 1926 kg/m^3 minimum density with 500 kg/m^3 binder content.

5. At a given mixture density, developing LWSCC with LF appeared to have a better flowability and passing ability compared to developing LWSCC with LC. This indicates promising potentials for using LF rather than LC to develop LWSCC mixtures, with higher reduction in the density while maintaining acceptable self-compactability properties.
6. Increasing the binder content from 500 kg/m^3 to 600 kg/m^3 helped to reduce the negative effect of expanded slate aggregates on the compressive strength. However, at a comparable density, mixtures with LF exhibited higher compressive strength compared to mixtures with LC at any binder content.
7. Replacing normal-weight aggregates by a similar volume of expanded slate aggregates (either LC or LF) reduced the mixture flowability and passing ability. The higher weight of crushed granite aggregates helped NWSCC mixture to experience better self-compactability under its own weight, allowing for higher flowability and passing ability compared to LWSCC mixtures developed with either LC or LF.

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3. Impact resistance and mechanical properties of optimized SCC developed with coarse and fine lightweight expanded slate aggregate

3.1. Abstract

This study evaluated the impact resistance and mechanical properties of a number of optimized self-consolidating concrete mixtures developed with lightweight expanded slate aggregate. The investigated parameters included different lightweight expanded slate types (fine and coarse), different aggregate volumes, and various binder contents (500 kg/m^3, 550 kg/m^3, and 600 kg/m^3). The mechanical properties of all developed mixtures were assessed using the compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity. On the other hand, the impact resistance for the tested mixtures was evaluated by drop-weight test conducted on both cylinders and small-scale prism beams. The results showed that despite the relatively low strength of lightweight aggregates, using a ternary binder material system (cement, metakaolin, and fly ash) helped to develop successful lightweight self-consolidating concrete mixtures with a density ranging from 1850 kg/m^3 to 2000 kg/m^3 and a strength of at least 50 MPa. Expanded slate fine aggregate showed better mechanical properties and impact resistance when compared to expanded slate coarse aggregate. The results also indicated that with the absence of self-compactability restrictions, it was possible to develop LWVC mixtures, with a density of up to 1784 kg/m^3 and compressive strength of around 40 MPa.

3.2. Introduction

Lightweight concrete (LWC) is a promising building material that has been attracting a great deal of attention in recent years across a wide range of construction projects. According to the ACI 213 guidelines (ACI Committee 213 2014), concrete with up to 1920 kg/m^3 can be classified as structural lightweight concrete. On the other hand, the Canadian code (Canadian Standards Association Committee A23.3 2004) defined two classes of structural lightweight concretes, namely, low-density and semi-low-density concrete. The dry density of the low-density concrete should not exceed 1850 kg/m^3 while the dry density of semi-low-density concrete ranges from 1850 kg/m^3 to 2150 kg/m^3. LWC has advantages over normal-weight concrete. The lower density of LWC helps to reduce the structure's self-weight, allowing for more savings in the construction costs (Wongsa et al. 2013, Nikbin et al. 2018, Zhang et al. 2018, Abdulkareem et al. 2014, Yu et al. 2015). Other advantages of LWC include low thermal conductivity, high fire resistance, and improved heat and sound insulation (Tasdemir et al. 2017, Sayadi et al. 2016, Go et al. 2012, Ting et al. 2019). However, the relatively low strength of lightweight aggregates negatively affects the mechanical properties of concrete composite (Hassan et al. 2015, Atmaca et al. 2017, Lo et al. 2007, Abouhussien et. al 2015). Therefore, the development of LWC requires certain design procedures in order to alleviate the low strength of lightweight aggregates and develop composite with adequate strength for multiple applications.

The benefits of LWC can be maximized when the feature of self-compactability is added, thus introducing an innovative type of high-performance concrete that combines the desirable properties of both LWC and self-consolidating concrete (SCC) (Ting et al. 2019, Grabois et al. 2016, Kim et al. 2010). However, the development of lightweight self-consolidating concrete (LWSCC) increases the risk of segregation due to the low density of lightweight aggregate particles compared to cementitious paste in such high flowable concrete (Lotfy et al. 2016, Karahan et al. 2016). Therefore, improving the viscosity of mixtures is essential to produce LWSCC with adequate stability and less risk of segregation. This can be reached by optimizing the binder materials system used in the mixture. Incorporating high-performance supplementary cementitious materials such as metakaolin (MK) can help to achieve sufficient viscosity and enhance particle suspension (Hassan et al. 2012). The high pozzolanic reactivity of this material can also effectively boost the strength of concrete composite (Hassan et al. 2012, Hassan and Mayo 2015, Hassan and Ismail 2016), which in turn alleviates the low strength of lightweight aggregates.

The superior properties of LWSCC make it a strong candidate for multiple structural applications. The first application of LWSCC was in the construction of the main girder of a cable-stayed bridge in Japan in 1992 (Okamura and Ouchi 2003). The technology of LWSCC has since been used in the construction of different structures such as long-span bridges, high-rise buildings, offshore structures, and pre-stressed and pre-cast elements (Shi and Yang 2005, Yao and Gerwick 2006, Hubertova and Hela 2007, Papanicolaou and Kaffetzakis 2011). In addition to resisting gravity loads, structures made with LWSCC are also required to have sufficient resistance against dynamic and impulsive loads. For example, offshore concrete platforms should be designed to endure impact loads resulting from the collision of waves, ships, and/or icebergs against the concrete's surface (Paik 2017, Clauss 2002). The relatively low strength of lightweight aggregate compared to normal-weight aggregate makes it more critical for LWSCC to resist impact loading. Therefore, evaluating properties such as impact resistance, toughness, and energy absorption for LWSCC is crucial and requires further investigation.

This study was conducted to evaluate the mechanical properties and impact resistance of a number of optimized LWSCC and lightweight vibrated concrete (LWVC) developed with expanded slate lightweight aggregate. The experimental program included 24 mixtures produced with different combinations of normal-weight and lightweight aggregates (fine or coarse), different aggregate volumes, and different binder contents. The performance of the developed mixtures was assessed based on the compressive strength, splitting tensile strength (STS), flexural strength (FS), modulus of elasticity (ME), and impact resistance. Two additional normal-weight SCC (NWSCC) mixtures were cast for comparison.

3.3. Research Significance

The desirable properties of LWSCC gives this concrete unique advantages for use in multiple structural applications. By reviewing the current literature, however, it was found that there is not sufficient research evaluating the impact resistance of LWSCC. Moreover, despite the improved strength of expanded slate aggregate compared to all other types of lightweight aggregate, no studies have evaluated the impact resistance of LWC made with this type of aggregate. Therefore, this investigation was designed to fill this gap of knowledge by assessing the mechanical properties and impact resistance for a number of optimized LWSCC mixtures developed with different combinations of normal-weight and lightweight expanded slate aggregates. The study exclusively evaluated the performance of expanded slate coarse aggregate compared to expanded slate fine aggregate in the development of LWSCC mixtures. The authors believe that this investigation will add to the available information regarding the use of expanded slate aggregates in developing LWSCC with promising potential for the construction industry.

3.4. Experimental Program

3.4.1. Material Properties

The materials used in this study are detailed as follows:

- Type GU Portland cement similar to ASTM C150 Type I (2012) was used in all developed mixtures. MK and fly ash (FA) conforming to ASTM C618 class N (2012) and ASTM C618 type F (2012), respectively, were used as binder materials to adjust the mixtures' viscosity and flowability.
- Two types of coarse aggregates and two types of fine aggregates were used as follows: crushed granite normal-weight coarse aggregate (NC), expanded slate lightweight coarse aggregate (LC), crushed granite normal-weight fine aggregate (NF), and expanded slate

lightweight fine aggregate (LF). The NC and NF had a specific gravity and absorption of 2.6 and 1%, respectively, while the LC and LF had a specific gravity of 1.53 and 1.8, respectively, and absorption of 7.1% and 10%, respectively. The gradation curves of all aggregates used are presented in Figure 3.1.

- A polycarboxylate-based high-range water-reducer admixture (HRWRA) conforming to ASTM C494 type F (2013) was used to achieve the workability requirements of both SCC and VC mixtures.

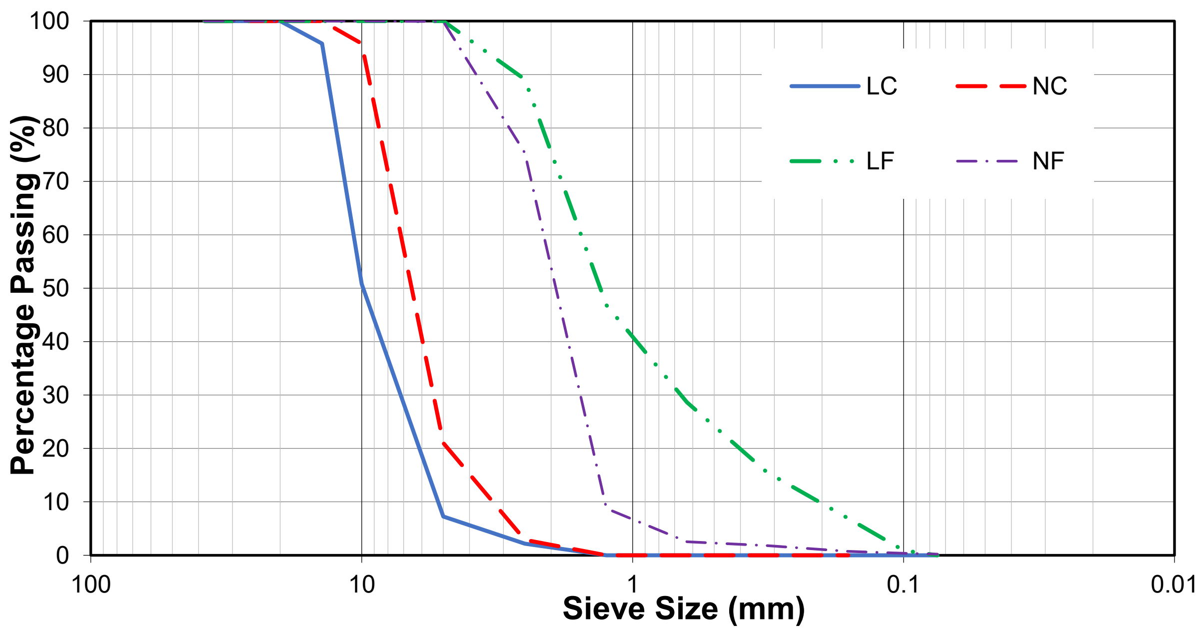


Figure 3.1 Gradation curves for fine and coarse normal-weight and lightweight aggregates

3.4.2. Scope of Work

3.4.2.1. Stage 1 – Development of LWSCC Mixtures

Despite the desirable properties and economic benefits of LWSCC over normal-weight concrete, the production of LWSCC is a challenge due to the high risk of segregation of the low-density lightweight aggregates. The high porosity and relatively low strength of lightweight aggregates, compared to conventional aggregates, also creates an additional challenge in the development of LWSCC with sufficient flowability and strength. Therefore, this study was conducted to develop a number of LWSCC mixtures with minimum possible density and adequate strength (at least 50 MPa) suitable for multiple structural applications. To accomplish this, a preliminary trial mix stage was conducted aimed at:

a. Adjusting the mixture paste's viscosity to achieve sufficient suspension and stability for lightweight aggregate particles in order to avoid segregation problems;
b. Improving the mixture paste's strength to alleviate the negative effects of the relatively low strength of the lightweight aggregate in order to achieve a composite with adequate mechanical properties.

It should be noted that this stage focused on developing LWSCC mixtures having a slump flow of 700 ± 50 mm. In this stage, the authors evaluated the interplay effect of the binder content, binder type, and water-to-binder (w/b) ratio on the mixtures' viscosity and strength. The results of the trial mix stage indicated that using binder content of less than 500 kg/m^3 was not enough to develop mixtures with sufficient stability, flowability, and passing ability. In addition, using only cement was not sufficient to develop mixtures with the required viscosity to achieve adequate stability for the aggregate particles and to reduce the risk of segregation. After trying different combinations of various binder materials, a ternary binder system consisting of 50% cement, 20% MK, and 30% FA was found to best achieve the required viscosity and flowability for LWSCC. By combining MK, with its clay-like consistency (to improve the viscosity and particle suspension), and FA, with its smooth and spherical particles (to improve the flowability of the mixture), the authors successfully reached optimized LWSCC mixtures. Furthermore, the high pozzolanic reactivity of MK also helped to achieve improved mechanical properties and alleviated the effect of using relatively low-strength lightweight aggregate in the mixture. The w/b ratio was also optimized in this stage, in which the minimum w/b ratio that could be used to achieve successful LWSCC mixtures was found to be 0.4. Table 3.1 shows the mixture compositions for all developed LWSCC mixtures.

With 500 kg/m^3 binder content, it was possible to reach a minimum density of 1929 kg/m^3 in LC-LWSCC mixtures (mixture 2) and 1900 kg/m^3 in LF-LWSCC mixtures (mixture 9), as shown in Table 3.1. Additional increase in the volume of lightweight aggregates to further reduce the mixture's density caused potential problems in LC- and LF-LWSCC mixtures. In LC-LWSCC, further increasing the volume of LC resulted in high blockage and friction between particles, which in turn decayed the flowability and reduced the passing ability of mixtures. On the other hand, increasing the volume of LF in the LWSCC mixtures increased the risk of segregation.

Table 3.1. Mixture proportions of all developed mixtures

Mix No.	Designation	Cement kg/m^3	MK kg/m^3	FA kg/m^3	Aggregate					Water kg/m^3	Air %	Dry density kg/m^3
					Coarse-to-fine aggregate ratio By weight	Normal-weight aggregates (kg/m^3)		Lightweight aggregates (kg/m^3)				
						NC	NF	LC	LF			
LC-LWSCC												
1	LC-SCC-500-0.5	250	100	150	0.50	-	869.4	434.7	-	200	3.3	2004
2	LC- SCC-500-0.8	250	100	150	0.80	-	681.6	545.2	-	200	3.4	1929
3	LC- SCC-550-0.48	275	110	165	0.48	-	831.1	398.9	-	220	3.0	1994
4	LC- SCC-550-1	275	110	165	1.00	-	559.0	559.0	-	220	3.5	1884
5	LC- SCC-550-1.1	275	110	165	1.10	-	525.9	578.5	-	220	3.5	1876
6	LC- SCC-600-0.44	300	120	180	0.44	-	806.6	354.9	-	240	3.2	2007
7	LC- SCC-600-1	300	120	180	1.00	-	522.3	522.3	-	240	3.3	1882
8	LC- SCC-600-1.25	300	120	180	1.25	-	451.2	564.0	-	240	3.4	1851
LF-LWSCC												
9	LF- SCC-500-0.9	250	100	150	0.90	617.3	-	-	685.9	200	3.4	1900
10	LF- SCC-500-1.25	250	100	150	1.25	746.0	-	-	596.8	200	3.6	1993
11	LF- SCC-550-0.7	275	110	165	0.70	492.5	-	-	703.7	220	3.6	1887
12	LF- SCC-550-1	275	110	165	1.00	617.3	-	-	617.3	220	3.7	1962
13	LF- SCC-550-1.44	275	110	165	1.44	748.0	-	-	526.8	220	3.3	2008
14	LF- SCC-600-0.6	300	120	180	0.60	413.7	-	-	689.6	240	3.2	1852
15	LF- SCC-600-1	300	120	180	1.00	576.7	-	-	576.7	240	3.4	1955
16	LF- SCC-600-1.67	300	120	180	1.67	755.9	-	-	452.6	240	3.8	1999
NWSCC												
17	NW-SCC-550-0.8	275	110	165	0.80	670.7	838.3	-	-	220	2.6	2270
18	NW-SCC-550-1	275	110	165	1.00	754.5	754.5	-	-	220	3.4	2261
LC-LWVC												
19	LC-VC-500-1.25	250	100	150	1.25	-	643.5	514.8	-	200	3.5	1826
20	LC-VC-550-1.5	275	110	165	1.50	-	637.8	425.2	-	220	3.7	1810
21	LC-VC-600-2	300	120	180	2.00	-	641.0	320.5	-	240	3.8	1784
LF-LWVC												
22	LF-VC-500-0.6	250	100	150	0.60	472.0	-	-	786.6	200	3.4	1834
23	LF-VC-550-0.5	275	110	165	0.50	388.0	-	-	776.1	220	3.2	1820
24	LF-VC-600-0.4	300	120	180	0.40	305.8	-	-	764.4	240	3.1	1799

Using higher binder content provides larger volume of mixture's paste, which offers better flowability, particle suspension, and higher strength. Therefore, binder contents of 550 kg/m^3 and 600 kg/m^3 (having a similar ternary binder material system) were used to develop LWSCC mixtures with higher volume of lightweight aggregates (lower density). At binder contents of 550 kg/m^3 and 600 kg/m^3, it was possible to reach a minimum density of 1876 kg/m^3 (mixture 5) and 1851 kg/m^3 (mixture 8), respectively, in LC-LWSCC mixtures. Meanwhile, these minimum densities reached up to 1887 kg/m^3 (mixture 11) and 1852 kg/m^3 (mixture 14), respectively, in LF-LWSCC mixtures. The fresh properties of all developed LWSCC mixtures are presented in Table 3.2.

