Analysis of abrasion rates in concrete surfaces of hydraulic structures

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Abstract. Abrasion of water-exposed surfaces in hydraulic structures can impose devastating defects in these surfaces leading to larger costs of rehabilitation and maintenance. One of the possible solutions is the improvement of concrete quality. Generally, several factors govern the abrasion resistance of hydraulic concrete. In the present study, previous experimental works, which carried out depending on the ASTM C 1138 test method, were collected, studied and analyzed precisely in order to estimate the effect of several factors that related with concrete quality on the abrasion rate of concrete. The results showed that the selection of cement type, inclusion of fibers, addition of silica fume and the election of the proper concrete type have the most effective influence among the remaining studied factors on the abrasion rate reduction.

1. Introduction

In addition to the predicted dynamic and static loads in the design of hydraulic structures, the drastic environmental effects must be taken into serious account [1]. Among these effects, these structures that are continuously exposed to water movement are subjected to the effect of abrasion phenomenon, which is defined as the progressive impairment of concrete surface due to the action of waterborne solids that pass over or hit the external concrete face of these structures. Basically, abrasion phenomenon can be considered as a critical case in the design and operation of strategic hydraulic structures as it can cause destructive effects. In the most intensive conditions, more than 1500 m3 of hydraulic concrete could be ruined, such undesired effect imposes considerable risks and high maintenance costs [2]. Generally, one of the effective possible solutions to reduce or totally avoid that risk is the use of a concrete mixture with a proper abrasion resistance. Thus, many abrasion test procedures were developed in order to evaluate the convenience of the suggested mixture [2]. The ASTM C1138 [3], ASTM C944 [4], ASTM C779 [5] and ASTM C418 [6] are the most widespread standard abrasion tests. On the other hand, the European standards introduced the Bohme disk test method [7]. Furthermore, different researchers suggested test devices to study the resistance of the hydraulic concretes against abrasion [8, 9]. Essentially, there are several factors that govern the abrasion rate, which can be categorized in pair of groups. Firstly, the characteristics of the used concrete, such as its grade, water to cementitious materials ratio, fiber inclusion, the size, hardness and shape of the used aggregate, the addition of cementitious materials and the surface curing. The second group includes factors related with the environmental action, such as water velocity, impact angle and the properties of the abrasive particles [1, 10-14].

In the available literature, there are vast studies that aimed to predict the effect of the different parameters using various test procedures. However, all of the available literature studies investigate the quantity of...
surface abraison in terms of abraison weight loss or abraison depth. On the other hand, the rate at which abraison occurs during the early or late periods of the abraison test is of significant importance. The variation of the rate of abraison with time may focus on the parameters that become more effective on abraison, positively or negatively, with time and along the service life of the concrete surfaces. Considering the gap of knowledge in this point, the state-of-art literature, which depended on the ASTM C 1138 method, was collected in this work, reviewed and analyzed. Based on which, comprehensive comparisons were carried out to evaluate the possible influences of various factors on the resulted abraison rate.

2. Required literature review

Several researches can be found in the literature on abraison of concrete using the water jet method or other test methods [7, 9, 15-20]. On the other hand, other researches concentrated on the numerical analysis of abraison in hydraulic structures [13]. However, to optimize the analysis and discussion presented in this work, only abraison tests that used the ASTM C 1138 test method were considered. Recently, several researchers conducted experiments depending on the underwater test method to study the abraison actions of various types of concrete mixtures [11-14, 21-25]. The effect of several cementitious materials, like fly ash and silica fume, was investigated in some researches, while the influence of different synthetic fibers or metallic fibers was investigated in others. The use of recycled materials was the focus of other researches, while others focused on the mixture grade or new concrete mixtures like geopolymer concrete, high performance concrete or engineered cementitious materials. However, the full data details are not easy to be extracted from most of the published works. Therefore, the analysis of abraison results conducted herein considered only those researches that data are available or can easily be extracted.

