CONCRETE RESEARCH LETTERS
www.crl.issres.net
Vol. 6 (3) – Sept. 2015

Abrasion Resistance of Concrete – Design, Construction and Case Study

Benjamin D. Scott[1] and Md. Safiuddin[2,C]

[1] *Structural Designer, Tacoma Engineers, 570 Bryne Drive, Unit M, Barrie,*
ON L4N 9P6, CANADA
[2] *Professor, School of Architectural Studies and Angelo del Zotto School of Construction*
Management, George Brown College, 146 Kendal Avenue, Room C303, Toronto,
ON M5T 2T9, CANADA

Received: 20/07/2015 – Revised 15/08/2015 – Accepted 30/08/2015

Abstract

One of the most common forms of deterioration imposed on concrete structures is surface abrasion. This mechanical wearing can be a catalyst for other forms of deterioration such as cracking and corrosion of reinforcing steel. This paper is intended to discuss the key aspects of concrete abrasion. The common sources and mechanics of the abrasion of concrete have been identified. The effects of constituent materials, mix composition and strength, and construction practices on the abrasion resistance of concrete have been discussed. This paper also identifies the common test methods that are used to determine the abrasion resistance of concrete. Moreover, a case study on The Confederation Bridge in Canada, the longest concrete bridge in the world over ice covered water, has been presented in this paper, highlighting how engineers handled the abrasion issue of concrete in their designs. Finally, this paper illuminates several key points for future work on the abrasion resistance of concrete.

Keywords: Abrasion resistance, concrete, Confederation Bridge, constituent materials, construction practices, mix composition.

---

1. Introduction

While concrete is designed primarily to withstand structural loads it must also contend an array of 'environmental forces'. The environmental loading can include extreme temperatures [1], wetting and drying [2], freezing and thawing [3], sulphate attack [4], chloride-laden sea water ingress [5] and other forms of natural attack. Abrasion can also be a form of natural attacks on concrete. It mechanically induces friction and rubbing that cause significant damages on concrete surface [6]. In the worst case, abrasion can completely wear away concrete from structural elements.

Abrasion, as defined by ASTM, is the physical wear due to hard particles or protuberances forced against and moving along a solid interface [7]. Abrasion resistance, therefore, can be defined

---

[C] Corresponding author. Md. Safiuddin
Email: safiq@yahoo.com, Telephone: 1-416-415-5000, ext. 6692; Fax: 1-416-415-4515

as the ability of a surface to resist being worn away by rubbing or friction. The abrasion resistance of a concrete depends on its paste hardness, aggregate hardness and aggregate/paste bond [8]. In general, the concrete's hardness, which is related to its strength determines how strong it will be to resist abrasion [9].

This paper has explored several topics related to the abrasion of concrete. It identifies the sources of concrete abrasion, how industry and researchers test the abrasion resistance of concrete, and how various concrete materials and practices (for example, curing and surface finishing techniques) influence abrasion resistance. Among different concrete constituent materials, the effects of aggregates, supplementary cementitious materials, and reinforcing fibres have been highlighted. This paper also discusses the mechanics of concrete abrasion, and how the water-to-cementitious materials (w/cm) ratio and compressive strength of concrete influence its abrasion resistance. In addition, this paper presents a case study examining The Confederation Bridge in eastern Canada and discussing how its design, construction, and ongoing maintenance have been influenced by the abrasion of concrete.

2. Literature Review

2.1. Sources and mechanics of concrete abrasion

ACI defines four ways in which abrasion could be imposed on a concrete surface; wear on concrete floors due to human traffic, wear due to vehicular traffic with studded tires and snow tire chains, abrasive materials in water affecting hydraulic structures such as dam spillways, and high water velocities creating cavitation at the concrete surface [10]. The majority of studies undertaken have focused on the first three forms of abrasion, with a particular interest on hydraulic structures.

Liu *et al.* [11] outlined the chronological process of abrading concrete with water-borne sand. A virgin concrete surface is first subjected to pre-abrasion peeling, slowly revealing the substrate beneath; the severity of this impact is related to the flow velocity and hydraulic pressure of the water. Next, solid particle (such as water borne sand) impact on the surface results in interface cracking between the concrete constituents; the extent of this cracking is governed by the size of the impacting particles. Finally, the abrasive erosion action occurs on the concrete surface; this is related to the water-borne particle velocity and hardness, in addition to the bond strength of the concrete constituents.

The hydraulic wear down of concrete can be described as a cyclic process as illustrated in Figure 1. The top layer of paste is worn down, exposing the top layer aggregate which is eventually plucked away. The rate at which this process occurs is highly dependent on the energy of the abrading system. Kryzanowski *et al.* [12] further described this energy as the transport capacity of the water. At low energy levels or flow rates, the concrete surface is polished or milled due to rolling or sliding sediments. As the transport capacity increases, solid particles will begin to impact the concrete surface. With continuing energy increases, the size and quantity of impacting particles increase, making the effect of abrasion more severe.

Many researchers have investigated the abrasion resistance of concrete surfaces under different testing conditions. Liu *et al.* [13] implemented a test program to determine the effect that surface cracks would have on abrasive wear of concrete. They used three crack orientations (0, 45 and 90 degrees to the test direction) and four crack widths (0.5, 1, 2, and 3 mm) in their study. The specimens were evaluated based on ASTM C944, the rotating cutter test. The results from the testing showed that the abrasion resistance decreased as the crack width increased. The cracks permit significant shearing action at the crack boundary, thus increasing wear. The abrasion loss due to cracks 1 mm wide and over increased by 100% as compared to the surfaces without cracks. The crack orientation also affected the amount of abrasion loss on the specimen. Perpendicular cracks experienced the most loss as the amount of contact length was maximized for the abrading cutter to damage the surface. These results highlight the importance of structural geometry when considering the abrasive losses of concrete. Placing surface discontinuities perpendicular to the direction of abrasive wear will result in a more severely worn surface.