Table 3.2. Fresh properties of all LWSCC mixtures

Mix No.	Designation	Slump T_{50} (sec)	V-funnel (sec)	L-box H2/H1
LC-LWSCC				
1	LC-SCC-500-0.5	2.18	12.0	0.88
2	LC- SCC-500-0.8	2.58	17.6	0.80
3	LC- SCC-550-0.48	1.95	10.6	0.90
4	LC- SCC-550-1	2.34	14.7	0.84
5	LC- SCC-550-1.1	2.52	17.2	0.81
6	LC- SCC-600-0.44	1.70	7.50	0.93
7	LC- SCC-600-1	2.07	10.7	0.88
8	LC- SCC-600-1.25	2.50	16.7	0.81
LF-LWSCC				
9	LF- SCC-500-0.9	2.20	12.5	0.87
10	LF- SCC-500-1.25	2.44	16.1	0.82
11	LF- SCC-550-0.7	1.80	8.90	0.91
12	LF- SCC-550-1	1.95	10.85	0.89
13	LF- SCC-550-1.44	2.36	15.25	0.84
14	LF- SCC-600-0.6	1.60	6.70	0.95
15	LF- SCC-600-1	1.78	8.20	0.92
16	LF- SCC-600-1.67	2.41	15.40	0.83

3.4.2.2. Stage 2 – Development of LWVC Mixtures

Since self-compactability properties are not a factor in the development of vibrated concrete, it was possible to utilize larger volumes of either LC or LF in LWVC and reach further reductions in the mixture's density. All LWVC mixtures were developed with a slump of 150 ± 30 mm. The dry density of LC- and LF-LWVC mixtures ranged from 1784 kg/m^3 to 1834 kg/m^3, as shown in Table 3.1.

It should be noted that the ACI 213 defines high-strength structural lightweight concrete as a concrete with a density between 1120 kg/m^3 and 1920 kg/m^3 and a minimum 28-day compressive strength of 40 MPa or greater. Meanwhile, the Canadian code classifies structural lightweight concrete into two categories: (a) low-density concrete: mixtures with a density not exceeding 1850 kg/m^3 and a 28-day compressive strength not less than 20 MPa; and (b) semi-low-density concrete: mixtures with a density between 1850 kg/m^3 and 2150 kg/m^3 and a 28-day compressive strength not less than 20 MPa. Therefore, according to both ACI 213 and the Canadian code, the mixtures developed in stage 1 and 2, with densities between 1784 kg/m^3 and 2008 kg/m^3 and strength between 40.4 MPa and 60.5 MPa, can be classified as high- strength semi-lightweight and lightweight concrete.

3.4.3. Details and Objective of all Developed Concrete Mixtures

In total, 24 mixtures were developed as follows (mixture composition is shown in Table 3.1):

a. Mixtures 1-8 were used to evaluate the effect of using different volumes of LC on the mechanical properties and impact resistance of LWSCC. Mixtures 1, 3, and 6 were developed with maximum possible strength and a density of around 2000 kg/m^3 (to represent reasonable lightweight concrete with maximized strength). Meanwhile, mixtures 2, 5, and 8 were developed with minimum possible density (regardless of the strength).

Mixtures 4 and 7 were added to investigate the effect of increasing the binder content on the mechanical properties and impact resistance of LC-LWSCC (with comparable density).

b. Mixtures 9-16 were used to evaluate the effect of using different volumes of LF on the mechanical properties and impact resistance of LWSCC. Mixtures 9, 11, and 14 were developed with a density of around 2000 kg/m^3 and maximum possible strength, while mixtures 10, 13, and 16 were developed with minimum possible density. Similar to mixtures 4 and 7, mixtures 12 and 15 were also added to investigate the effect of increasing the binder content on the mechanical properties and impact resistance but for LWSCC with LF.

c. Mixture 8 was compared to mixture 14 in order to determine the mechanical performance of LC-LWSCC compared to LF-LWSCC at the same density.

d. Mixtures 17 and 18 were developed as NWSCC mixtures for comparison with their counterpart LWSCC mixtures (mixtures 3 and 13) at similar aggregate volume replacement levels.

e. Mixtures 19-21 and mixtures 22-24 were developed as LC-LWVC and LF-LWVC, respectively. These mixtures were added to study the possibility of further increasing the percentages of either LC or LF in the mixtures (further reduction of the density), taking advantage of the absence of the fresh properties' restrictions of SCC.

The selected mixtures were divided into five categories: LC-LWSCC, LF-LWSCC, LC-LWVC, LF-LWVC, and NWSCC. In each category, mixtures were designated according to type of aggregate used (LC, LF, NC, NF), concrete type (SCC or VC), binder content (500, 550, 600 kg/m^3), and coarse-to-fine aggregate ratio. For example, an LWSCC mixture produced with LC, binder content of 500 kg/m^3, and LC/NF ratio of 0.5 would be labeled as LC-SCC-500-0.5, while an LWVC mixture developed with LF, binder content of 500 kg/m^3, and NC/LF of 0.6 would be labeled as LF-VC-500-0.6.

3.4.4. Fresh and Mechanical Properties Tests

The self-compactability capability of all developed LWSCC and NWSCC mixtures was evaluated according to EFNARC (2005) using slump flow, V-funnel, and L-box tests. The slump flow and V-funnel tests were conducted to assess the flowability of mixtures, while the L-box was used to evaluate the passing ability. The segregation resistance of lightweight aggregates was visually evaluated by examining the distribution of aggregate particles along three splitted hardened concrete cylinders for each mixture. The workability of LWVC mixtures was measured by the slump tests as per ASTM C143. The results obtained from the fresh properties tests are listed in Table 3.2.

The mechanical properties were evaluated by testing the compressive strength, splitting tensile strength (STS), flexural strength (FS), and modulus of elasticity (ME). The compressive strength, STS, and ME tests were conducted on concrete cylinders having a diameter of 100 mm and a height of 200 mm according to ASTM C39 (2014), ASTM C496 (2011), and ASTM C469 (2014), respectively. A four-point loading test was performed on 100 mm x 100 mm x 400 mm prisms to evaluate the FS for all developed mixtures according to ASTM C78 (2010). Each test was conducted on three specimens for each developed mixture after 28 days. It should be noted that all specimens were exposed to a moist-curing regime until the date of testing.

3.4.5. Impact Resistance Test

The impact resistance of all developed mixtures was assessed using a drop-weight test on cylindrical and small-scale beam specimens, as follows:

a. Drop-weight test on cylindrical specimens with 150 mm diameter and 63.5 mm height as per procedures given by the ACI committee 544 (1999): This test was conducted by dropping a hammer weighing 4.45 kg, which was left to free fall from a height of 457 mm, onto a 63.5 mm steel ball positioned at the center of the top surface of the tested concrete specimen. The number of blows required to induce failure in the tested specimens was recorded to evaluate their impact resistance.
b. Drop-weight test on small-scale beams having a cross section of 100 mm x 100 mm, a total length of 400 mm, and a loading span of 350 mm: This test evaluated the flexural impact resistance of the developed mixtures using three-point impact loading setup. A 4.45 kg hammer was dropped from a height of 150 mm onto a 63.5 mm steel ball located on the midspan of the tested beams. Similar to previous setup, the impact resistance was evaluated by recording the number of blows that induced failure in the tested specimens.

For both tests, three specimens for each developed mixture were tested after 28 days from casting. The ultimate impact energy of all tested specimens (either cylinders or beams) was calculated according to Eq. 1:

$$IE = N\,mgh \qquad (1)$$

Where N is the number of blows that induced failure; m is the mass of the drop hammer (4.45 kg); g is the acceleration due to gravity (9.81 m/s^2); and h is the drop height (457 mm or 150 mm).

3.5. Discussion of Results

3.5.1. LWSCC Mixtures

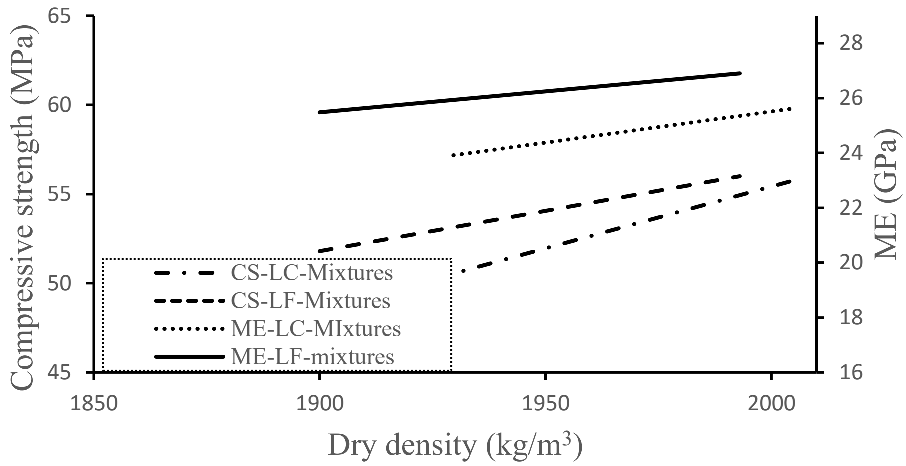
3.5.1.1. Compressive Strength and ME

The results of compressive strength and ME for all developed LWSCC mixtures are shown in Table 3.3 and Figure 3.2. From the results, it can be seen that decreasing the mixture's density with the inclusion of either LC or LF reduced the compressive strength and ME (i.e., the higher the volume of lightweight aggregate used, the higher the reductions in the mixture's density, strength, and ME). This is mainly attributed to the relatively low strength of lightweight aggregates compared to normal-weight aggregates, which in turn decreases the overall strength and ME of concrete composite. Moreover, regarding the ME, the inclusion of higher volumes of LWA (porous structure) increased the compressibility and allowed for more strain at the same level of loading compared to the normal weight aggregate, which in turn decreased the ME. For example, in LC-LWSCC with binder content of 500 kg/m^3, when the density decreased by 75 kg/m^3 due to increasing the volume of LC (mixtures 1-2), the 28-day compressive strength and ME were reduced by 9.3% and 6.3%, respectively. Also, in LF-LWSCC mixtures with binder content of 500 kg/m^3, a reduction in the density of 93 kg/m^3 due to increasing the volume of LF (mixtures 9-10) led to a decrease in the 28-day compressive strength and ME reaching up to 7.5% and 5.3%, respectively.

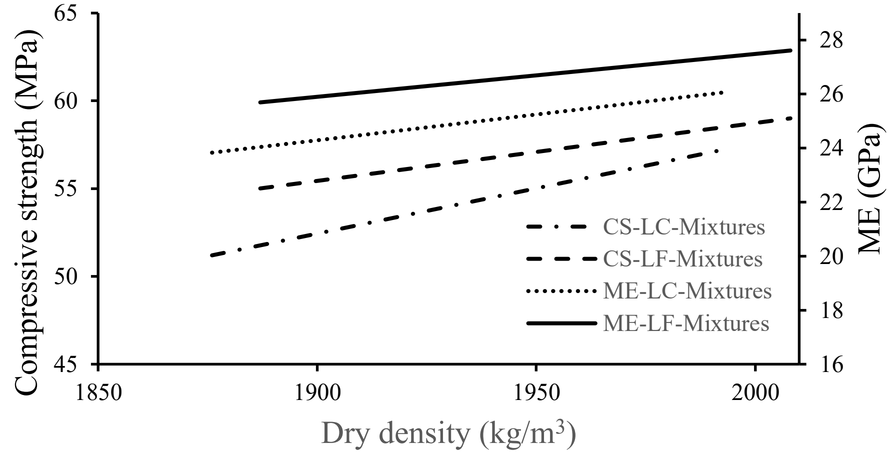
Table 3.3 Mechanical properties and impact resistance of all tested mixtures

Mix No.	Mixture designation	f'_c (MPa)		*STS* (MPa)		*FS* (MPa)		*ME* (GPa)		Cylindrical specimens			Beam specimens		
		f'_c	SD*	*STS*	SD*	*FS*	SD*	*ME*	SD*	Number of blows	SD*	Energy (J)	Number of blows	SD*	Energy (J)
LC-LWSCC															
1	LC-500-0.5-S	55.7	0.22	3.0	0.21	3.74	0.17	25.5	0.19	32	4.3	638.4	18	5.2	117.9
2	LC-500-0.8-S	50.5	0.43	2.41	0.16	3.18	0.21	23.9	0.26	23	2.4	458.9	11	3.9	72.0
3	LC-550-0.48-S	57.2	0.16	3.19	0.17	4.1	0.11	26.06	0.10	37	5.8	738.2	20	4.4	131.0
4	LC-550-1-S	52.9	0.35	2.63	0.12	3.65	0.12	24.34	0.12	28	2.4	558.6	15	2.9	98.2
5	LC-550-1.1-S	50	0.40	2.39	0.13	3.36	0.20	23.5	0.27	26	3	518.7	12	4.1	78.6
6	LC-600-0.44-S	59.3	0.13	3.5	0.11	4.65	0.15	27.48	0.23	43	4.1	857.9	25	3.7	163.7
7	LC-600-1-S	57.5	0.35	3.1	0.11	4.22	0.17	25.67	0.34	37	3.3	738.2	21	1.9	137.5
8	LC-600-1.25-S	51.5	0.49	2.7	0.16	4	0.19	24.9	0.18	32	4.7	638.4	16	2.1	104.8
LF-LWSCC															
9	LF-500-0.9-S	51.8	0.54	2.75	0.19	3.72	0.182	25.48	0.19	30	3.9	598.5	13	2.1	85.1
10	LF-500-1.25-S	56.0	0.78	3.35	0.12	4.19	0.208	26.9	0.15	38	2.4	758.1	20	1.9	131.0
11	LF-550-0.7-S	55.5	0.46	3.2	0.11	4.05	0.186	25.9	0.20	35	4.8	698.3	18	2.7	117.9
12	LF-550-1-S	56.2	0.28	3.34	0.14	4.3	0.201	26.34	0.22	37	1.6	738.2	20	3.9	131.0
13	LF-550-1.44-S	59.8	0.42	3.7	0.12	4.5	0.216	27.95	0.16	43	5.3	857.9	26	3.7	170.3
14	LF-600-0.6-S	56.4	0.77	3.25	0.15	4.36	0.178	26.1	0.36	39	2.5	778.1	19	4.1	124.4
15	LF-600-1-S	59.6	0.51	3.65	0.16	4.67	0.211	27.4	0.12	44	3.4	877.8	26	4.9	170.3
16	LF-600-1.67-S	60.5	0.83	3.75	0.14	4.75	0.234	28.5	0.23	46	2.5	917.7	27	4.3	176.8
NWSCC															
17	NW-550-0.8-S	73.9	0.67	4.87	0.29	5.72	0.27	30.60	0.12	63	7	1256.9	40	6.1	261.93
18	NW-550-1-S	71.2	0.49	4.70	0.37	5.64	0.31	30.43	0.15	59	9.3	1177.1	38	5.4	248.83
LC-LWVC															
19	LC-500-1.25-V	40.4	0.56	2.2	0.17	3.11	0.16	21.85	0.14	20	4.3	399.0	8	2.4	52.4
20	LC-550-1.5-V	41.1	0.47	2.25	0.11	3.15	0.3	21.89	0.23	21	3.2	419.0	9	1.3	58.9
21	LC-600-2-V	41.9	0.69	2.19	0.23	2.98	0.21	21.60	0.30	19	3.9	379.1	9	3	58.9
LF-LWVC															
22	LF-500-0.6-V	41.3	0.74	2.45	0.25	3.35	0.25	22.81	0.25	21	2.3	419.0	9	1.8	58.9
23	LF-550-0.5-V	42.1	0.93	2.4	0.19	3.30	0.14	22.11	0.17	22	4.9	438.9	10	2.2	65.5
24	LF-600-0.4-V	42.9	0.82	2.21	0.13	3.27	0.29	21.47	0.35	24	4.1	478.8	12	2.5	78.6