Abid et al. [10] directed an experimental work to study the wear resistance of self-compacting concrete (SCC). Three different concrete grades of 30, 40 and 50 MPa were prepared. Micro-steel fibers were added with contents of 0.50, 0.75 and 1.0% for the mixture of the lowest grade, while 70 kg/m3 of silica fume was added to that of the highest grade. The cast samples were tested at different ages. Test results showed that the period from 7 to 28 days had greater effect on wear resistance improvement that of the period extended from 28 to 90 days. Considering the 50 MPa group as an example, the resistance improvement through the first period was 78% of the total improvement due to the maturing to 90 days, compared to 7 days. Moreover, the fiber addition increased the abraison resistance of SCC. At 90-day age, the improvement percentages in wearing resistance were 8, 14 and 26% due to the fiber addition in quantities of 0.50, 0.75 and 1.0%, respectively. Finally, the improvement of SCC grade highly increased the abraison resistance. At 90-day age, when the concrete strength was increased to 40 and 50 MPa (compared to 30 MPa), the wear resistance improved by 23.8 and 77.8%, respectively.

Abid et al. [11] conducted experiments on the abraison of engineered cementitious composites (ECC). Five dosages of 6 mm polyvinyl alcohol fibers (PVA) were added to the mixtures with different quantities (0, 0.50, 1.0, 1.5 and 2.0%). Fly ash and silica sand were added to the prepared mixtures with constant contents of 684 and 455 kg/m3, respectively. The tests of the cast specimens were conducted after 3, 7 and 28 curing days. Testing time was 72 hr for all samples except those of 3-day age, where the tests were terminated after 48 hr due to the intensive abraison rate. The attained compressive strength for all samples was approximately 47 MPa. The obtained results revealed that at 28-day age, the inclusion of small PVA quantities (0.50 and 1%) enhanced the wear resistance by about 20%, while the addition of large fiber quantities (1.5 and 2%) improved the resistance by 50 and 95%, respectively.

Horszczaruk [13] tested the abraison resistance of the plain and fiber-reinforced high performance concrete. Three kinds of fibers were added. The first is hook-ended steel fibers with length of 30 mm and aspect ratio of 60, while the second is hook-ended steel fiber with length of 50 mm and aspect ratio of 50. Both types of steel fibers were added with the same quantity (70 kg/m3). Finally, polypropylene fibers with length of 19 mm were added with quantity of 1.8 kg/m3. The resulted compressive strengths were 100.1, 91.8, 99.3 and 98.2 MPa for the plain and first to third kind of fibers, respectively. All the prepared mixtures contained silica fume with constant quantity (45 kg/m3). Testing time was prolonged.
to be ten 12-hour intervals in order to obtain better estimation for the abrasion resistance differences for the concrete samples. Results of the conducted experiments showed that after 120 hr of testing, the highest depth of wear was 3.27 mm, which was obtained when steel fibers of 50 mm were added. On the other hand, the lowest value of wearing depth was 2.89 mm, which was attained due to the inclusion of 30 mm steel fibers.

Horszczaruk [14] conducted an experimental work to evaluate the abrasion damage of high strength concrete. Three different cement types of CEM I 42.5R, 52.5R and cement of blast furnace CEM III 42.5R were used. Silica fume was added with a quantity of approximately 46 kg/m³. Three types of fibers were included; 30 and 50 mm length steel fibers were used with a content of 70 kg/m³ and polypropylene fibers with length of 19 mm were used with a quantity of 1.8 kg/m³. Testing time was also extended to 120 hours, while maturing age was 28 days. The test results displayed that the underwater test procedure is appropriate for the evaluation of wear resistance of high strength concrete specimens with a compressive strength approaching 120 MPa. The obtained depths of wear were 3.96, 4.25 and 9.21 mm for samples of plain concrete made up with cement type of 52.5R, 42.5R and CEM III/A 42.5R, respectively. The lowest abrasion loss was 2.89 mm, which was attained for samples prepared with 52.5R cement and steel fibers of 30 mm in spite of its moderate compressive strength as compared with that of the other samples.