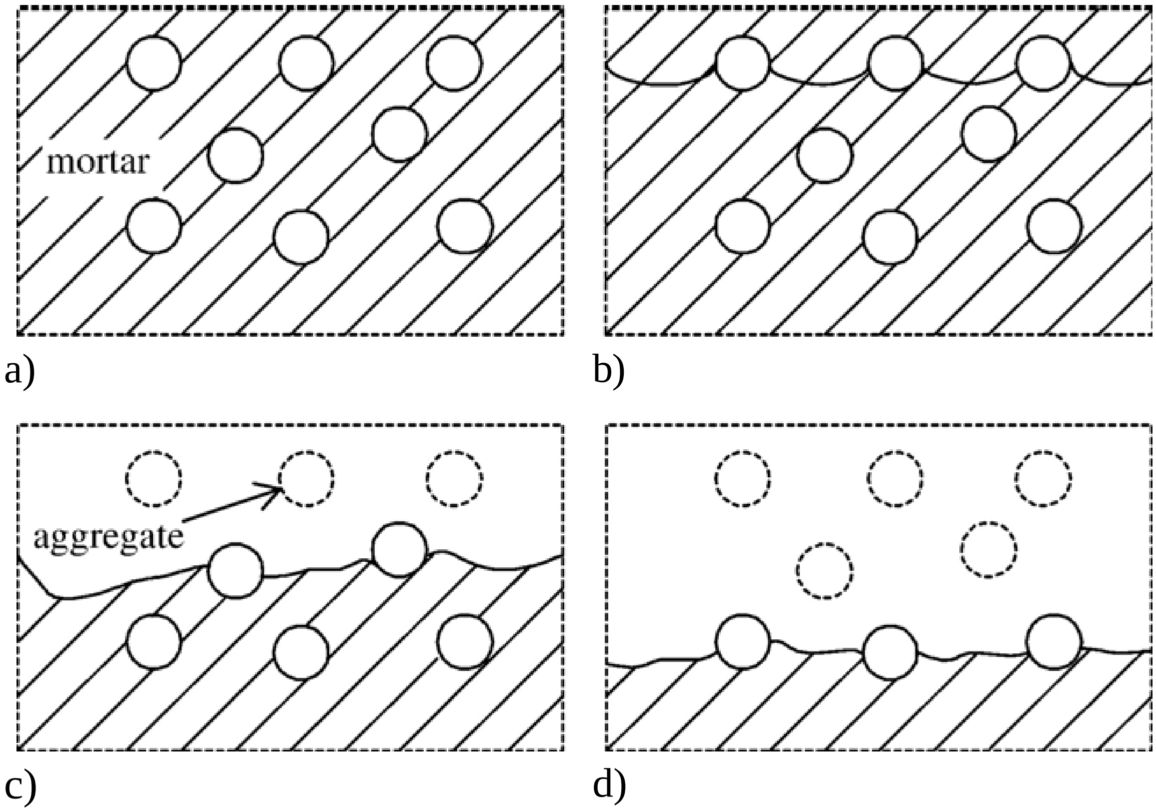

Figure 1. Sequence of abrading concrete surface in hydraulic structures [11] [a) initial stage, b) concrete surface under abrasive action, c) loss of coarse aggregate and mortar from concrete surface, d) further loss of coarse aggregate and mortar from concrete surface].

2.2. Testing of abrasion resistance

Several ASTM procedures have been developed to assess the abrasion resistance of concrete and reflect the forms at which this physical attack is manifested [7]. ASTM C418 test method simulates the action of waterborne abrasives and abrasives under traffic on concrete structures using sandblasting. ASTM C779 provides three test methods to determine the abrasion resistance of horizontal concrete surfaces in field and lab conditions. Method A of ASTM C779 simulates light to moderate foot traffic and light to medium tire wheeled traffic using a revolving disk machine. Method B of ASTM C779 uses the dressing wheel cutter and imposes high compressive impact loads to simulate the rolling, pounding and cutting action of steel wheels or the effect of studded tires. Method C of ASTM C779 makes the use of a ball bearing machine to create repeated dynamic loading through strong impacts, similar to that of rolling wheels.

ASTM C994 gives the rotating cutter method to determine the abrasion resistance of concrete or mortar surfaces; this method can be applied to both fabricated and cored specimens. It is primarily used in the quality control of concrete bridges subjected to traffic, and has a much more rapid abrasive effect than the aforementioned ASTM test methods. Reproducibility is difficult with this test. The last test method is ASTM C1138 (Underwater Method) that determines the abrasion resistance of concrete, replicating the abrasive action of water-borne particles on hydraulic structures.

The above-mentioned ASTM tests do not predict the length of service that can be expected from a specific concrete. However, they show the quality of the surface and effectively evaluate how different variables can affect the abrasion resistance of concrete. Table 1 summarizes which tests should be used to determine the abrasion resistance of concrete in different abrading conditions.

TABLE 1. APPLICATION OF TESTS FOR ABRASION RESISTANCE OF CONCRETE [1].

Type of Abrasion	ASTM C418	ASTM C779			ASTM C944	ASTM C1138
		Method A	Method B	Method C		
Foot traffic or light to medium tire-wheeled traffic etc.		X			X	
Forklift, heavy tire-wheeled traffic, automobile with chains, heavy steel wheeled traffic or studded tires			X	X	X	
Abrasive Erosion of waterborne particles on hydraulic structures	X					X

The testing standards introduced by ASTM have been widely adopted around the world for testing concrete abrasion resistance. A few other tests are conducted, as other countries have adopted their own standards for testing. In Canada for example, a common method is the Los Angeles test (also known as the rattler test) as prescribed in CSA A23.2-16A and 17A. This test targets the aggregate used in a concrete mix, citing that the aggregate properties generally give a good indication of the concrete abrasion performance. In this test, aggregate is placed in a steel drum with steel balls. The drum is agitated for a specified amount of time. The amount of mass loss from the test gives an indication of the abrasion resistance of the mix. For more accurate results, the standard recommends full testing of the concrete itself.