Note: SD is the standard deviation



(a)



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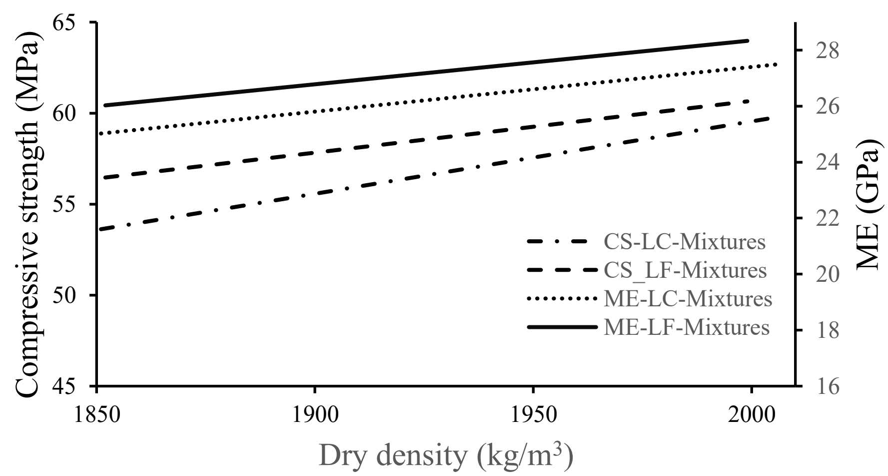


(c)

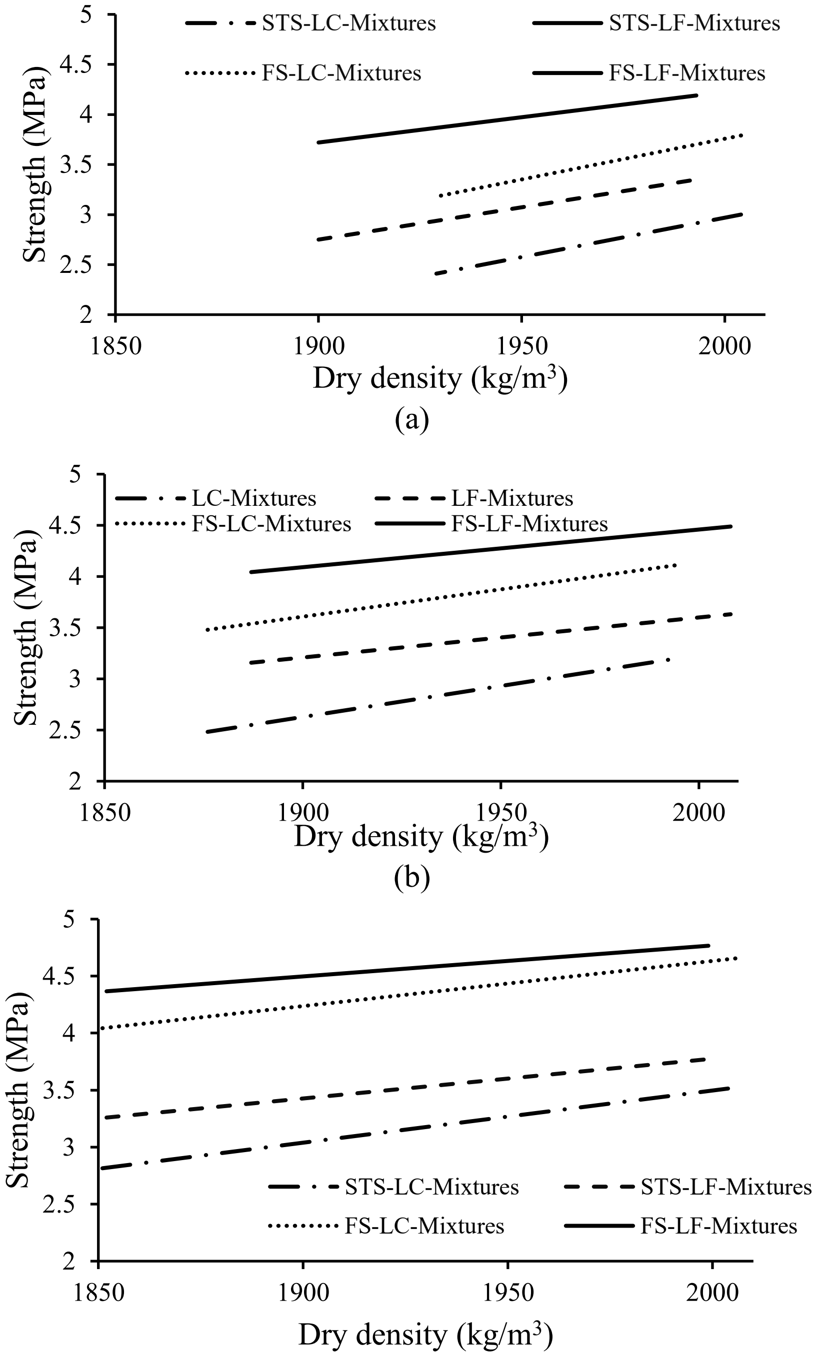
Figure 3.2. Relationship between compressive strength, ME and dry density of LC-LWSCC and LF-LWSCC at binder content of (a) 500 kg/m^3, (b) 550 kg/m^3, and (c) 600 kg/m^3

Figure 3.2 show the trend of reductions in the 28-day compressive strength and ME within the investigated range of density (1850 kg/m^3 to 2000 kg/m^3). From the figures, it can be seen that at a given density, LWSCC mixtures with LC showed lower compressive strength and ME than that of LWSCC mixtures with LF at any binder content (higher strength-to-density ratio for mixtures with LF compared to mixtures with LC). For example, at binder content of 600 kg/m^3 and density of around 1850 kg/m^3, the LF-LWSCC (mixture 14) had a 28-day compressive strength and ME of 9.5% and 4.8%, respectively, higher than that of LC-LWSCC (mixture 8). This result is related to the higher internal pores in LC compared to LF, which can be concluded from their specific gravities (1.53 and 1.8 for LC and LF, respectively). And since both aggregates were similar in terms of material type, the higher porous structure exhibited the lower strength. This highlights a promising potential and better feasibility for using the LF over the LC in the development of LWSCC.

Figure 3.2 also show that at 500 kg/m^3 binder content, the slope of reduction trend line for LC-LWSCC mixtures was steeper than for the LF-LWSCC mixtures. Increasing the binder content to 550 kg/m^3 and 600 kg/m^3 reduced the distance between the two lines. This indicates that mixtures with LC showed noticeable improvement at higher binder content.

3.5.1.2. STS and FS

The STS and FS of all developed LWSCC mixtures are presented in Figure 3.3, in addition to Table 3.3. The results of STS and FS followed the same trend as the results of compressive strength and ME (i.e., decrease in the STS and FS as the mixture's density decreased) but with higher rate of reduction. For example, in LC-LWSCC mixtures with 500 kg/m^3 binder content, a 75 kg/m^3 decrease in the mixture's density reduced the STS and FS by up to 19.7% and 15%, respectively, while these reductions were 9.3% and 6.3% in the compressive strength and ME, respectively.



(c)

Figure 3.3 Relationship between STS, FS and dry density of LC-LWSCC and LF-LWSCC at binder content of (a) 500 kg/m^3, (b) 550 kg/m^3, and (c) 600 kg/m^3

This finding indicates that the tensile strength of concrete was the most affected by the inclusion of lightweight aggregates. The maximum reduction was recorded by the STS (most of the concrete section is exposed to tensile stress), followed by the FS (half of the concrete section is exposed to tensile stress), then the compressive strength and ME. The results also indicated that the mixtures with LF showed a similar trend as the mixtures with LC but with less reduction values.

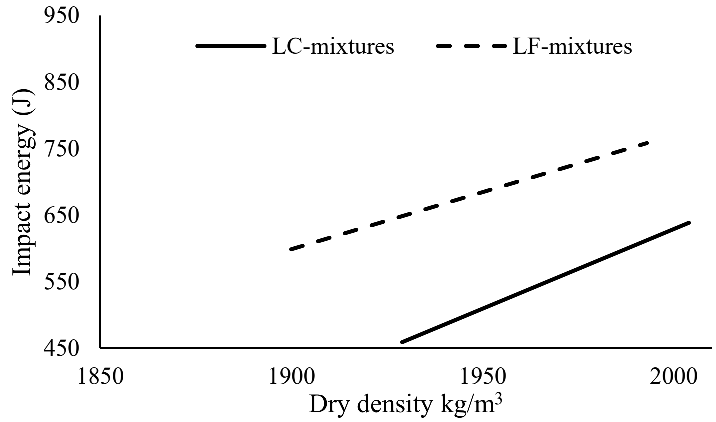
The results also indicated that increasing the binder content had a positive effect on the STS and FS, higher than its effect on the compressive strength and ME. As shown in Table 3.3, by comparing mixture 4 with mixture 7 (LC-LWSCC mixtures with almost comparable density), it can be seen that increasing the binder from 550 kg/m^3 to 600 kg/m^3 increased the STS and FS by 17.9% and 15.6%, respectively. The more pronounced increases in the STS and FS compared to compressive strength and ME may be related to the beneficial effect of the higher binder content on enhancing the bonding between aggregate particles and matrix's paste, which had a higher effect on the STS compared to the compressive strength and ME. Similar results were found in LF-LWSCC mixtures in comparing mixture 12 to mixture 15 (LF-LWSCC mixtures with almost comparable density).

Figure 3.3 display the relationship between the STS and FS of all developed LWSCC mixtures and their corresponding dry density for each binder content. From the figures, it can be noticed that by increasing the binder content, the reduction in STS and FS decreased within the investigated range of density, in which mixtures with higher binder content (550 kg/m^3 and 600 kg/m^3) had a less steep slope than mixtures with lower binder content (500 kg/m^3). In addition, by increasing the binder content, the two trend lines moved closer to each other, indicating a better improvement of LC-LWSCC with higher binder contents.

3.5.1.3. Impact Resistance

Table 3.3 and Figure 3.4 and Figure 3.5 show the results of the drop-weight test on both cylindrical and beam specimens. From the results, it can be seen that the impact resistance of LWSCC (for either cylinders or beams) exhibited the highest reductions, due to incorporating lightweight aggregates, compared to the other mechanical properties. For example, at 500 kg/m^3 binder content, a 75 kg/m^3 and 93 kg/m^3 reduction in the density of LC-LWSCC mixtures and LF-LWSCC mixtures, respectively, exhibited a decay in the impact resistance of cylindrical specimens by 28.1% and 21.1%, respectively. More pronounced decreases were recorded in the beam specimens, in which the reduction in the impact resistance reached up to 38.9% and 35% when the density reduced by 75 kg/m^3 in LC-LWSCC mixtures and 93 kg/m^3 in LF-LWSCC mixtures, respectively. These reductions in the impact resistance were attributed to the negative influence of either lightweight aggregates on the compressive and tensile strengths of LWSCC. The higher reductions in the impact resistance of beam specimens (compared to cylindrical specimens) can be related to the fact that the impact resistance under flexural loading is more affected by the tensile strength of concrete compared to the impact resistance of cylindrical specimens. And since the tensile strength was significantly affected by the inclusion of lightweight aggregates (as indicated by STS and FS), the impact resistance of beam specimens obviously experienced higher decays.

As seen in Figure 3.4 and Figure 3.5, similar to the other mechanical properties, LWSCC mixtures developed with LF exhibited better impact resistance for both cylindrical and beam specimens compared to that developed with LC (at comparable density). For example, at a density of almost 1850 kg/m^3, the impact resistance of cylindrical and beam specimens of LF-LWSCC mixture was 21.8% and 18.7%, respectively, higher than that of LC-LWSCC mixture (mixture 8 compared to mixture 14).