3. ASTM C 1138 abrasion test method

As aforementioned, various standard and even non-standard abrasion test procedures were directed to evaluate the abrasion rate of concrete. Specifically, the ASTM C 1138, which is called as the underwater method, is agreed to be the most used abrasion test that can better simulate the phenomenon that takes place during the operation of hydraulic structures [7]. The underwater test apparatus (Figure 1) consists of cylindrical steel tank with height and diameter of 450 and 305 mm, respectively. The concrete sample must be placed inside it. An agitation paddle, which is rotated by a motor at a rotation velocity of 1200 ± 100 rpm, is used to agitate 70 balls of various diameters (12.7, 19 and 25.4 mm) made up with chromium steel. Basically, these balls simulate the actual abrasive particles. The total test period extended to six 12-hour intervals. The mass of concrete sample must be weighted before and after each interval in order to record the weight decrement, which represents the amount of abrasion damage [3].

![Figure 1. Scheme of the underwater test apparatus [3].](image-url)
4. Analysis of abrasion rate

In this section, the effect of the type of the used cement, compressive strength, tensile strength, water to cement ratio, silica fume and fibers on the rate of abrasion erosion are discussed in details. The term abrasion rate used in this research refers to the quantity of abrasion occurred in the concrete surface during a specific time period of abrasion testing, which is measured as depth of abrasion in mm per time period in hours. The abrasion rate can simply be calculated using the abrasion depths of each two successive time steps using the following formula:

\[ AR = \frac{(AD_{T+1} - AD_T)}{P} \]  

where: \( AR \) is the abrasion rate in (mm/hr), \( AD_T \) and \( AD_{T+1} \) are the abrasion depths (in mm) for a certain sample at a specific testing time step and the next step, respectively, and \( P \) is the time period between that two successive time steps (hr).

4.1. Effect of cement type

Figure 2 shows the abrasion depth and rate of three different samples of high strength concrete (HSC) that were prepared using three various types of cement. Two ordinary Portland cement type CEM I 52.5R and 42.5R, while the third is blast furnace cement (CEM IIIA 42.5). Tests were carried out at the same age (28 days) and cement contents were exactly equal (470 kg/m³). Obviously, it can be noticed that the blast furnace cement exhibited the highest abrasion rate along the testing time, while cement of 52.5R and 42.5R were fluctuated throughout the test. At the end of the experiments, the abrasion rates were 0.023, 0.0321 and 0.061 mm/hr for cement types of CEM I 52.5R, I 42.5R and IIIA 42.5, respectively. Undoubtedly, this indicates that the use of blast furnace cement gives high and continuous abrasion damage counter to the two other types, especially CEM I 52.5R, which exhibited the lowest final abrasion rate and depth.

![Figure 2. Effect of cement type on (a) abrasion depth (b) abrasion rate](image)

4.2. Effect of water to cement ratio (w/c)

At the same age of 28 days, abrasion depth and rate of four specimens having various w/c ratios are displayed in Figure 3. One can conclude that sample of higher w/c ratio exhibited the greater abrasion losses and larger abrasion rate. This conclusion is entirely compatible with the findings of previous studies [25, 26]. As it is already known, the increase of w/c ratio significantly decreases the strength and surface hardness of concrete [27]. After 72 hours of testing, the abrasion rates were 0.075, 0.0275, 0.025
and 0.0146 mm/hr for samples with w/c ratios of 0.61, 0.29, 0.3 and 0.36, respectively. It can be observed that in spite of the relatively high w/c ratio of the mixture of previous study [10] and moderate compressive strength as compared with the remaining samples, it exhibited the lowest abrasion loss and smallest final abrasion rate. This can be attributed to its concrete type, where it was cast using self-compacting concrete. Generally, SCC can show abrasion resistance value higher than that of an ordinary vibrated concrete of a lower w/c ratio and higher compressive strength [15].