2.3. Effects of constituent materials on abrasion resistance of concrete

2.3.1. Aggregates

Laplante *et al.* [14] tested four different types of concrete coarse aggregate as a portion of a large testing program and compared the resulting abrasion resistance with the abrasion resistance of respective concrete. The types of coarse aggregate used were granite, limestone, dolomitic limestone and trap rock. The abrasion loss of each aggregate was determined using Los Angeles (LA) abrasion loss test and the concrete mixes were tested based on ASTM C779. Their test results showed that limestone experienced the most loss, with granite and trap rock experiencing the least loss (refer to Figure 2). They also observed that the abrasive losses of the concrete mixes reflected the aggregate strength, with the softer rocks experiencing much more abrasive wear than the harder granite and trap rock. The researchers concluded that aggregate type is the most significant factor influencing the abrasion resistance of concrete.

The effects of aggregate hardness were also investigated by Kiliç *et al.* [15]. Five different types of crushed coarse aggregate namely gabbro, basalt, quartzite, limestone and sandstone were evaluated. The compressive strength and LA abrasion loss were determined for each rock type. They observed a strong correlation between aggregate hardness and abrasion resistance, where the softer, weaker aggregates suffered greater abrasion loss than stronger aggregate. In higher compressive strengths, concrete crushed before the compressive strength of the rock was reached. In these situations, the strength of the cement paste was the limiting factor for the strength of concrete.

Dhir *et al.* [16] carried out a test program that investigated the effect of maximum aggregate size on abrasion resistance. Four maximum aggregate sizes were tested; 5, 10, 20 and 40 mm, with compression strength remaining constant for each. Their test results showed that the abrasion depth decreased as the coarse aggregate size increased. The researcher reported that the 40 mm aggregate sample experienced more severe dynamic loading resulting in higher abrasive losses than 10 and 20 mm aggregates.

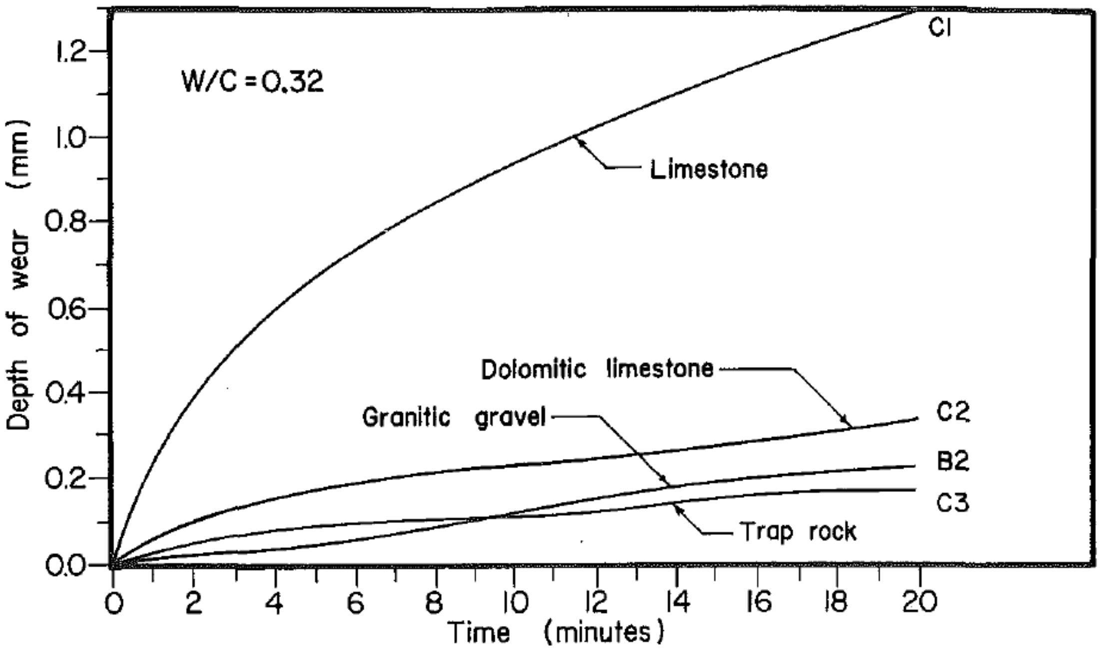

Figure 2. Abrasive wear of concrete with various aggregate types [14] (C1, C2, C3, and B2 refer to the different types of aggregate as indicated).

Liu *et al.* [11] also incorporated maximum aggregate size into their testing program. Three maximum aggregate sizes of 5, 13 and 25 mm were incorporated into the concrete mixes with low and high compressive strengths (approximately 25 and 90 MPa, respectively). For the low-strength concretes, the increase in the maximum aggregate size increased abrasion resistance. The researchers explained that larger aggregates reduced the percentage of surface area for the weaker cement paste to cover, thus making better bond and reducing the amount of aggregates to be removed by abrasive actions. Also, larger aggregates required more energy to dislodge when low-strength concrete was subjected to abrasive attack. In high strength concrete, no such correlation was apparent with aggregate sizes.

Some efforts have been placed into examining newer aggregate types such as recycled concrete aggregate. Evangelista and de Brito [17] investigated the abrasion resistance of concrete incorporating fine recycled concrete aggregate and compared their results with concrete including natural or virgin fines. They cast concretes using fine recycled concrete aggregate at the 30% and 100% replacement levels of regular fines. Their test results showed that the abrasion resistance of concrete improved with a 5% and 30% reduction in abrasion loss for the 30% and 100% replacement of regular fines, respectively. The authors stated that this was due to the better bond between cement paste coarse aggregate.

Konin and Kouadio [18] tested the abrasion resistance of concrete where the coarse aggregate was either entirely recycled concrete or natural. Concrete specimen size was 65mm × 65mm × 60 mm prisms for abrasion testing. Figure 3 shows a plot comparing the modulus of elasticity with the abrasion loss for natural aggregate and recycled aggregate concretes. The recycled aggregate concrete performed much better than the natural aggregate concrete in resisting abrasion. The researcher explained that the primary reason for the improved abrasion resistance of recycled aggregate concrete was the improved bond between aggregate and cement matrix.