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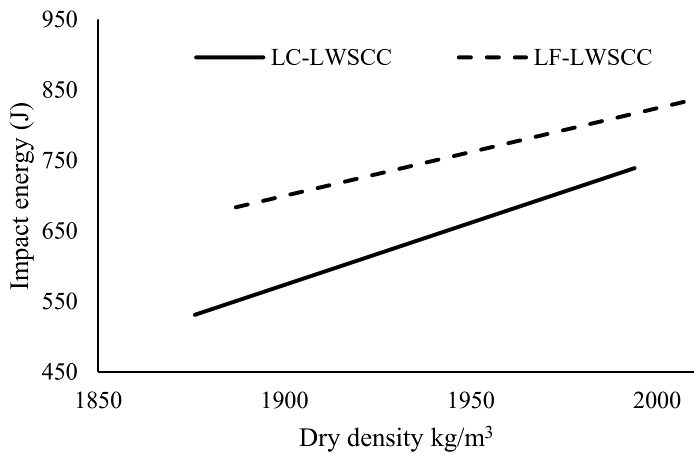

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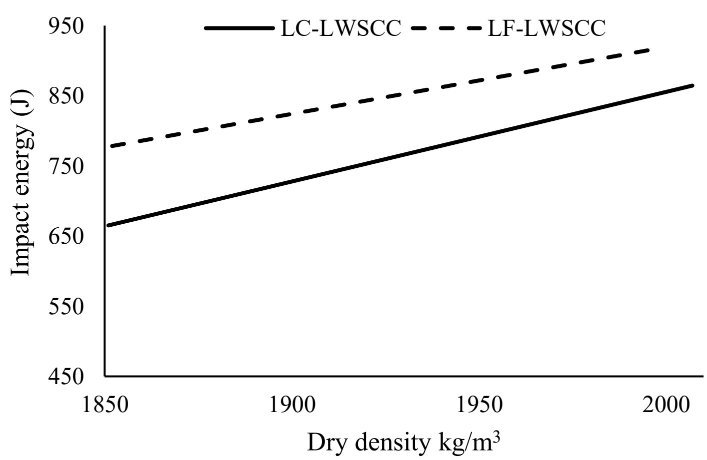
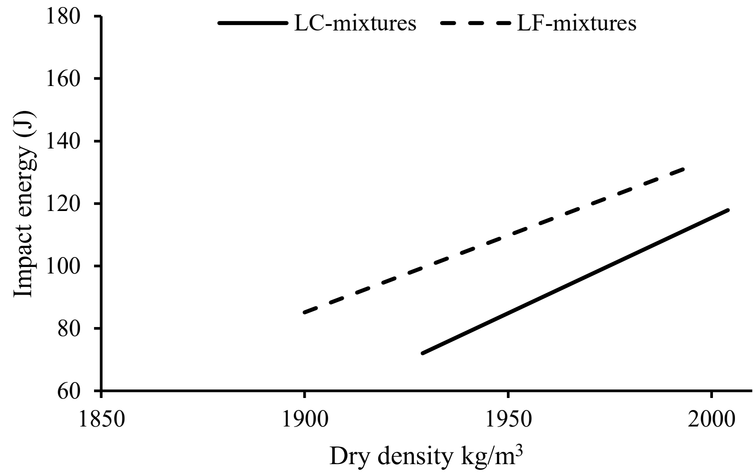
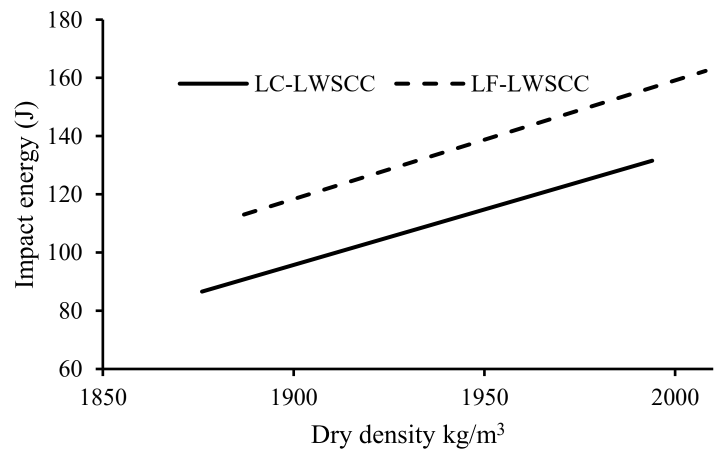


(c)

Figure 3.4 Relationship between impact energy for cylinder specimens and dry density of LC-LWSCC and LF-LWSCC at binder content of (a) 500 kg/m^3, (b) 550 kg/m^3, and (c) 600 kg/m^3



(a)



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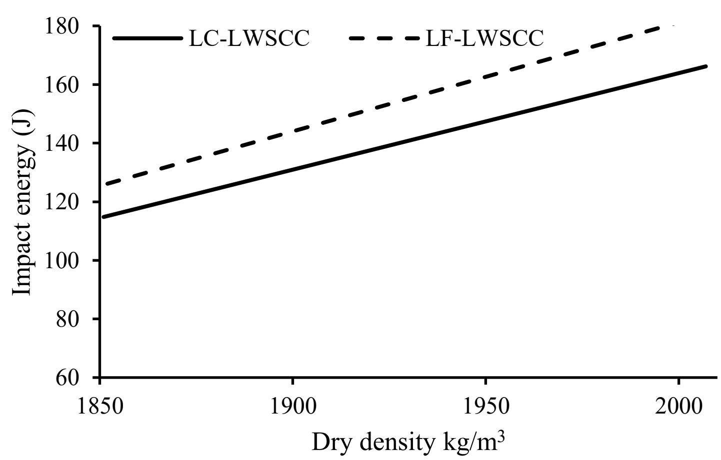

(c)

Figure 3.5 Relationship between impact energy for beam specimens and dry density of LC-LWSCC and LF-LWSCC at binder content of (a) 500 kg/m^3, (b) 550 kg/m^3, and (c) 600 kg/m^3

Increasing the binder content improved the compressive and tensile strengths of LWSCC, alleviating the decay in the impact resistance due to the inclusion of lightweight aggregates. These improvements, for example, reached up to 32.2% and 18.9% in the impact resistance of cylindrical specimens for LC-LWSCC (mixture 4 vs. mixture 7) and LF-LWSCC (mixture 12 vs. mixture 15), respectively, when the binder increased from 550 kg/m^3 to 600 kg/m^3. Higher improvements were exhibited by beam specimens (compared to cylindrical specimens) at higher binder contents, in which the increases in the impact resistance of beam specimens for LC-LWSCC and LF-LWSCC mixtures reached up to 40% and 30%, respectively.

3.5.1.4. LWSCC Mixtures Compared to NWSCC Mixtures

This section evaluates the reductions in the mechanical properties and impact resistance of concrete due to replacing normal-weight aggregates with lightweight aggregates (either fine or coarse) at similar aggregate volume (Table 3.1). Comparing the LC-LWSCC mixture to the NWSCC mixture (mixture 3 vs. mixture 17), it can be seen that as the density decreased from 2270 kg/m^3 to 1994 kg/m^3 (a 276 kg/m^3 reduction), the compressive strength, STS, FS, and ME decreased by 22.6%, 34.5%, 28.3%, 14.8%, respectively, while the impact resistance of cylindrical and beam specimens decreased by 41.3% and 50%, respectively (see Table 3.3). The same behavior was observed in mixture 13 (LF-LWSCC) compared to mixture 18 (NWSCC), in which decreasing the density from 2261 kg/m^3 to 2008 kg/m^3 (a 253 kg/m^3 reduction) was accompanied by a reduction in the compressive strength, STS, FS, and ME of up to 16%, 21.3%, 20.2%, and 8.2%, respectively. The impact resistance of cylindrical and beam specimens also decreased by 27.1% and 31.6%, respectively. This is attributed to the porous structure and the relatively low strength of the LC or LF compared to the normal-weight aggregate used in this study, which was crushed granite aggregate with high strength and hardness.

3.5.2. LWVC Mixtures

This section discusses the feasibility of using LC and LF in developing LWVC mixtures with density less than 1850 kg/m^3. All the obtained results for LWVC mixtures are shown in Table 3.3. As seen previously, at binder content of 500 kg/m^3, 550 kg/m^3, 600 kg/m^3, the minimum possible density reached was 1929 kg/m^3, 1876 kg/m^3, and 1851 kg/m^3, respectively, in LC-LWSCC mixtures, and 1900 kg/m^3, 1887 kg/m^3, and 1852 kg/m^3, respectively, in LF-LWSCC mixtures, with a compressive strength of at least 50 MPa. Further reductions were not possible due to the self-compactability restrictions (mainly passing ability in LC-LWSCC and segregation in LF-LWSCC). And since LWVC can be developed with acceptable workability and less risk of segregation (self-compactability is not a key factor), it was possible to use a higher volume of lightweight aggregate in LWVC to achieve further reductions in the mixture's density. Unlike the LWSCC mixtures, at a binder content of 500 kg/m^3 the density of LWVC reached 1826 kg/m^3 and achieved the target stability. Meanwhile, further reduction in the density (i.e., inclusion of higher volumes of lightweight aggregates) required higher binder content to compensate for the low strength of lightweight aggregates. The use of 550 kg/m^3 and 600 kg/m^3 binder contents successfully contributed to developing LC-LWVC mixtures with a density of 1810 kg/m^3 and 1784 kg/m^3, respectively, and a strength of 41.1 MPa and 41.9 MPa, respectively. Similar findings were obtained in LF-LWVC mixtures, in which at 550 kg/m^3 and 600 kg/m^3 binder contents, mixtures with a density that ranged from 1820 kg/m^3 to 1799 kg/m^3 and a compressive strength of around 42.5 MPa were developed.

3.5.3. Performance of Code-Based Equations in Predicting STS, FS, and ME

This section evaluates the performance of design code equations in predicting the STS, FS, and ME against the results obtained experimentally. The theoretical values for STS, FS, and ME were calculated based on equations proposed by the ACI-318 and CSA 2004, as follows:

1. ACI-318

$$FS_{th} = 0.62\,\lambda\,\sqrt{f_c'}$$

$$ME_{th} = {\gamma_c}^{1.5}\,0.043\;\sqrt{f_c'}$$

$$STS_{th} = 0.56\,\lambda\,\sqrt{f_c'}$$

Where λ is a modification factor to account for the use of lightweight aggregate; λ was taken as 0.85 in this study because the replacement was for either fine or coarse aggregates; γ_c is the density of concrete; and f_c' is the compressive strength.

2. CSA 2004

$$FS_{th} = 0.6\,\lambda\,\sqrt{f_c'}$$

$$ME_{th} = \left(\frac{\gamma_c}{2300}\right)^{1.5}\left(3300\,\sqrt{f_c'} + 6900\right)$$

Where λ was taken as 0.85 for lightweight concrete mixtures having a density ranging from 1850 kg/m^3 to 2150 kg/m^3 (which was LWSCC mixtures in this study) and 0.75 for lightweight concrete mixtures having a density of less than 1850 kg/m^3 (which was LWVC in this study).

Table 3.4 shows the ratios between the experimental values of FS and ME and those predicted by the ACI and CSA. From the results, it can be seen that the ACI and CSA yielded reasonable estimations for the FS and ME. The predicted values were within the range of 1 ± 0.20 of the experimental values, which can be an acceptable accuracy for code prediction, as stated by both ACI and CSA. In LWSCC mixtures, with a density higher than 1850 kg/m^3, the experimental-to-predicted ratios calculated based on ACI's equation ranged from 0.85 to 1.16 (average of 1.04) for FS values and from 0.89 to 1.01 (average of 0.95) for ME values. The CSA exhibited more conservative predictions for both FS and ME compared to the ACI's predictions, in which the experimental-to-predicted ratios ranged from 0.88 to 1.2 (average of 1.07) for FS values and from 0.99 to 1.16 (average of 1.07) for ME values. The difference between the ACI and CSA was seen more in LWVC mixtures, especially in the FS predictions, in which the experimental-to-predicted ratios ranged from 0.87 to 0.99 for the ACI and from 1.02 to 1.16 for the CSA. These findings could be attributed to the fact that the CSA, in the FS equation, proposed a varied modification factor (λ = 0.85 or 0.75) based on density, while the ACI proposed a constant value for λ (= 0.85) for replacing either coarse or fine aggregate, as previously explained in the equations.

Since the CSA does not propose an equation for estimating the STS, only the ACI prediction equations were evaluated. As seen in Table 3.4, the ACI appeared to overestimate the STS, in which the experimental-to-predicted ratios ranged from 1.01 to 0.71 (average of 0.84). The overestimation was also found to increase as the volume of lightweight aggregate increased (density decreased). The maximum overestimations were observed in the LWVC mixtures. This finding is attributed to the use of a constant modification factor of 0.85. Therefore, considering a varied modification factor based on density similar to that proposed by the CSA may help to enhance the predictability of the ACI's equations. However, the above evaluation is still based on limited tested mixtures. Therefore, it is recommended that further experimental investigations be conducted for more reliable assessment.

Table 3.4 Performance of code-based equations on predicting FS, ME, and STS of LWSCC and LWVC mixtures

Mix No.	Mixture designation	Experimental results/ ACI's predictions			Experimental results/ CSA's predictions	
		FS	ME	STS	FS	ME
LC-LWSCC						
1	LC-SCC-500-0.5	0.96	0.89	0.84	0.98	0.99
2	LC- SCC-500-0.8	0.85	0.92	0.71	0.88	1.03
3	LC- SCC-550-0.48	1.03	0.90	0.89	1.06	1.01
4	LC- SCC-550-1	0.95	0.95	0.76	0.98	1.06
5	LC- SCC-550-1.1	0.90	0.95	0.71	0.93	1.06
6	LC- SCC-600-0.44	1.15	0.92	0.95	1.18	1.04
7	LC- SCC-600-1	1.09	0.96	0.86	1.12	1.09
8	LC- SCC-600-1.25	1.06	1.01	0.79	1.09	1.13
LF-LWSCC						
9	LF- SCC-500-0.9	0.98	0.99	0.80	1.01	1.11
10	LF- SCC-500-1.25	1.06	0.94	0.94	1.10	1.06
11	LF- SCC-550-0.7	1.03	0.99	0.90	1.07	1.11
12	LF- SCC-550-1	1.09	0.94	0.94	1.12	1.06
13	LF- SCC-550-1.44	1.10	0.93	1.01	1.14	1.06
14	LF- SCC-600-0.6	1.10	1.01	0.91	1.14	1.16
15	LF- SCC-600-1	1.15	0.95	0.99	1.19	1.08
16	LF- SCC-600-1.67	1.16	0.95	1.01	1.20	1.09
LC-LWVC						
19	LC-VC-500-1.25	0.93	1.02	0.73	1.09	1.11
20	LC-VC-550-1.5	0.93	1.03	0.74	1.09	1.12
21	LC-VC-600-2	0.87	1.03	0.71	1.02	1.12
LF-LWVC						
22	LF-VC-500-0.6	0.99	1.05	0.80	1.16	1.14
23	LF-VC-550-0.5	0.97	1.02	0.78	1.13	1.11
24	LF-VC-600-0.4	0.95	1.00	0.71	1.10	1.09

3.6. Conclusions

This study investigated the mechanical properties and impact resistance of a number of optimized LWSCC and LWVC mixtures developed with either coarse or fine expanded slate lightweight aggregates. The study investigated the effect of using different lightweight aggregate types (fine or coarse), different aggregate volumes, and various binder contents (500 kg/m^3, 550 kg/m^3, and

600 kg/m^3). Two normal-weight SCC specimens were cast for comparison. From the results described in this study, the following conclusions can be drawn:

1. Using a w/b ratio of 0.4 and a ternary binder material system of 50% cement, 20% MK, and 30% FA contributed to developing LWSCC mixtures with density ranging from 1850 kg/m^3 to 2000 kg/m^3 and having a strength of at least 50 MPa.
2. Increasing the volume of either LF or LC reduced the mechanical properties and impact resistance of LWSCC mixtures. This reduction was more pronounced in the impact resistance of concrete, followed by the STS, FS, compressive strength, and then the ME. For example, in LC-LWSCC mixtures, a 75 kg/m^3 reduction in the density decreased the impact resistance, STS, FS, compressive strength, and ME by 28.1%, 19.7%, 16.1%, 9.3%, 6.6%, respectively.
3. Increasing the binder content alleviated the reductions in the mechanical properties and impact resistance due to the inclusion of LC or LF. It also allowed for further increases in the volume of lightweight aggregates, which can be used safely in LWSCC mixtures (further decrease in the mixture's density) while maintaining adequate stability and strength for multiple structural applications.
4. At a given mixture density, LWSCC mixtures developed with LF exhibited better mechanical properties and impact resistance compared to that developed with LC, at any binder content. This finding indicates the advantage of using LF over LC in the development of LWSCC mixtures.
5. In LWVC mixtures, where there are no restrictions to achieve self-compactability, it was possible to use higher volumes of either LC or LF (compared to LWSCC), reaching a

density of up to 1784 kg/m^3 and a strength of 41.9 MPa. This indicates promising potentials for the use of expanded slate aggregate in the construction industry.

6. At similar aggregate volume, replacing normal-weight aggregate by either LC or LF contributed to decreasing the density of mixtures but decayed the mechanical properties and impact resistance. For example, a 276 kg/m^3 reduction in the density of LC-LWSCC mixtures was accompanied by a decrease in the compressive strength, STS, FS, and ME of 22.6%, 34.5%, 28.3%, 14.8%, respectively, and a decrease in the impact resistance of cylindrical and beam specimens of 41.3% and 50%, respectively. Also, a 253 kg/m^3 reduction in the density of LF-LWSCC mixtures showed a reduction in the compressive strength, STS, FS, and ME of 16%, 21.3%, 20.2%, and 8.2%, respectively, and a reduction in the impact resistance of cylindrical and beam specimens of 23.7% and 31.6%, respectively.
7. The ACI and CSA code equations reasonably predicted the STS, FS, and ME of the developed mixtures within a range of 1 ± 0.20 of the experimental values. However, the CSA appeared to be more conservative than the ACI in predicting the FS, especially in mixtures with density less than 1850 kg/m^3.

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4. Abrasion and scaling resistance of lightweight SCC containing expanded slate aggregate

4.1. Abstract

This study evaluated the abrasion resistance for a number of lightweight self-consolidating concrete (LWSCC) incorporating coarse and fine lightweight expanded slate aggregates (LC or LF). The study also investigated the abrasion resistance before and after exposure to freezing and thawing cycles in the presence of de-icing salt. The investigated parameters included different volumes of LC and LF aggregates, different binder contents (500 kg/m^3, 550 kg/m^3, 600 kg/m^3), and different types of concrete (LWSCC, lightweight vibrated concrete, and normal-weight self-consolidating concrete). Increasing the percentage of expanded slate aggregate decreased the abrasion resistance. However, LF showed better performance compared to LC. Mixes with LF showed higher strength-per-weight ratio and higher abrasion and salt scaling resistance compared to mixes with LC. The results also showed that abraded samples (exposed to abrasion before salt scaling) had higher mass losses due to salt scaling (with an average of 26.8%) compared to non-abraded ones. Higher mass loss was also observed in mixes exposed to abrasion after the exposure to salt scaling. The average increases in the mass loss of salt scaled specimens compared to non-scaled ones were 26% and 43.3% in the rotating-cutter and sand-blasting abrasion tests, respectively.

4.2. Introduction

Lightweight concrete has been used widely in construction, where the reduction of the structure's self-weight in turn reduces concrete cross sections, steel reinforcement, and total construction costs (Babu et al., 2006, Kayali, 2008, Hassanpour et al., 2012). In offshore and marine environments, using lightweight concrete proved advantageous over normal concrete as the weight of the concrete is an important factor in designing floating marine structures (Babu et al., 2006, Bagon, and

Frondistou-Yannas, 1976, Chen, and Liu, 2004, Chen, and Liu 2013). Expanded slate and expanded clay aggregates are some of the main lightweight aggregates (LWAs) that have been used in offshore oil field structures. For example, expanded clay aggregate was used in the construction of the Heidrun offshore hull as a partial replacement for normal-weight coarse aggregate, achieving a concrete density of 1950 kg/m^3 and compressive strength of 60-70 MPa (Haug, and Fjeld, 1996). Also, in the Hibernia offshore oil field, 50% of the normal-weight coarse aggregate was replaced by expanded slate lightweight coarse aggregate, achieving semi-lightweight concrete with 2150 kg/m^3 and compressive strength of 79.9 MPa (Abouhussien et al., 2015). Compared to all other types of LWAs, expanded slate aggregate is believed to have higher quality and strength. However, the use of expanded slate aggregate in the development of lightweight concrete is not well evaluated and needs further investigation.

Developing self-consolidating concrete (SCC) using LWA aims to combine benefits of both SCC and lightweight concrete (Iqbal et al., 2015, Nepomuceno et al., 2018). However, designing LWSCC mixes is a challenge and requires more investigation. LWAs usually have high rates of water absorption (as a result of the high porosity), which negatively affects the flowability of SCC mixes (Madandoust et al., 2011). Moreover, LWAs tend to float over the paste matrix due to the large difference in density between LWAs and cement paste, increasing the challenge of optimizing the stability of SCC (Law Yim Wan et al., 2018). The use of supplementary cementing materials, however, proved to improve the mix viscosity and particle suspension and can play a significant role in designing successful LWSCC mixes (Abouhussien et al., 2015).

Wearing of the concrete surface is a common obstacle facing concrete serviceability and strength (Horszczaruk, 2005). Concrete in marine environments and offshore structures in cold regions is vulnerable to abrasion caused by the continuous impact of gravel or sand particles on the concrete surface (Chalee et al., 2010, Li et al., 2006). Drifting ice sheets in Arctic areas can also slide against the concrete surface with high friction force and cause abrasion (Ismail, and Hassan, 2019, Safiuddin, and Scott, 2015). Besides the damage caused by abrasion, repeated freezing and thawing cycles in the presence of salt (salt scaling) in marine cold regions induce more internal cracks and deteriorate the concrete surface (Panesar, and Shindman, 2012, Persson, 2003). This salt scaling deterioration is expected to reduce the resistance of concrete to abrasion and/or aggravate the damage caused by abrasion (Ismail, and Hassan, 2019). On the other hand, crushing the surface of concrete by abrasion negatively affects the paste matrix and makes the concrete more vulnerable to freezing and thawing attack (Ismail, and Hassan, 2019). Despite the importance of the interplay of abrasion and salt scaling damage in concrete (Zaki, 2019), this research is missing from the literature.

Increasing the compressive strength was shown to improve the abrasion resistance of normal-weight concrete (Siddique, 2003, Atiş, 2002). In addition, the use of high pozzolanic supplementary cementing materials such as silica fume and metakaolin (MK) proved to increase the strength, densify the concrete matrix, and improve the abrasion resistance (Rashad, 2013, Liu, 2007). However, some supplementary cementing materials, which usually used to improve the flowability of SCC, such as fly ash (FA), may not have an obvious effect on improving the abrasion resistance of concrete (Uysal, 2012, Cai et al., 2016). Katherine et al. (2018) investigated the effect of using different supplementary cementing materials, including FA, MK, silica fume, and slag, on the abrasion resistance of normal-weight SCC mixes. Five normal-weight SCC mixes with total binder content of 500 kg/m^3 were investigated. The abrasion resistance was estimated according to ASTM C 944 (rotating-cutter test) by determining the percent mass loss and the abraded depth of each specimen. It was concluded that the replacement of cement by 20% MK resulted in the highest abrasion resistance while using 30% FA had the lowest abrasion resistance among all other tested specimens.

Increasing the binder content and/or reducing the water-to-binder ratio enhanced the abrasion and salt scaling resistance of normal-weight concrete. Ghafoori et al., (2013) tested the abrasion resistance of normal-weight SCC and vibrated concrete mixes with different binder contents and water to binder ratios. The abrasion resistance of his specimens was assessed according to ASTM C779, 2012a (ball bearing procedure), in which the concrete specimen was abraded by 12 18-in diameter steel balls equally spaced inside a bearing plate. The abrasion resistance of the SCC and vibrated concrete mixes were evaluated by assessing the abrasion depth after 20 mins or when the abrasion depth reached 3 mm. It was found that the abrasion resistance increased, on average, by 22% when the binder content increased by 60 kg/m^3 and by 41%, on average, when the water-to-binder ratio reduced by 0.05.

The abrasion and salt scaling resistance of lightweight concrete, especially LWSCC containing expanded slate, are not well evaluated in the literature. However, because of the high porosity and relatively lower strength of LWAs compared to normal-weight aggregates, LWSCC is expected to have lower abrasion and salt scaling resistance compared to normal-weight concrete. Nevertheless, optimizing the mix proportions of LWSCC, together with the appropriate use of supplementary cementing materials, is expected to alleviate this reduction and improve the overall strength of the mix. This study aimed to optimize/develop some LWSCC mixes containing expanded slate aggregate (either coarse or fine) with high abrasion resistance. The interplay of abrasion and salt scaling damage in the developed mixes was also covered in this study. The variables were different volumes of lightweight expanded slate aggregate, binder contents (500 kg/m^3, 550 kg/m^3, and 600 kg/m^3), and the effect of concrete type (LWSCC, lightweight vibrated concrete (LWVC), and normal-weight self-consolidating concrete (NWSCC)).

4.3. Research Significance

Marine and offshore structures, especially those in Arctic areas, are typically exposed to abrasion under harsh environmental conditions. Such abrasion is mainly caused by continuous collisions between concrete surfaces and sand/gravel and/or drifting ice sheets. The effect of abrasion on concrete can be even worse if the structure is located in areas exposed to freezing and thawing. A review of the current literature shows that limited research has examined the abrasion resistance of lightweight concrete compared to normal-weight concrete. In addition, no available studies have investigated the interplay between abrasion and salt scaling in lightweight concrete. Moreover, despite the higher strength and durability of the expanded slate aggregate compared to all other LWAs (Omar, and Hassan, 2019), very few studies have investigated the behavior of this LWA in LWSCC. This study aimed to bridge these knowledge gaps by investigating the abrasion resistance of LWSCC containing expanded slate LWAs (either coarse or fine). The study also included the interplay of abrasion and salt scaling. Abrasion resistance of NWSCC mixes and LWVC mixes were also included in this study for comparison.

4.4. Experimental Program

4.4.1. Materials

Type GU Canadian Portland cement, MK, and FA conforming to ASTM C150, ASTM C618 type N, and ASTM C618 type F, respectively, were used as binder materials in all concrete mixes. Two types of expanded slate LWA were used: 1) LC with 1.53 specific gravity, 7.1% absorption, and 12.5 mm maximum aggregate size; 2) LF with 1.8 specific gravity, 10% absorption, and 4 mm maximum aggregate size. Normal-weight coarse aggregate (NC) with a maximum size of 10 mm and normal-weight fine aggregate (NF) were used. These normal-weight aggregates have 2.6 specific gravity and 1% absorption. The gradation curves for the LWAs and normal-weight aggregates used are presented in Figure 4.1. Glenium 7700 (conforming to ASTM C494 type F with a specific gravity of 1.2) was used in all SCC mixes as a high-range water-reducer admix to obtain the required level of flowability (700 ± 50 mm slump flow diameter).

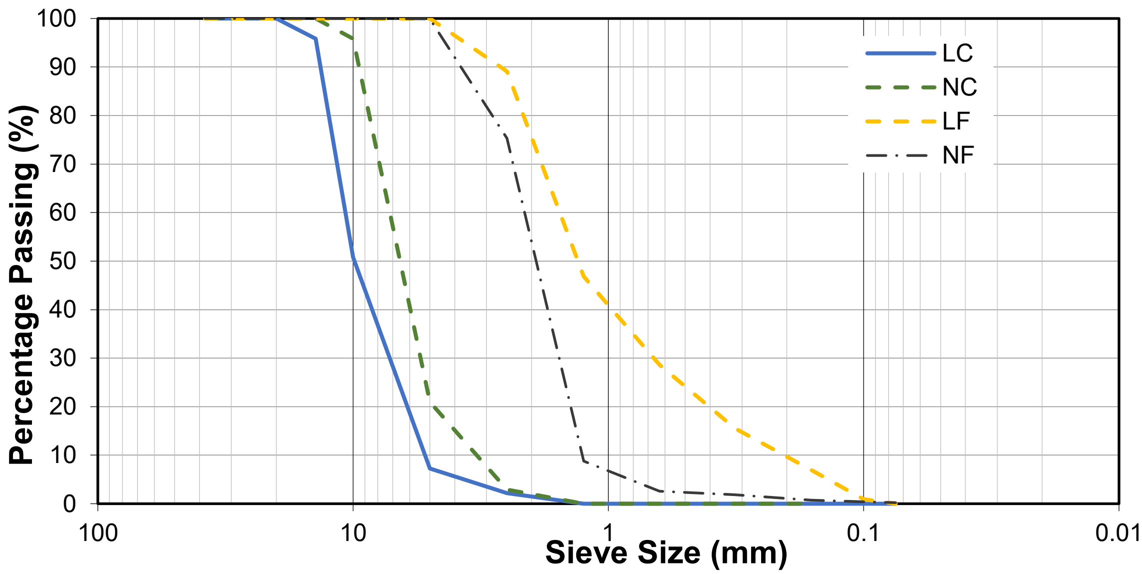


Figure 4.1 Fine and coarse normal-weight and LWAs gradation curves

4.4.2. Mix Composition

In this study, the authors aimed to develop SCC mixes using expanded slate lightweight coarse or fine aggregate (LC or LF) with densities ranging from 1850 kg/m^3 to 2000 kg/m^3. Using LWAs to develop SCC has several challenges. The fact that LWAs tend to float at the surface of concrete during mixing, because of their low density, becomes even more challenging in SCC mixes with such high flowability. In addition, the high absorption of LWAs makes it more difficult to optimize the mix proportions and negatively affects the flowability of the mix. Therefore, a trial mixes stage was conducted to optimize the mix proportions/composition in order to develop some target successful SCC mixes to be tested in this investigation. The investigated parameters in the trial mixes stage included 1) the volume of LWAs in the mix (by varying the weight of coarse to the weight of fine aggregate ratio of either LC or LF) to target minimum possible density with acceptable SCC fresh properties; 2) the use of different types and contents of supplementary cementing materials to target optimum strength, flowability, and viscosity of the mix; and 3) the water-to-binder ratio (w/b) to target the minimum possible w/b ratio.

The results of the trial mixes stage were as follows:

1. MK and FA were found to be the most effective supplementary cementing materials that improve the mix viscosity and flowability. The inclusion of MK improved the particle suspension and reduced the risk of segregation in LWSCC. In addition, MK played an effective role in increasing the compressive strength of the developed mixes. On the other hand, the use of FA was necessary to improve the mix flowability and reduce the amount of cement in such high binder content mixes.
2. A minimum binder content of 500 kg/m^3 and a minimum w/b ratio of 0.4 were required to achieve acceptable levels of flowability for all developed mixes without overdosing the high-range water-reducer admix. However, with 500 kg/m^3 binder content, it was only possible to use limited amount of LWA (to maintain acceptable SCC fresh properties), which obtained a minimum possible SCC density of 1900 kg/m^3. Therefore, the trial mixes stage included developing mixes with 550 kg/m^3 and 600 kg/m^3 binder contents to allow using higher volumes of LWA in order to further reduce the density of the developed SCC mixes and maintain acceptable fresh properties.

In total, sixteen LWSCC mixes, two NWSCC mixes, and six LWVC mixes were developed (see Table 4.1).