2.3.2. Supplementary cementitious materials

Laplante *et al.* [14] compared the abrasion resistance concrete mixes with no supplementary cementitious material and 7.5% silica fume replacement by weight. The concretes were produced with the same amount of binder materials and using two types of coarse aggregate. Including silica fume helped to reduce the abrasion loss experienced in the concrete. However, the researchers identified that silica fume had a less significant contribution to abrasion resistance, citing aggregate type and w/cm ratio having greater influence. ASTM's guide entitled "Significance of Tests and Properties of Concrete and Concrete-Making Materials" including "Abrasion Resistance" gives reference to the work of Laplante *et al.* [14], citing the inclusion of silica fume increases compressive strength, and thus improves the abrasion resistance of concrete [7].

Naik *et al.* [19] investigated the effects of substituting Class C fly ash on the abrasion resistance of concrete mixes. The researchers selected five levels of cement replacement, ranging from 15% to 70%. The abrasion tests were performed at 28, 91 and 365 days. The abrasive resistance was comparable for the replacement levels of 15% and 30%. Above these levels, the concretes did not perform well with good abrasion resistance. These results have been confirmed in other studies [7, 20].

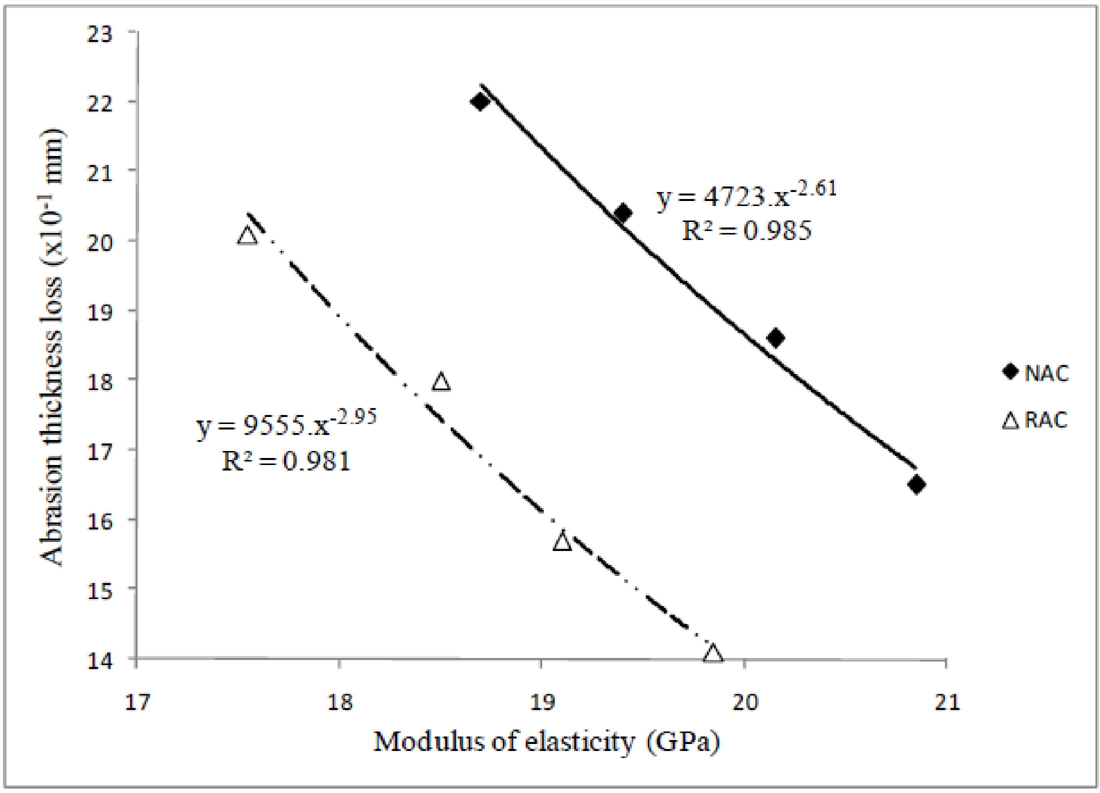

Figure 3. Abrasion loss versus modulus of elasticity for natural and recycled concrete aggregates [18] (NAC: normal aggregate concrete, RAC: recycled aggregate concrete).

2.3.3. Reinforcing fibres

Fibres are a commonly selected material when designing high performance concrete (HPC). Horszczaruk [21] carried out extensive tests to compare the abrasion resistance of HPC with that of high performance fibre reinforced concrete (HPFRC). Polypropylene and two sizes of steel fibres were used in his study. The abrasion resistance was evaluated using ASTM C1138 – Underwater Method. The results showed that the polypropylene fibres provided the greatest amount of improvement; the small steel fibres also provided improvement while the large steel fibres having no effect. The abrasive test tended to cut or pull out the steel fibres from the cement matrix. Conversely, the polypropylene fibres offered higher adhesion to the cement matrix and formed a more compact, stronger structure. An interesting physical development was observed during the testing; termed by the researcher as a ‘shadow zone’. In this situation, the exposed fibre would shield the concrete from abrasion as seen in Figure 4. This phenomenon was most apparent with fibres oriented perpendicular to the concrete surface. Parallel fibres would not provide the same resistance.