Table 4.1 Mix proportions for all mixtures

	Mix No.	Mix designation	Binder content (kg/m^3)			Water (kg/m^3)	Aggregate (kg/m^3)				Air %
			Cement	MK	FA		NC	LC	NF	LF	
LC-LWSCC	1	LC-SCC-500-0.5	250	100	150	200	-	434.7	869.4	-	3.3
	2	LC-SCC-500-0.8	250	100	150	200	-	545.2	681.6	-	3.4
	3	LC-SCC-550-0.48	275	110	165	220	-	398.9	831.1	-	3.0
	4	LC-SCC-550-1.1	275	110	165	220	-	578.5	525.9	-	3.5
	5	LC-SCC-550-1	275	110	165	220	-	559.0	559.0	-	3.5
	6	LC-SCC-600-0.44	300	120	180	240	-	354.9	806.6	-	3.2
	7	LC-SCC-600-1.25	300	120	180	240	-	564.0	451.2	-	3.4
	8	LC-SCC-600-1	300	120	180	240	-	522.3	522.3	-	3.3
LF-LWSCC	9	LF-SCC-500-1.25	250	100	150	200	746	-	-	596.8	3.6
	10	LF-SCC-500-0.9	250	100	150	200	617.3	-	-	685.9	3.4
	11	LF-SCC-550-1.44	275	110	165	220	748	-	-	526.8	3.3
	12	LF-SCC-550-0.7	275	110	165	220	492.5	-	-	703.7	3.6
	13	LF-SCC-550-1	275	110	165	220	617.3	-	-	617.3	3.7
	14	LF-SCC-600-1.67	300	120	180	240	755.9	-	-	452.6	3.8
	15	LF-SCC-600-0.6	300	120	180	240	413.7	-	-	689.6	3.2
	16	LF-SCC-600-1	300	120	180	240	576.7	-	-	576.7	3.4
NWSCC	17	NW-SCC-550-0.8	275	110	165	220	670.7	-	838.3	-	2.6
	18	NW-SCC-550-1	275	110	165	220	754.5	-	754.5	-	3.4
LC-LWVC	19	LC-VC-500-1.25	250	100	150	200	-	643.5	514.8	-	3.5
	20	LC-VC-550-1.5	275	110	165	220	-	637.8	425.2	-	3.7
	21	LC-VC-600-2	300	120	180	240	-	641.0	320.5	-	3.8
LF-LWVC	22	LF-VC-500-0.6	250	100	150	200	472.0	-	-	786.6	3.4
	23	LF-VC-550-0.5	275	110	165	220	388.0	-	-	776.1	3.2
	24	LF-VC-600-0.4	300	120	180	240	305.8	-	-	764.4	3.1

Table 4.2 summarizes the objective of selecting/developing each mix in this investigation. In general, the main strategy in developing the tested mixes was as follows:

1. To develop LWSCC mixes with minimum possible density while maintaining acceptable fresh properties and compressive strength higher than 40 MPa.
2. To develop LWSCC mixes with a density not exceeding 2000 kg/m^3 (representing semi-lightweight concrete) and having the highest possible strength.
3. To develop the above two mixes (minimum possible density LWSCC and highest strength LWSCC with a density not exceeding 2000 kg/m^3) using three binder contents: 500 kg/m^3 , 550 kg/m^3, and 600 kg/m^3. Increasing the binder content in SCC mixes is known to improve the flowability, passing ability, and particle suspension (AbdelAleem, and Hassan, 2018). And in the development of LWSCC, it is expected that the fresh properties (especially passing ability and segregation) would restrict increasing the percentage of LWA in the mix. Therefore, the main objective of investigating three binder contents in this investigation was to present the advantage of using higher binder contents in further reducing the mix density (by allowing higher percentages of LWA to be used safely in LWSCC while maintaining acceptable SCC fresh properties).
4. To develop LWSCC mixes using LC and LF to study the advantage/disadvantage of each aggregate type on the fresh properties, strength, abrasion, and scaling resistance of the developed mixes.
5. To develop LWSCC mixes with comparable coarse-to-fine aggregate ratio of 1 to study the scaling resistance of LWSCC (mixes 5, 8, 13, and 16).
6. To develop NWSCC mixes to be compared with LWSCC

7. To develop LWVC mixes (using both LC and LF) for comparison with LWSCC mixes. As mentioned above, in the development of LWSCC mixes, it is expected that the limits of acceptable SCC fresh properties would restrict increasing the percentage of LWAs in the mix and further reduce the mix density. Therefore, this investigation included developing LWVC to study how the absence of the fresh properties restrictions can allow further reduction in the mix density. In addition, the investigation also included LWVC to study the abrasion and scaling resistance of lightweight mixes with lower densities (compared to LWSCC mixes).

All mixes were designated according to the type of aggregate used (LC, LF, NW), type of concrete (SCC or VC), binder content, and the course-to-fine aggregate ratio (LC/NF, NC/LF, or NC/NF). For example, mix 1, which is designated as LC-SCC-500-0.5, is an SCC mix with a binder content of 500 kg/m^3 and LC/NF of 0.5. Also, mix 24, which is designated as LF-VC-600-0.4, is a VC mix with 600 kg/m^3 binder content and 0.4 NC/LF.

Table 4.2 Main strategy in developing the tested mixtures

	Mix No.	Binder content (kg/m^3)	Mix designation	Objective	Restrictions for adding additional LWA
LC-LWSCC	1	500	LC-SCC-500-0.5	To obtain maximum possible strength with density not exceeding 2000 kg/m^3	-
	2		LC-SCC-500-0.8	To obtain minimum possible density (SCC mix)	Exceeding this volume of LC resulted in unacceptable passing ability for LWSCC mix (L-box test ratio <0.8)
	3	550	LC-SCC-550-0.48	To obtain maximum possible strength with density not exceeding 2000 kg/m^3	-
	4		LC-SCC-550-1.1	To obtain minimum possible density (SCC mix)	Exceeding this volume of LC resulted in unacceptable passing ability for LWSCC mix (L-box test ratio <0.8)
	5		LC-SCC-550-1	To study the scaling resistance of LWSCC (at coarse-to-fine aggregate ratio = 1)	-
	6	600	LC-SCC-600-0.44	To obtain maximum possible strength with density not exceeding 2000 kg/m^3	-
	7		LC-SCC-600-1.25	To obtain minimum possible density (SCC mix)	Exceeding this volume of LC resulted in unacceptable passing ability for LWSCC mix (L-box test ratio <0.8)
	8		LC-SCC-600-1	To study the scaling resistance of LWSCC (at coarse-to-fine aggregate ratio = 1)	-
LF-LWSCC	9	500	LF-SCC-500-1.25	To obtain maximum possible strength with density not exceeding 2000 kg/m^3	-
	10		LF-SCC-500-0.9	To obtain minimum possible density (SCC mix)	Exceeding this volume of LF increased the risk of segregation of LF in the mix[a]
	11	550	LF-SCC-550-1.44	To obtain maximum possible strength with density not exceeding 2000 kg/m^3	-
	12		LF-SCC-550-0.7	To obtain minimum possible density (SCC mix)	Exceeding this volume of LF increased the risk of segregation of LF in the mix[a]
	13		LF-SCC-550-1	To study the scaling resistance of LWSCC (at coarse-to-fine aggregate ratio = 1)	-
	14	600	LF-SCC-600-1.67	To obtain maximum possible strength with density not exceeding 2000 kg/m^3	-
	15		LF-SCC-600-0.6	To obtain minimum possible density (SCC mix)	Exceeding this volume of LF increased the risk of segregation of LF in the mix[a]
	16		LF-SCC-600-1	To study the scaling resistance of LWSCC (at coarse-to-fine aggregate ratio = 1)	-
NWSCC	17	550	NW-SCC-550-0.8	To be compared with LC-LWSCC mixes (mix 3)	-
	18		NW-SCC-550-1	To be compared with LF-LWSCC mixes (mix 11)	-
LC-LWVC	19	500	LC-VC-500-1.25	To obtain the minimum possible density (to study how the absence of SCC fresh properties can further reduce the mix density) (VC mixes)	Achieving strength greater than 40 MPa
	20	550	LC-VC-550-1.5		
	21	600	LC-VC-600-2		
LF-LWVC	22	500	LF-VC-500-0.6		
	23	550	LF-VC-550-0.5		
	24	600	LF-VC-600-0.4		

Note: a*: segregation resistance was assessed by two methods: 1) cutting a concrete cylinder (100 mm diameter x 200 mm high) into four equal segments for each mix and obtaining the density of each segment; 2) splitting a concrete cylinder (100 mm diameter x 200 mm high) and examining the aggregate distribution; and 1 kg/m^3 = 0.06243 lb/ft^3

4.4.3. Fresh Properties and Compressive Strength Tests

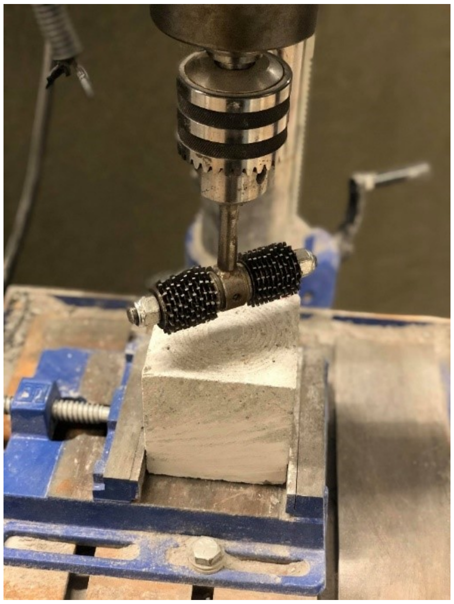
The fresh properties of the developed LWSCC mixes were assessed according to EFNARC 2005 guidelines. The flowability and deformability were determined using the slump flow test, while the viscosity was evaluated by T_{50} (time required to reach a 500 mm slump flow diameter) and V-funnel tests. On the other hand, the passing ability of the developed LWSCC mixes was determined using the L-box test. Since the investigated mixes in this study contained LWAs, the segregation resistance was assessed by two methods: 1) dividing a 100 mm diameter x 200 mm high concrete cylinder into 4 equal parts and then obtaining the density of each part. 2) splitting a 100 mm diameter x 200 mm high concrete cylinder and then examining the aggregate distribution in each half. The compressive strength test of the selected mixes was performed on three concrete cylinders having 100 mm diameter x 200 mm height, conforming to ASTM C39.

4.4.4. Abrasion Resistance Test

Two methods were used to evaluate the surface abrasion resistance of the selected concrete mixes:

1) Rotating-cutter method (according to ASTM C944): The test consists of subjecting a concrete cubic specimen (100 mm dimension) to mechanical abrasion. The abrasion is caused by blades attached to a spindle, which is installed in a press drill (figure 4.2a) and rotates on top of the concrete surface while applying a constant force of 98 N on the specimen. After the completion of the test, the specimen's surface is cleaned and the difference between the original weight of the specimen and the weight after the abrasion is measured to represent the abrasion resistance of concrete.
2) Sandblasting method (according to ASTM C418): A concrete specimen is subjected to silica sandblasting using a blasting nozzle from a height of 75 ± 2.5 mm for 1 minute inside a sandblasting cabinet (figure 4.2b). The sandblasting results in cavitation of the concrete

surface. The difference between the weight of the concrete before and after sandblasting represents the abrasion resistance of concrete specimens in the sandblasting method. In addition, the depth of the cavitation generated in the concrete is also measured as another indication of the abrasion resistance of concrete.



(a)

(b)

Figure 4.2 Abrasion test setups: a) rotating-cutter test and b) sandblasting test

4.4.5. Salt Scaling Test

The concrete resistance to scaling under freezing and thawing in the presence of salt was determined according to ASTM C672. The target from this test was to determine: 1) the surface scaling resistance of concrete; 2) the effect of abrasion on reducing the surface scaling resistance of concrete (specimens exposed to surface scaling after the exposure to abrasion); and 3) the effect of surface scaling on reducing the abrasion resistance of concrete (specimens exposed to abrasion after the exposure to surface scaling). The selected mixes to perform this test were mixes 5, 8, 13, and 16.

4.5. Discussion of Results

4.5.1. Assessment of the Developed Mixes

As seen in Table 4.2, in the development of minimum possible density LWSCC mixes with LC, the main restriction that hindered increasing the amount of LC (to further reduce the density) was the passing ability. On the other hand, in the development of minimum possible density LWSCC mixes with LF, the main restriction that hindered increasing the amount of LF was the increased risk of segregation of LF in the mix. Increasing the binder content in the mix (from 500 kg/m^3 to 600 kg/m$^{3)}$ showed a noticeable improvement in the stability and passing ability, which allowed further increase in the amount of LWA used (further reduction in the density). As seen in Table 4.3, by using 100 kg/m^3 extra binder (600 kg/m^3 compared to 500 kg/m$^{3)}$, not only was the density of the mix further reduced but the strength was enhanced. For example, in the development of minimum possible density LWSCC mixes with LF, increasing the binder content from 500 kg/m^3 to 600 kg/m^3 allowed further reduction in the mix density from 1900 kg/m^3 to 1852 kg/m^3 and increased the compressive strength by 8.9% (mix 10 compared to mix 15).

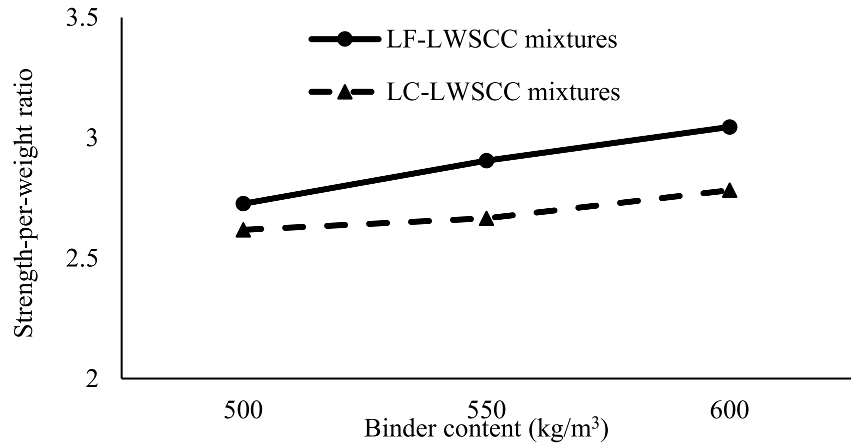
With regard to the development of maximum-strength LWSCC with density not exceeding 2000 kg/m^3, increasing the binder content from 500 kg/m^3 to 600 kg/m^3 not only improved the strength but also showed noticeable improvements in the fresh properties of the mix. For example, by using 100 kg/m^3 extra binder in the development of maximum-strength LWSCC (density not exceeding 2000 kg/m^3) with LC, the compressive strength of the mix increased by 6.5%, and both the passing ability (H2/H1) and flowability (T_{50} and V-funnel) improved (mix 1 compared to mix 6, see Table 4.3).

Figure 4.3 shows the strength-per-weight ratio for mixes with minimum possible density and mixes with maximum possible strength (density not exceeding 2000 kg/m^3). As seen from the figure, increasing the binder content increased the strength-per-weight ratio for all developed mixes. For example, in the mix with minimum possible density with LF, increasing the binder content from 500 kg/m^3 to 600 kg/m^3 increased the strength-per-weight ratio from 2.7 to 3.05. Figure 4.3 also indicates that the use of LF in LWSCC mixes exhibited higher strength-per-weight ratio (at all binder contents) compared to LC in both mixes with minimum possible density and mixes with maximum possible strength (density not exceeding 2000 kg/m^3).