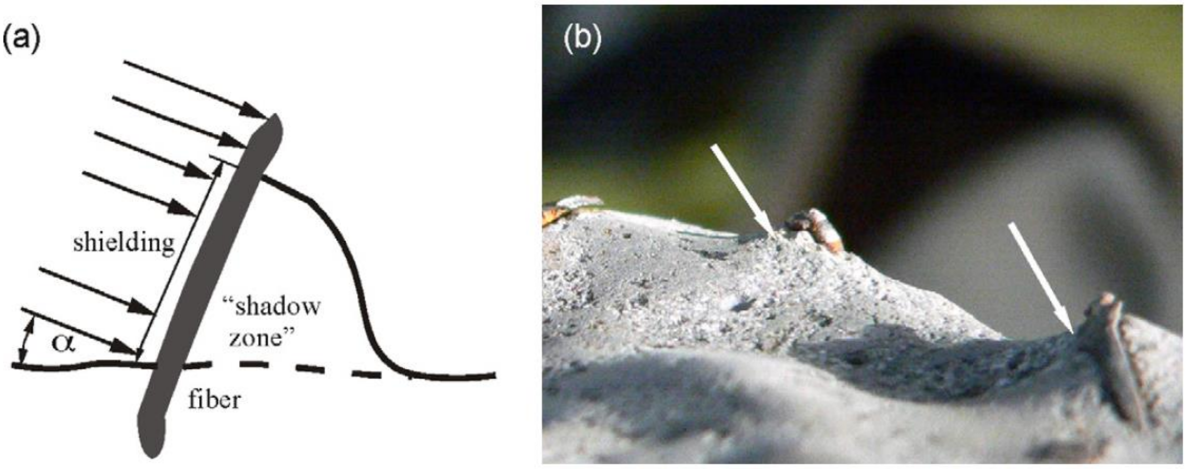

Figure 4. Shadow zone formed with steel fibres shielding concrete [21].

The performance of steel fibre reinforced concrete was also tested by Cheng *et al.* [22]. The researchers examined silica fume concrete at several w/cm ratios, and with the inclusion of 0.5% and 1.0% steel fibres. They found that the inclusion of steel fibres when the w/cm ratio was high did not enhance the abrasion resistance. However, when testing concrete mixes with lower w/cm ratios, the researchers found that after long-term curing, the inclusion of the fibres provided marginal improvement to the abrasion resistance. This work reinforces the findings of Horszczaruk [21], as the inclusion of steel fibres to a mix had resulted in little to no positive effect on the abrasion resistance of concrete.

Advances in ultra-high performance concrete (UHPC) has resulted in expanded applications and increased limits of reinforced concrete as a material. Sbia *et al.* [23] studied the optimization of UHPC with nano- and micro-scale fibres. One of the evaluation metrics was comparing the abrasion resistance of UHPC mixes. The researchers used ASTM C944 to test the concretes. While the inclusion of the nano- and micro-scale fibres did improve the abrasion performance, there was no distinct correlation between the percent inclusion of the reinforcing particles and resulting mass loss. The researchers concluded that the inclusion of nano- and micro-scale fibres do not have significant impact on the abrasion resistance of UHPC.

2.4. Effects of mix composition and strength on abrasion resistance of concrete

2.4.1. Water-to-cementitious materials (w/cm) ratio

Many researchers investigated the abrasion resistance of concrete by varying the w/cm ratio in their test program [14] [16]. Liu et al. [11] tested concretes with four different w/cm ratios, ranging from 0.26 to 0.50. As the w/cm ratio decreased, the observed abrasion resistance increased. This is because the concretes with lower w/cm ratios had lower porosity, better bond and increased compressive strength. Figure 5 shows surfaces of two different concretes that were prepared with the w/cm ratios of 0.28 and 0.36, and later exposed to three hours of abrading after proper curing. More interfacial cracks and deeper paste wear can be observed on the concrete sample with 0.36

w/cm ratio (right). The concrete sample with 0.28 w/cm ratio (left) had a denser and stronger cement matrix, and thus had experienced lower abrasion loss. The abrasion loss was 45% higher on the concrete sample with the higher w/cm ratio of 0.36.

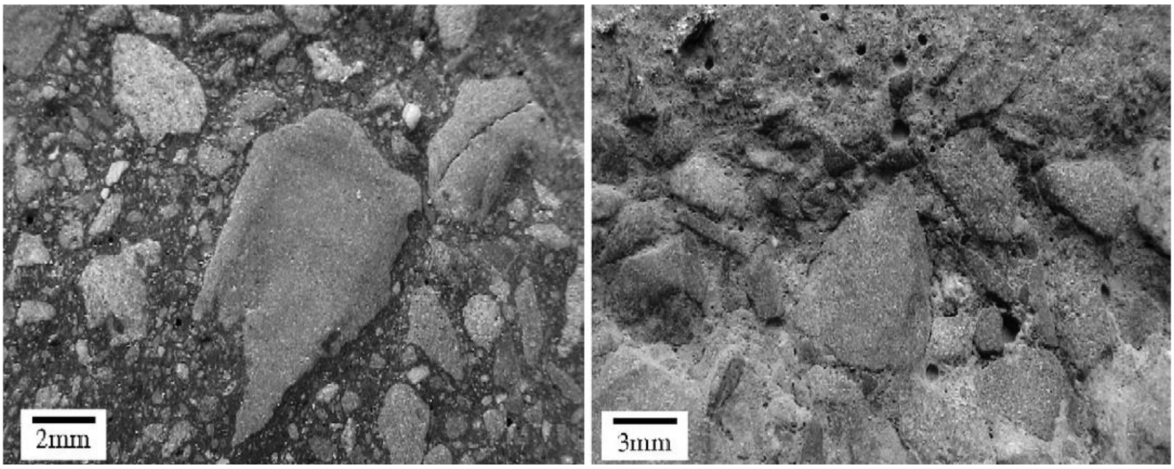

Figure 5. Abraded surface of concretes with varying w/cm ratios - 0.28 (left) and 0.36 (right) [11].

2.4.2. Compressive strength versus abrasion resistance

Many researchers agree that there is a general trend between abrasion resistance and compressive strength, where increasing the strength of concrete reduces the effects of abrasion [11] [16] [24]. This dependence appears to follow a slightly asymptotic relationship, where the largest improvement in abrasion resistance is evident with relatively low increase in compressive strength. At compressive strengths beyond 60 MPa, the performance gain of concrete with regard to abrasion resistance is not significant.

2.5. Concrete practices

Liu *et al.* [13] identified an important aspect of concrete abrasion resistance; they reported that it is a surface property as opposed to a bulk property. While compressive strength, a bulk property, is a good primary indicator of how well a concrete will resist abrasion, the quality of the surface-layer or cover concrete (covercrete) becomes crucial in determining abrasive wear resistance. How a concrete surface is cured and finished should be considered for its abrasion resistance.