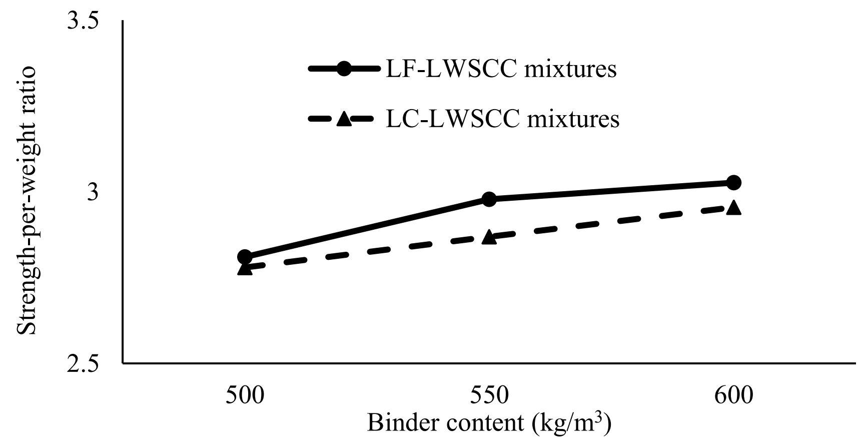
Table 4.3 Fresh properties of LWSCC and NWSCC mixes, abrasion resistance, compressive strength, and density of all tested mixes

	Mix no.	Mix designation	Mix objective[a]	L-box H2/H1	Slump T_{50} (sec)	V-funnel (sec)	Rotating-cutter test		Sandblasting test			f'_c (MPa)	Density (kg/m^3)
							M_r (gm)	M_r/D (x 10^3)	M_s (gm)	M_s/D (x 10^3)	Cavitation Depth (cm)	28-days	28-days
LC-LWSCC	1	LC-SCC-500-0.5	MS	0.88	2.18	12.0	11.6	5.79	3.14	1.57	1.00	55.7	2004
	2	LC-SCC-500-0.8	MD	0.80	2.58	17.6	15.0	7.78	4.68	2.43	1.37	50.5	1929
	3	LC-SCC-550-0.48	MS	0.90	1.95	10.6	10.5	5.27	2.76	1.38	0.86	57.2	1994
	4	LC-SCC-550-1.1	MD	0.81	2.52	17.2	15.4	8.21	4.70	2.51	1.50	50	1876
	5	LC-SCC-550-1	-	0.84	2.34	14.7	12.8	6.79	3.85	2.04	1.21	52.9	1884
	6	LC-SCC-600-0.44	MS	0.93	1.70	7.50	9.3	4.63	2.50	1.25	0.73	59.3	2007
	7	LC-SCC-600-1.25	MD	0.81	2.50	16.7	14.1	7.62	4.40	2.38	1.29	51.5	1851
	8	LC-SCC-600-1	-	0.88	2.07	10.7	10.3	5.47	2.73	1.45	0.92	57.5	1882
LF-LWSCC	9	LF-SCC-500-1.25	MS	0.82	2.44	16.1	10.1	5.07	2.88	1.44	0.89	56	1993
	10	LF-SCC-500-0.9	MD	0.87	2.20	12.5	13.8	7.26	3.86	2.03	1.19	51.8	1900
	11	LF-SCC-550-1.44	MS	0.84	2.36	15.25	9.1	4.53	2.45	1.22	0.74	59.8	2008
	12	LF-SCC-550-0.7	MD	0.91	1.80	8.90	11.5	6.25	2.97	1.64	0.93	55.5	1887
	13	LF-SCC-550-1	-	0.89	1.95	10.85	10.6	5.4	2.9	1.48	0.86	56.2	1962
	14	LF-SCC-600-1.67	MS	0.83	2.41	15.40	8.7	4.35	2.46	1.23	0.76	60.5	1999
	15	LF-SCC-600-0.6	MD	0.95	1.60	6.70	10.7	5.78	2.74	1.48	0.88	56.4	1852
	16	LF-SCC-600-1	-	0.92	1.78	8.20	9.1	4.63	2.62	1.34	0.99	59.6	1955
NW-SCC	17	NW-SCC-550-0.8	-	0.96	1.81	9.29	5.7	2.51	2.12	0.93	0.64	73.9	2270
	18	NW-SCC-550-1	-	0.86	2.20	12.70	6.0	2.65	2.04	0.90	0.67	71.2	2261
LC-LWVC	19	LC-VC-500-1.25	-	-	-	-	19.7	10.8	6.08	3.33	1.83	40.4	1826
	20	LC-VC-550-1.5	-	-	-	-	18.5	10.2	5.92	3.27	1.79	41.1	1810
	21	LC-VC-600-2	-	-	-	-	17.8	9.98	5.85	3.28	1.71	41.9	1784
LF-LWVC	22	LF-VC-500-0.6	-	-	-	-	17.8	9.71	5.27	2.87	1.63	41.3	1834
	23	LF-VC-550-0.5	-	-	-	-	16.3	8.96	4.46	2.45	1.57	42.1	1820
	24	LF-VC-600-0.4	-	-	-	-	15.3	8.50	4.18	2.32	1.49	42.9	1799

Note: a*: MS: mixes with maximum possible strength with density not exceeding 2000 kg/m^3 ; and MD: mixes with minimum possible density; 1 MPa = 0.145 ksi; 1 kg/m^3 = 0.06243 lb/ft^3; and 1 gm = 0.0022 lbs.



(a)



(b)

Figure 4.3 Strength-per-weight ratio for LWSCC tested mixes: a) mixes with lowest possible density, and b) mixes with maximum possible strength (density not exceeding 2000 kg/m3)

The flowability and viscosity of SCC are classified according to the European Guidelines for Self-Compacting Concrete to assess the suitability for different structural applications. Regarding the flowability of SCC mixes, three classes were proposed according to the slump flow diameter: SF1 (550-650 mm), SF2 (660-750 mm), and SF3 (760-850 mm). On the other hand, the concrete mix viscosity was classified based on the T_{50} and V-funnel times, where two classes were proposed: VS1/VF1 and VS2/VF2. VS1/VF1 class has T_{50} and V-funnel times less than or equal to 2 and 8 seconds, respectively, while the VS2/VF2 class has a T_{50} time greater than 2 seconds and V-funnel times ranging from 9 to 25 seconds. In this investigation, mixes 6, 12, 15, and 16 can be classified as SF2/VS1/VF1, which are characterized by good filling ability even with congested reinforcement and high self-leveling. While all other developed LWSCC mixes had a $T_{50} > 2$ seconds and/or V-funnel flow time ranging from 9 to 25 seconds, which can be classified as SF2/VS2/VF2. According to the European Guidelines, both classes are suitable for many applications such as slabs, columns, piles, walls, and ramps.

4.5.2. Abrasion Resistance

4.5.2.1. Effect of LWA Volume

Table 4.3 and Figure 4.4 show the results of mass loss due to rotating-cutter and sandblasting tests. The sand cavitation depth (abrasion depth) of the sandblasting test is also reported in Table 4.3 for all tested mixes. At any binder content, reducing the density of the mixes, by increasing the content of LWAs (LF or LC), results in increased mass loss due to abrasion. For example, looking at mix 2 compared to mix 1 (mixes with LC and similar binder content), a reduction in density of 3.7% resulted in increased mass loss of 29.3% and 49%, in both rotating-cutter and sandblasting tests, respectively. Similarly, by comparing mix 10 to mix 9 (mixes with LF and similar binder content), a 4.7% reduction in density resulted in a 36.6% and 34% increase in mass loss in both rotating-cutter and sandblasting tests, respectively. These results were also confirmed from the cavitation depth (D_s) in sandblasting tests. The reduction in abrasion resistance with increasing the volume of LWAs (decreasing the mix density) is related to the weak and porous structure of the LWA. The higher the content of LWA, the easier it was for the blades to abrade the surface of specimens in the rotating-cutter test and for the impulsiveness of sand in the sandblasting test in LWSCC specimens. In addition, increasing the content of LWA reduces the compressive strength of LWSCC, which negatively affects the abrasion resistance of concrete (Pyo et al. 2018). The results also indicated that the increase in the mass loss with the increase of LWA showed significantly higher values in the rotating-cutter test compared to the sandblasting test, in all tested mix (see Table 4.3). This may be related to the fact that in the rotating-cutter test, more surface area of LWA is exposed to the rotating-cutter blades compared to the sandblasting test, which affects a relatively smaller area. However, it should be noted that each test can be more representative of a particular case in real application. For example, the rotating-cutter test better simulates the deterioration of concrete surface under traffic loading on highways and bridges, while the sandblasting test simulates concrete subjected to water-borne abrasion (ASTM C944[28] and C418[37]).

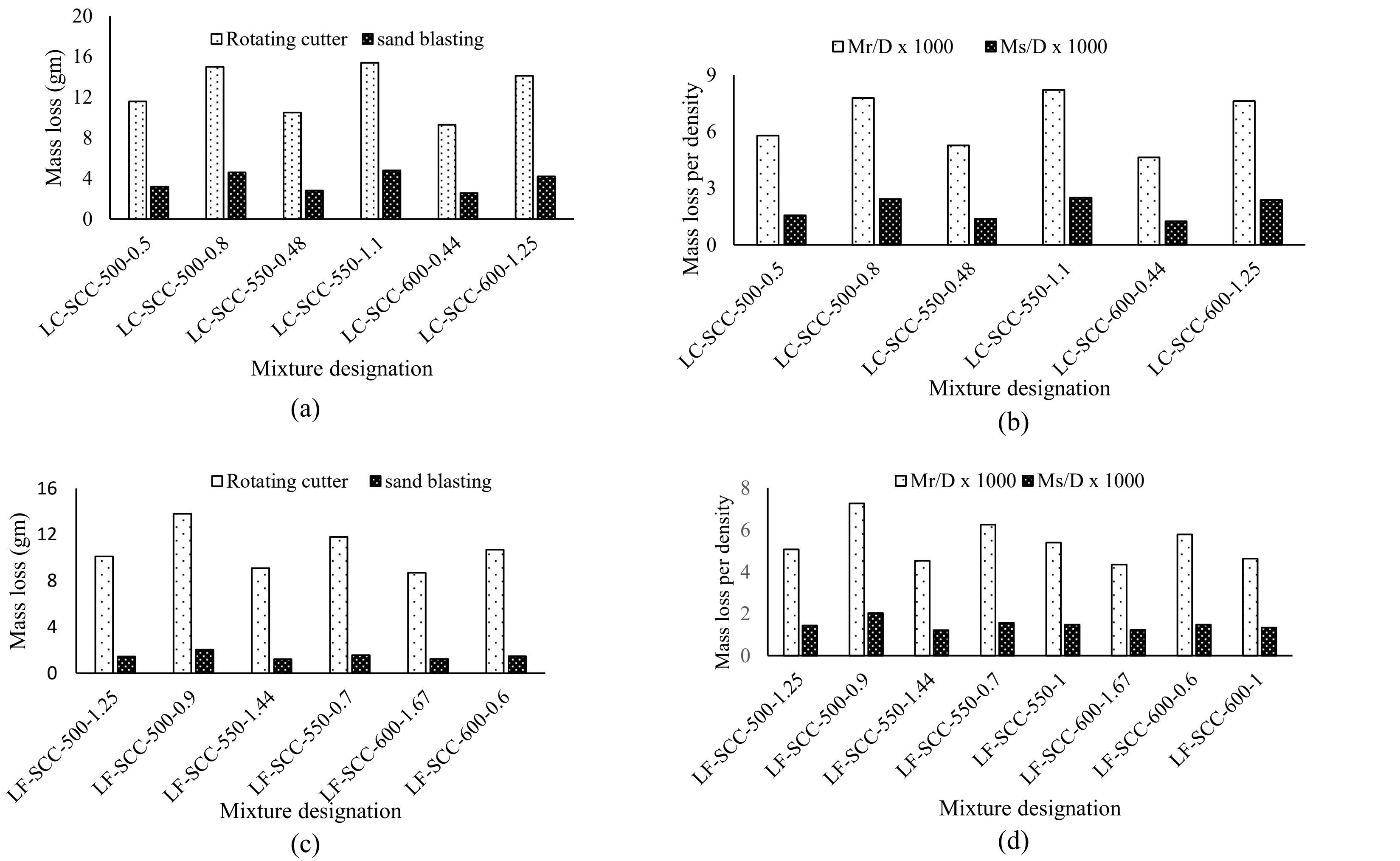


Figure 4.4 Effect of LWA volume on the abrasion resistance of LWSCC mixes: a) mass loss due to rotating-cutter and sandblasting tests for LC-LWSCC mixes, b) mass loss-per-density for rotating-cutter and sandblasting tests for LC-LWSCC mixes, c) mass loss due to rotating-cutter and sandblasting tests for LF-LWSCC mixes, d) mass loss-per-density for rotating-cutter and sandblasting tests for LF-LWSCC mixes

4.5.2.2. Effect of Binder Content

It can be seen from Table 4.3 that increasing the binder content from 550 kg/m^3 to 600 kg/m^3 (at comparable mix density) improved the abrasion resistance regardless of the type of concrete (LC- or LF-LWSCC). When comparing mix 5 (550 kg/m^3 binder content and 1884 kg/m^3 density) with mix 8 (600 kg/m^3 binder content and 1882 kg/m^3 density), it can be seen that mix 5 had 24.2% and 41% higher mass loss in rotating-cutter and sandblasting tests, respectively, compared to mix 8. Similar behavior was also noted in mixes with LF, when comparing mix 13 (550 kg/m^3 binder content and 1962 kg/m^3 density) with mix 16 (600 kg/m^3 binder content and 1955 kg/m^3 density). Increasing the binder content improves the stiffness of the paste matrix and enhance the bond strength between aggregates and cement paste, which improves the abrasion resistance.

4.5.2.3. Evaluation of Abrasion Resistance in Different Concrete Types

In order to evaluate the behavior of each concrete on abrasion resistance, the ratio between the mass loss and the density of the rotating-cutter (M_r/D) and sandblasting (M_s/D) tests were determined and recorded for each mix. From Table 4.3 and Figure 4.4, it can be seen that LF-LWSCC mixes had lower M_r/D and M_s/D compared to their counterpart LC-LWSCC mixes, indicating better abrasion performance for LF compared to LC. For example, when comparing mix 1 (500 kg/m^3 binder and 2004 kg/m^3 density) with mix 9 (similar binder content of 500 kg/m^3 and 1993 kg/m^3 density), it can be found that the M_r/D and M_s/D in mix 9 were 12.4% and 8.3%, respectively, less than mix 1. Similar behavior was also noted at higher binder contents (550 kg/m^3 and 600 $kg/m^{3)}$. Moreover, by looking at the average mass loss in all LWSCC mixes with LC (mixes 1-8) compared to all LWSCC mixes with LF (mixes 9-16), it can be found that the average mass loss in mixes with LF was 15.3% and 20% less than the average mass loss in mixes with LC, in rotating-cutter and sandblasting tests, respectively (see Table 4.3). This result may be related to the fact that LC is larger and contains more internal voids compared to LF (1.53 specific gravity for LC compared to 1.8 for LF, as mentioned above).

In order to evaluate the behavior of LWSCC compared to NWSCC, mix 3 was compared to mix 17 (at same binder content and coarse aggregate volume) and mix 11 was compared to mix 18 (at same binder content and fine aggregate volume) (Table 4.3). NWSCC, mix 17, exhibited 45.7% and 23.2% lower mass losses in rotating-cutter and sandblasting tests, respectively, compared to its counterpart LC-LWSCC (mix 3). Similarly, NWSCC, mix 18, showed 34.1% and 16.7% lower mass losses in rotating-cutter and sandblasting tests, respectively, compared to its counterpart LF-LWSCC mix (mix 11).

4.5.2.4. LWVC vs. LWSCC Mixes

As indicated previously, with the absence of fresh properties restriction of SCC (especially the passing ability and segregation resistance), it was possible to increase the volume of LWA in LWVC to develop mixes with further reductions in density. It should be noted that the compressive strength was the only restriction that hindered increasing the amount of LWA in the development of LWVC (all mixes should have a compressive strength greater than 40 MPa in this investigation). To evaluate the performance of LWVC, mixes 19, 20, and 21 were compared to mixes 2, 4, and 7, respectively (LWVC compared to LWSCC with similar binder contents and containing LC); and mixes 22, 23, and 24 were compared to mixes 10, 12, and 15, respectively (LWVC compared to LWSCC with similar binder contents and containing LF) (Table 4.3). It can be seen that with the absence of fresh properties restrictions of SCC, it was possible to develop minimum possible density LWVC mixes with a reduction in density (compared to those with minimum possible density in LWSCC mixes) ranging from 2.9%-5.3% accompanied by an increase in mass loss (reduction in abrasion resistance) ranging from 20.1%-43% in rotating-cutter tests and 26%-52.6% in sandblasting tests.

4.5.3. Scaling Resistance

4.5.3.1. Scaling Resistance of Non-Abraded Surfaces of LWSCC Mixes

Table 4.4 presents the scaling resistance of non-abraded surfaces of LWSCC mixes 5, 8, 13, and 16. Increasing the binder content from 550 kg/m^3 to 600 kg/m^3 improved the scaling resistance of LWSCC mixes. For example, in LC-LWSCC mixes, the mass loss due to salt scaling for non-abraded surfaces was reduced from 0.95 kg/m^2 to 0.78 kg/m^2 as the binder content increased from 550 kg/m^3 to 600 kg/m^3 (mix 5 compared to mix 8) (densities were 1884 kg/m^3 and 1882 kg/m^3, respectively). Similar result was observed in LF-LWSCC mixes. When comparing mixes 13 with 16 (densities of 1962 kg/m^3 and 1955 kg/m^3), it can be seen that the mass loss due to scaling was reduced by 12.3% when the binder content increased by 50 kg/m^3 in similar mix composition. This can be attributed to the fact that higher binder content provides stronger and denser matrix, which reduces the effect of saline solution penetrating the surface of concrete and disintegrating the cement paste.

The results also showed that LWSCC with LF exhibited higher salt scaling resistance than LWSCC mixes with LC. From Table 4.4, the average mass loss due to salt scaling for LWSCC with LF and LC were 0.61 kg/m^2 and 0.87 kg/m^2, respectively.

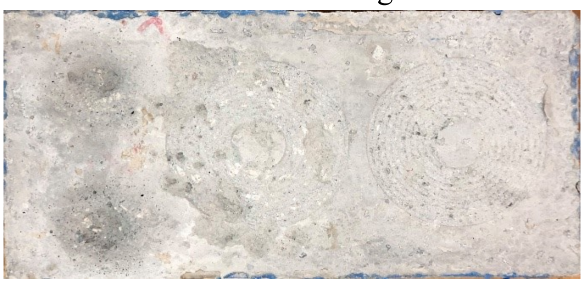
Figure 4.5 shows the surface condition of the salt scaled LWSCC specimens, classified as per ASTM C672. It can be seen that the two LC-LWSCC mixes had visual ratings of 5 (see Figure 4.5) as the LC appears on the surface. On the other hand, the surface of LF-LWSCC mixes had visual ratings of 3-4 (see Figure 4.5), indicating a higher scaling resistance of mixes with LF compared to mixes with LC. As mentioned before, LC has higher internal voids (lower density and higher absorption rate) compared to LF, which increases the chances of scaling the concrete surface.

Table 4.4 Salt scaling before and after abrasion mixes (mixes with coarse-to-fine aggregate ratio of 1)

Mix no.	Mix designation	Mass loss due to rotating-cutter test (gm)		Mass loss due to sandblasting test (gm)		Mass loss due to salt scaling test (kg/m^2)	
		Non-scaled surface	Scaled surface	Non-scaled surface	Scaled surface	Non-abraded surface	Abraded surface
5	LC-SCC-550-1	12.4	16.4	3.76	5.95	0.95	1.24
8	LC-SCC-600-1	10.3	13.0	2.98	4.13	0.78	0.97
13	LF-SCC-550-1	10.9	13.5	2.71	3.90	0.65	0.83
16	LF-SCC-600-1	9.4	11.3	2.65	3.17	0.57	0.7

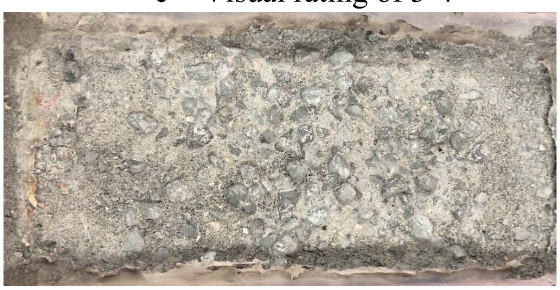
a- Visual rating of 5

b- Visual rating of 5

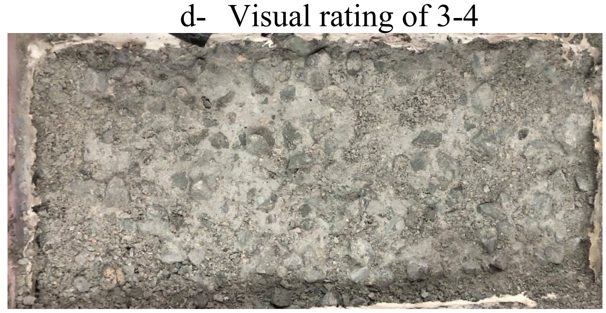


c- Visual rating of 3-4

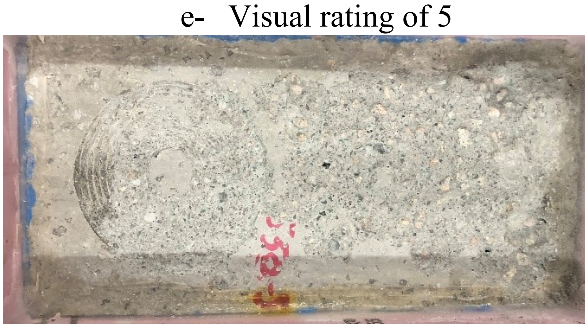
d- Visual rating of 3-4



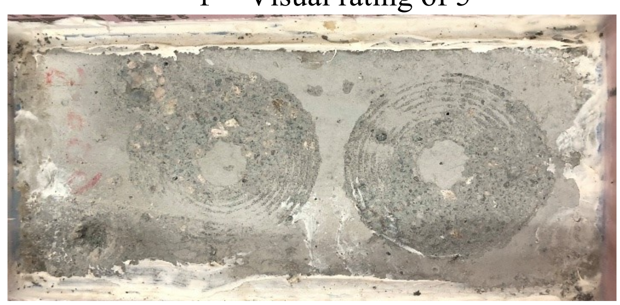
e- Visual rating of 5



f- Visual rating of 5



g- Visual rating of 3-4



h- Visual rating of 3-4

Figure 4.5 Combined effect of salt scaling and abrasion: scaling of abraded surfaces: a) LC-SCC-550-1, b) LC-SCC-600-1, c) LF-SCC-550-1, and d) LF-SCC-600-1; and abrasion of salt scaled surfaces: e) LC-SCC-550-1, f) LC-SCC-600-1, g) LF-SCC-550-1, and h) LF-SCC-600-1

4.5.3.2. Scaling Resistance of Abraded Surface of LWSCC Mixes

The mass loss from salt scaling test of the abraded specimens of mixes 5, 8, 13, and 16 followed the same trend as the non-abraded specimens (see Table 4.4). However, in all tested specimens, the abraded surfaces showed higher mass losses compared to non-abraded ones. The ratios of mass loss of abraded to non-abraded specimens were 1.31, 1.24, 1.28, and 1.23 for mixes 5, 8, 13, and 16, respectively, indicating an average of 26.8% extra mass loss in abraded specimens. This is related to the fact that abrasion due to rotating-cutter or sandblasting damages the concrete surface and makes it more permeable to the saline solution, which promotes more deterioration under the effect of salt scaling. The results also showed that the lowest scaling resistance occurred in the mix with lower binder content and LC (mix 5) (similar to the case of non-abraded specimens).

4.5.3.3. Abrasion Resistance of Scaled Surfaces

Table 4.4 presents the mass loss due to abrasion from rotating-cutter and sandblasting tests for the salt scaled specimens of mixes 5, 8, 13, and 16. In general, the abrasion resistance of the salt scaled specimens was lower than the non-scaled specimens, in all tested mixes. The mass loss ratios of the salt scaled specimens to non-scaled ones in the rotating-cutter test were 1.32, 1.26, 1.24, and 1.2 in mixes 5, 8, 13, and 16, respectively (an average of 26% higher mass loss), while these ratios were 1.58, 1.38, 1.44, and 1.28 (an average of 43.6% higher mass loss) in the sandblasting test. Increasing the binder content had a positive effect on the abrasion resistance of the salt scaled specimens. For example, the mass loss due to rotating-cutter and sandblasting tests was reduced by 20.7% and 30.6% when the binder content increased from 550 kg/m^3 to 600 kg/m^3 in mixes with LC (mix 8 compared to mix 5). It can also be noted from Table 4.4 that LF-LWSCC mixes had higher abrasion resistance for the salt scaled specimens compared to LC-LWSCC mixes. For example, the mass loss due to the rotating-cutter test of mix 8 (600 kg/m^3 binder and contains LC) was 13 gm, while this mass loss was 11.3 gm in mix 16 (600 kg/m^3 binder and contains LF). Similar behavior was observed in the sandblasting test and in mixes with 550 kg/m^3 binder content (mix 5 compared to mix 13).

4.6. Conclusion

This study evaluated the performance of LWSCC mixes, using either expanded slate coarse or fine aggregate, when subjected to abrasion. The study also evaluated the interplay of salt scaling (exposure to freezing and thawing with the presence of salt) and abrasion of some LWSCC mixes. The studied parameters were the percentage of LWAs in the mix, binder content (500 kg/m^3, 550 kg/m^3, and 600 kg/m^3), and concrete type (LWSCC, NWSCC, and LWVC). The following conclusions can be drawn from this study:

1. In the development of minimum possible density LWSCC mixes, the main restriction that hindered increasing the volume of LC in the mixes was the passing ability (H2/H1 < 0.8) while the main restriction for increasing the volume of LF was the increased risk of segregation. The minimum possible density of LWSCC mix with expanded slate aggregate was 1851 kg/m^3. This mix showed 51.5 MPa compressive strength at 28 days.
2. A minimum binder content of 500 kg/m^3 and minimum w/b ratio of 0.4 were required in the development of LWSCC mixes with expanded slate aggregates. However, with 500 kg/m^3 binder, it was only possible to develop mixes with minimum possible density of 1900 kg/m^3. Increasing the binder content to 600 kg/m^3 improved the mix stability and allowed to reach LWSCC with up to 1851 kg/m^3 density.
3. Increasing the percentage of expanded slate aggregate (reduction of the mix density) resulted in lower abrasion resistance due to the lower stiffness of this aggregate compared to normal-weight aggregate. For example, a 3.7% decrease in the mix density in mixes with

LC resulted in a 29.3% and 49% increase in mass loss, in both rotating-cutter and sandblasting tests, respectively. Similarly, a 4.7% reduction in density in mixes with LF resulted in a 36.6% and 34% increase in mass loss, in both rotating-cutter and sandblasting tests, respectively.

4. The rotating-cutter test showed significantly higher values of mass loss in all tested mixes compared to the sandblasting test. This was due to the nature of the rotating-cutter test, which exposed a higher surface area of LWAs to the rotating-cutter blades compared to the sandblasting test, which affected a relatively smaller area.
5. The use of LF in LWSCC exhibited higher strength-per-weight ratio (at all binder contents) compared to LC. In addition, mixes with LF exhibited higher abrasion resistance and higher salt scaling resistance than mixes with LC. This was due to the higher internal voids in larger expanded slate aggregates (LC) compared to finer ones (LF).
6. All abraded samples (exposed to abrasion before salt scaling) showed higher mass losses compared to non-abraded ones. Abraded specimens showed an average of 26.8% extra mass loss compared to non-abraded ones.
7. Higher mass loss was observed in mixes exposed to abrasion after the exposure to salt scaling. The average increase in the mass loss of salt scaled specimens compared to non-scaled ones were 26% and 43.6% in the rotating-cutter and sandblasting tests, respectively.
8. In the absence of fresh properties restrictions, it was possible to develop LWVC mixes with further reduction in the mix density (up to 1784 kg/m^3 compared to minimum of 1851 kg/m^3 in LWSCC). These mixes showed an increase in the mass loss (reduction in abrasion resistance) ranging from 20.1%-43% in rotating-cutter and 26%-52.6% in sandblasting tests, compared to their counterpart LWSCC mixes with minimum possible density.

4.7. Chapter References

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5. Summary and recommendation

5.1. Summary

An experimental program was established to study the stability, mechanical properties, impact, abrasion and scaling resistance of LWSCC developed with expanded slate fine and coarse aggregate. The development and properties of the developed LWSCC mixtures were discussed in chapters 2, 3 and 4. The study demonstrated in this thesis is divided into two stages. The first stage aims to optimize successful LWSCC mixtures incorporating either expanded slate fine or coarse aggregate. The second stage focuses on investigating the mechanical properties, impact, abrasion and scaling resistance of the optimized LWSCC mixtures. The following conclusions can be carried out from the study:

- In order to achieve acceptable fresh properties for LWSCC mixtures, a minimum binder content of 500 kg/m^3 and a minimum W/B ratio of 0.4 was required. In addition, a trinary binder content composed of 20% MK, 30% FA and 50% cement was necessary to enhance the stability and improved the flowability of mixtures without overdosing the amount of HRWRA. Moreover, using MK helped to achieve composite with adequate strengths for multiple structural applications, compensating the negative effect of the low strength of LWSCC.
- The minimum mixture density that could be achieved using LC was 1929 kg/m^3 (at a binder content of 500 kg/m^3), while the minimum mixture density that could be achieved using LF was 1900 kg/m^3 (at the same binder content). Optimizing LWSCC with LC aggregate depended on the passing ability of SCC mixture: increasing the LC aggregate in the mixture reduced the passing ability below the acceptable limit of SCC mixtures. On the other hand,

optimizing LWSCC with LF aggregate depended on the risk of segregation risk: further addition of LF aggregate results in a segregated mixture.

- Increasing the volume of LC aggregate in LWSCC mixture reduced the amount of HRWRA required to produce acceptable SCC fresh properties. However, the flowability and passing ability decreased and the risk of segregation increased when the volume of LC increased in LWSCC mixtures.
- Increasing the volume of LF in LWSCC mixtures enhanced the flowability, passing ability and viscosity of the mixture. However, increasing the volume of LF aggregate increased the risk of segregation in LWSCC mixtures.
- The mechanical performance of LWSCC was negatively affected by increasing the volume of LWA (either LC or LF), This was more pronounced in the results of the impact resistance and splitting tensile strength compared to the other mechanical properties.
- The durability of LWSCC mixtures against abrasive action was significantly decreased when the volume of LWA (LC or LF) increased in the mixture.
- Increasing the binder content allowed more LWA to be utilized in LWSCC mixture, achieving further reductions in the density with acceptable fresh properties and stability. The minimum density obtained at 600 kg/m^3 binder content was 1851 kg/m^3 in LWSCC mixtures with LC aggregate and 1850 kg/m^3 in LWSCC with LF aggregate.
- Increasing the binder content was found to improve the mechanical properties, impact, abrasion and scaling resistance of the LWSCC developed with either LC or LF aggregate.
- At comparable density, using LF appeared to be more effective alternative (compared to LC) to develop LWSCC with better properties in both fresh and hardened state.

- It was possible to develop LWVC mixtures with reduced density (up to 1784 kg/m^3) compared to minimum of 1851 kg/m^3 in LWSCC. These mixtures achieved a minimum compressive strength of 40.4 MPa and showed a significant reduction in the impact and abrasion resistance compared to their counterpart LWSCC mixtures with minimum possible density.

5.2. Recommendation for future research

1. Comparing the performance of other types of LWA to expanded slate aggregate, in terms of impact resistance and durability of LWSCC

2. Using advanced methods to test the impact resistance of LWSCC, to provide more accurate and consistent results (full scale LWSCC beams under impact loading, for example)

3. Conducting further investigation on the durability of LWSCC using expanded slate aggregate (chloride permeability test and/or water permeability test)

4. Using different techniques to compensate for the negative effects of using LWA in the mixture (inclusion of fibres, for example)

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