Kevern *et al.* [25] tested the abrasion resistance of concrete under six different curing regimes. The types of curing evaluated were air curing, moist curing under plastic for 7 and 28 days, soybean oil curing, white pigment curing, and curing with non-film evaporation retardant. The moist cured specimens performed the best with the least abrasive losses, where the moisture trapped by the plastic sheet helped to densify the concrete surface. The air cured specimens experienced the most abrasive losses from the concrete surface.

Dhir *et al.* [16] focused on the duration of moist curing and its effects on abrasion resistance. The concrete specimens fabricated from of the same mix were moist cured for 1, 4, 7, and 28 days. The abrasion test results showed that the abrasion resistance increased with the longer duration of moist curing. The abrasion resistance of concretes from 7-day curing was 100% better than that of the concretes under 1-day moist curing. These results have been replicated and ASTM recommends 5-7 days of moist curing for concrete that will undergo abrasive attack [7].

Sadegzadeh *et al.* [26] conducted an extensive test program analysing the surface microstructure of concrete and how it is influenced by surface finishing techniques. Three types of finishing were used; hand, power and repeated power finishing. The researchers compared abrasion loss and also determined the pore volume on the surface and middle layers of the concrete. The surface treatments applied brought excess mix water to the concrete surface that was eventually evaporated. As a result, the local w/c ratio and pore volume decreased, thus increasing the hardness of the outermost millimetres of the concrete. The repeated power finishing drastically improved the micro-hardness of the cement matrix, resulting in abrasion resistance improvement of nearly 3 times over hand-finished specimens. ASTM confirms these findings and recommends some sort of surface finishing, with emphasis placed on power finishing.

2.6. Summary

From the research discussed, providing abrasion resistant concrete is possible by considering a combination of several factors. Sound, hard aggregates should be selected along with other constituent materials that would result in a dense, robust concrete. Having high strength and low w/cm is critical for concrete to resist stresses imposed by abrasion. Above all, moist curing and a finishing regime to maximize surface hardness of the concrete are paramount for maximizing abrasion resistance, regardless of the concrete constituents. The performance of concrete against abrading can be determined using a suitable test method given by ASTM.

3. Case Study – The Confederation Bridge

Canada’s Confederation Bridge spans thirteen kilometres across Northumberland Strait, linking mainland Canada to Prince Edward Island. It is the longest bridge spanning over ice-covered water in the world. This climate posed a unique challenge for the engineers; the challenge was how to design a 100-year structure to resist the abrasive forces of the ice floes each year. This case study will focus on how abrasion influenced the design of the bridge piers, the type of concrete used to make the structure, and what is currently being done to monitor the health of the piers.

3.1. Ice shield design

Sea ice is present in Northumberland Strait, the body of water that The Confederation Bridge spans, between December and March of each year. The ice floes can have an average thickness of 2.3 m and may reach a maximum depth of 2.5 m. Depending on the season, the bridge piers may see 3000-4000 km of ice each winter. The designers needed to avoid having an ice-keel, where ice would compress and impose significant dynamic loads on the bridge [27]. A typical cross-section of the Confederation Bridge pier can be seen in Figure 6.

The pier shaft maintains consistent cross-sectional shape down from the bridge deck but fans out sharply 4m above the waterline to form a conical ice shield. The ice shield is angled at 52° in order for the ice to ride up the sides of the pier and break under its own weight. While this design significantly reduces the severity of the ice forces imposed on the structure, the engineers would still need a durable, abrasive resistant concrete mix to withstand the floes over the duration of the bridge’s life.

The abrasive wear on the ice piers is further compounded by the presence of freeze-thaw attack. The concrete exposed to this environment has performed poorly [29]. As the freeze-thaw attacks weaken the surface layers of the concrete, the material is prone to deeper abrasive wear. For example, concrete structures in Norway had experienced as much as 50 mm of abrasive wear due to ice over 20 years [30]. Engineers would need to develop a unique high performance concrete to combat the severe environment present in the Northumberland Strait.

3.2. Mix design

A number of measures were taken by the engineers to ensure that a durable concrete was put in place. A high strength, high performance concrete mix was selected. The local aggregate available in Prince Edward Island, red sandstone, was deemed to be too weak for this application [27]. Special aggregates were imported to the construction site to meet the mix requirements. This aggregate had a rough, irregular surface intended to improve the strength of bond with the cement paste. Fly ash and silica fume were incorporated in the mix to increase the strength of concrete and densify the cement matrix. Finally, a water reducing admixture was added to reduce the mix's w/cm ratio. The compressive strength of the concrete mix used in The Confederation Bridge was 95 MPa.

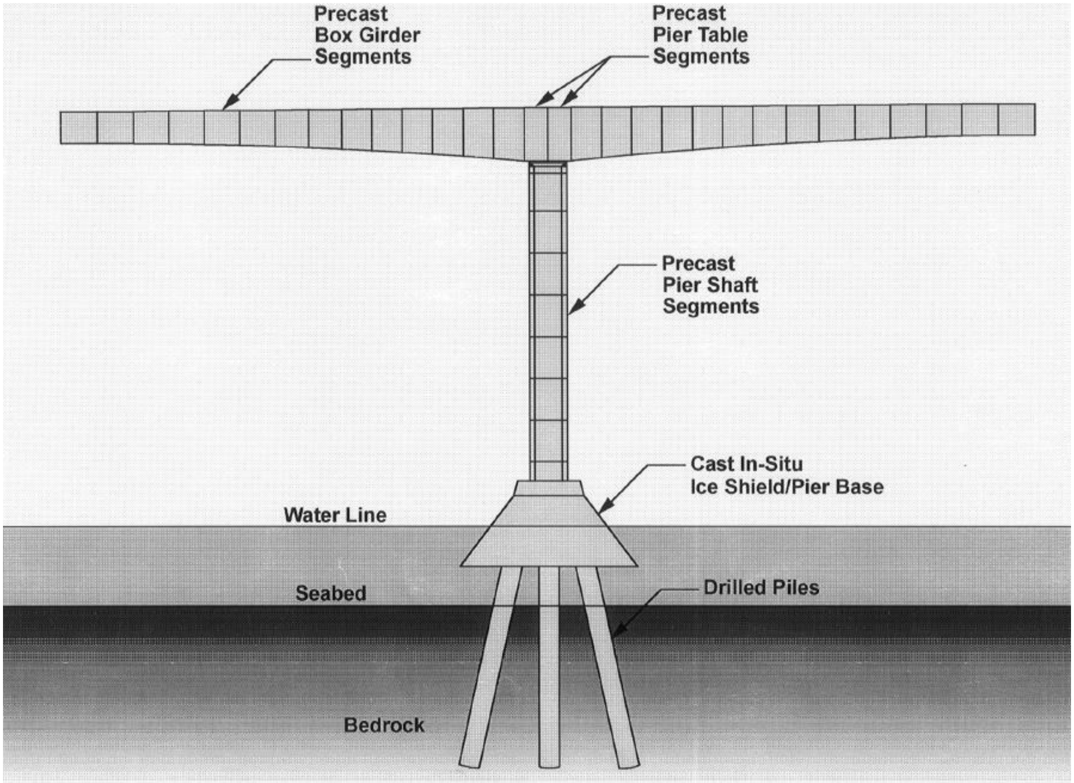

Figure 6. Typical elevation view of The Confederation Bridge pier and deck [28].

3.3. *Monitoring*

The Confederation Bridge is currently under the operation and maintenance of Straight Crossing Development. Maintaining the bridge is an ongoing process and one of these operations is to closely monitor the ice shield abrasion. This section summarizes what measures are being taken to gauge how the bridge is performing to resist the abrasion caused by ice floes.

3.3.1. Ice abrasion assessment

In 2007, a study was published summarizing five years of data collection on two ice shield piers of The Confederation Bridge [31]. The purpose of this research was to investigate the surface characteristics of the piers and determine the rate of abrasion loss. Each year, silicon moulds were cast for both piers considering a small area of each pier as seen in Figure 7. This figure (close-up view) shows that the surface layer of concrete had been abraded away, leaving coarse aggregates 'proud' of the surface. Through the moulding process, three dimensional plaster replicas of the in-situ concrete surface were produced for both piers. To maintain consistency from year-to-year, major aggregate surface defects were used as a reference point for each subsequent cast.

A precise measuring technique was used to determine the abrasion loss from the ice shield piers. Five individual aggregates were selected and the vertical distance from the top of aggregate to cement paste was recorded. The process was repeated for each subsequent year. Any changes to the depth of cement paste or height of aggregate would show the occurrence of abrasion. The average abrasion rate was found to be 0.31 mm/year. The researcher found that abrasion tended to replicate a cyclic process where the majority of wear would alternate between the aggregates and paste.

Figure 7. Area of ice shield pier used to create silicon mould; normal view (left), close-up view (right); (the white residues borders the area where the mould was cast) [31].

The visual observation of the cast surfaces showed that the 31% of the aggregates visible at the start of the study had been removed due to abrasion. Using this rate, it was estimated that 13 years of exposure would remove an entire layer of aggregate [31]. Overall, the ice shield piers are performing well. The abrasive wear is present but it is occurring at a slow and steady rate. The Confederation Bridge is a standout example of how thoughtful design, manufacture, and maintenance can minimize the effects of abrasive wear, resulting in a durable, robust concrete structure.

4. Future Work

Understanding the mechanics of abrasion is crucial to mitigate its harmful effects on concrete. Since abrasion is a common deterioration mechanism for concrete, more research must be carried out to understand the correlation between the magnitude of abrasive force and the severity of abrasion.

The performance of concrete significantly depends on its microstructural characteristics. On the other hand, the mix composition of concrete greatly influence its microstructural characteristics. Therefore, comprehensive research must be conducted to investigate how the mix composition and microstructural characteristics of concrete affect its abrasion resistance.

The abrasion resistance of concrete is affected by its surrounding environmental conditions, since they may weaken the concrete. The effects of different environmental factors are complex due to their variable nature. More research is needed to comprehend the damaging mechanisms of different environmental factors and how their detrimental effects can be minimized to improve the abrasion resistance of concrete.

5. Conclusions

Abrasion can be manifested on concrete in many forms and severities. Providing a concrete with high abrasion resistance relies on a variety of factors. The materials selected have a large influence on the resistance level, as does the mix composition, strength gain, and construction practices. From examples like The Confederation Bridge, it can be seen that proper design and materials selection can significantly improve a concrete's ability to handle the wear and tear of abrasion. Although many studies have been carried out on the abrasion resistance of concrete, more research is required to understand the mechanics of abrasion and how it is linked with the mix composition and microstructural characteristics of concrete. It is also important to comprehend how the different environmental factors affect the abrasion resistance of concrete.

Acknowledgements

The authors would like to thank Donald McGinn, P. Eng., Director of Engineering and Maintenance at The Confederation Bridge, for his generosity in supplying photos and reports concerning the abrasion monitoring of the ice shields.

References

[1] Ghani, U.; Sabbir, F.; and Khan, K. M., (2006) Effect of Temperature on Different Properties of Concrete, Proceedings of the 31st Conference on Our World in Concrete and Structures, Singapore.

[2] Medeiros, M. H. F.; Gobbi, A.; Réus, G. C.; and Helene, P., (2013) Reinforced Concrete in Marine Environment: Effect of Wetting and Drying Cycles, Height and Positioning in Relation to the Sea Shore, Construction and Building Materials, Vol. 44, pp. 452-457.

[3] Janssen, D. J.; and Snyder, M. K., (1994) Resistance of Concrete to Freezing and Thawing, Report No. SHRP-C-391, Strategic Highway Research Program, National Research Council, Washington, USA.

[4] Clifton, J. R.; Frohnsdorff, G.; and Ferraris, C., (1999) Standards for Evaluating the Susceptibility of Cement-based Materials to External Sulfate Attack, Materials Science of Concrete – Sulfate Attack Mechanisms, American Ceramic Society, Ohio, USA.

[5] Lee, N. P.; and Chisholm, D. H., (2005), Durability of Reinforced Concrete Structures under Marine Exposure in New Zealand, BRANZ Study Report SR 145, BRANZ Ltd., Judgeford, New Zealand.

[6] Portland Cement Association (PCA), (2002) Types and Causes of Concrete Deterioration, Concrete Information, PCA R&D Serial No. 2617, PCA, Illinois, USA.

[7] Bakke, K. J., (2006) Abrasion Resistance, Significance of Tests and Properties of Concrete and Concrete-Making Materials, ASTM STP 169D, Bridgeport, pp. 184-193.

[8] Papenfus, N., (2003) Applying Concrete Technology to Abrasion Resistance, Proceedings of the 7th International Conference on Concrete Block Paving, Sun City, South Africa.

[9] Yazici, Ş.; Sezer, G. İ., (2007), Abrasion Resistance Estimation of High Strength Concrete, Journal of Engineering Sciences, Vol. 13, No. 1, pp. 1-6.

[10] American Concrete Institute (ACI), (2008) Guide to Durable Concrete, ACI, Michigan, USA.

[11] Liu, Y.-W.; Yen, T.; and Hsu, T.-H., (2005) Abrasion Erosion of Concrete by Water-borne Sand, Cement and Concrete Research, pp. 1814-1820.

[12] Kryžanowski, A; Mikoš, M.; Šušteršic, J.; and Planinc, I., (2009) Abrasion Resistance of Concrete in Hydraulic Structures, ACI Materials Journal, Vol. 106, No. 4, pp. 349-356.

[13] Liu, Y.-W.; and Pann, K.-S., (2011) Abrasion Resistance of Concrete Containing Surface Cracks, Journal of the Chinese Institute of Engineers, pp. 683-694.

[14] Laplante, P.; Aïtcin P.-C.; and Vezina, D., (1991) Abrasion Resistance of Concrete, Journal of Materials in Civil Engineering, Vol. 3, No. 1, pp. 19-28.

[15] Kiliç, A.; Atiş, C. D.; teymen, A.; Karahan, O.; Özcan, F.; Bilim, C.; and Özdemir, M., (2008) The Influence of Aggregate Type on the Strength and Abrasion Resistance of High Strength Concrete, Cement and Concrete Composites, Vol. 30, No. 4, pp. 290-296.

[16] Dhir, R. K.; Hewlett, P. C.; and Chan, Y. N., (1991) Near-surface Characteristics of Concrete: Abrasion Resistance, Materials and Structures, Vol. 24, pp. 122-128.

[17] Evangelista L.; and de Brito, J., (2007) Mechanical Behaviour of Concrete Made with Fine Recycled Concrete Aggregates, Cement and Concrete Composites, Vol. 29, No. 5, pp. 397-401.

[18] Konin, A.; and Kouadio, D. M., (2012) Mechanical and Abrasion Resistance of Recycled Aggregates Concrete in Relation to the Cement Content, Modern Applied Science, Vol. 6, No. 1, pp. 88-96.

[19] Naik, T. R.; Singh, S. S.; and Hossain, M. M., (1995) Abrasion Resistance of High Strength Concrete Made with Class C Fly Ash, ACI Materials Journals, Vol. 92, No. 6, pp. 649-659.

[20] Naik, T. R., Singh, S. S.; and Ramme, B. W., (1998) Mechanical Properties and Durability of Concrete Made with Blended Fly Ash, ACI Materials Journal, Vol. 95, No. 4, pp. 454-460.

[21] Horszczaruk, E. K., (2009) Hydro-abrasive Erosion of High Performance Fiber-reinforced Concrete, Wear, Vol. 267, Nos. 1-4, pp. 110-115.

[22] Cheng, T.-C.; Cheng, A.; Huang, R.; and Lin, W.-T., (2014) Abrasion Properties of Steel Fiber Reinforced Silica Fume Concrete According to Los Angeles and Water Abrasion Tests, Materials Science, Vol. 20, No. 4, pp. 498-502.

[23] Sbia, L. A.; Peyvandi, A.; Soroushian, P.; and Balachandra, A. M., (2014) Optimization of Ultra-High-Performance Concrete with Nano- and Micro-scale Reinforcement. Cogent Engineering, Vol. 1, No. 1. Article No. 990673.

[24] Atis, C. D., (2002) High Volume Fly Ash Abrasion Resistant Concrete, Journal of Materials in Civil Engineering, Vol. 14, No. 3, pp. 274-277.

[25] Kevern J. T.; Schaefer V. R.; and Wang K., (2009) The Effect of Curing Regime on Pervious Concrete Abrasion Resistance, Journal of Testing and Evaluation, Vol. 37, No. 4, JTE101761.

[26] Sadegzadeh, M.; Page, C. L.; and Kettle, R. J., (1987) Suface Microstructure and Abrasion Resistance of Concrete, Cement and Concrete Research, Vol. 17, No. 4, pp. 581-590.

[27] Barrett, W.; MacKay, A.; and Thurston, H., (1998) Building the Bridge to P.E.I., Nimbus Publishing, Halifax, Nova Scotia, Canada.

[28] Tadros, G., (1997) The Confederation Bridge: An Overview, Canadian Journal of Civil Engineering, Vol. 24, No. 6, pp. 850-866.

[29] Sætre, K., (2014) Ice Abrasion on Fiber Reinforced Concrete. Master’s Thesis, Department of Structural Engineering, Norwegian University of Science and Technology, Trondheim, Norway.

[30] Huovinen, S., (1990) Abrasion of Concrete by Ice in Arctic Sea Structures, ACI Materials Journal, Vol. 87, No. 3, pp. 266-270.

[31] Newhook, J. P.; and McGinn, D. J., (2007) Ice Abrasion Assessment - Piers of Confederation Bridge, Proceedings of Confederation Bridge Engineering Summit, Charlottetown, Prince Edward Island, Canada.