4.3. Effect of silica fume
For the same concrete age, cement type (CEM I 42.5R) and fiber content (0%), sample of higher silica fume content showed the lowest abrasion rate. As shown in Figure 4, throughout the original testing period (72 hours), the average of the abrasion damage rate were 0.105, 0.035 and 0.0176 mm/hr for samples with silica fume contents of 0, 47 and 70 kg/m3, respectively. It can be observed that the rate of abrasion was decreased by 66 and 83% due to the addition of 47 and 70 kg/m3 of silica fume, respectively. Basically, the addition of silica fume significantly enhances the rheological characteristics and also minimizes the cracking risks that occur in concrete due to the hydration heat, and hence it considerably reduces the abrasion erosion damage [28].

![Figure 3. Effect of w/c ratio on (a) abrasion depth (b) abrasion rate](image)

![Figure 4. Effect of silica fume on (a) abrasion depth (b) abrasion rate.](image)
4.4. Effect of compressive strength

Figure 5 presents the resulted abrasion depth and rate for concrete samples of different obtained compressive strengths at the same maturing age of 28 days. From Figure 5.a, it is worth mentioning that the highest and the lowest abrasion depths were recorded for two samples of the same compressive strength (48 MPa) but of different concrete types. Form Figure 5.b, one can notice that within the same concrete type, as compressive strength increases, the wear rate reduces significantly, such as for the three mixtures of reference [14] and also for the three ones of reference [10]. Basically, the abrasion loss of concrete surface is majorly connected with its compressive strength, but it is not necessarily that all mixtures that with enhanced compressive strength could retained lower abrasion rates [7, 14].

4.5. Effect of concrete tensile strength

Typically like the effect of compressive strength, it can be observed that for the same concrete type, such as for the three different SCC mixtures of reference [10] and also for those of reference [11], the abrasion rate directly related with its splitting tensile strength as shown in Figure 6. According to the results of Abid et al. [10], the final abrasion rates for samples with tensile strengths of 3.8, 4.5 and 5 MPa were 0.059, 0.046 and 0.015 mm/hr, respectively.

![Figure 5](image1.png)

**Figure 5.** Effect of compressive strength on (a) abrasion depth (b) abrasion rate.

![Figure 6](image2.png)

**Figure 6.** Effect of tensile strength on (a) abrasion depth (b) abrasion rate.
4.6. Effect of fiber inclusion
For the same maturing age of 28 days, Figure 7 presents the abrasion loss and rate of different types and contents of fibers. For samples of reference [10], the inclusion of 15 mm steel fibers with quantity of 78 kg/m³ (1% by volume) reduces the average abrasion rate by approximately 18.5%. Moreover, for mixtures of reference [11], the addition of 13 kg/m³ (1%) of polyvinyl alcohol fiber (PVA) minimized the mean abrasion rate by 38.4%. Finally, for samples of [13], the inclusion of 1.8 kg/m³ (0.1%) of polypropylene fibers (PP), 70 kg/m³ of 50 mm steel fiber and 70 kg/m³ of 30 mm steel fibers reduced the abrasion rate by 16.3, 0 and 10.7%, respectively. Thus, based on the reviewed results, the PP fibers of 19 mm are the most effective fibers that can be used to decrease the abrasion rate in concrete, while the steel fiber of 50 mm has the lowest influence on the abrasion resistance. It should be addressed here that steel fiber is a proven discrete reinforcement that have positive influence on the concrete structural characteristics. Steel fibers can enhance the tensile, flexural and shear strengths of concrete. It can also significantly develop higher ductility and higher strain energy absorption under static and dynamic loads [29-34].

![Figure 7. Effect on fiber inclusion on (a) abrasion depth (b) abrasion rate.](image)

5. Conclusions
According to the conducted analysis, which was carried out on the collected literature works and considering the limits of the investigated parameters in these works, the followings are the main conclusions:
1. The use of blast furnace cement (CEM IIIA 42.5) to reduce the abrasion damage of concrete cannot be considered as a good decision. It exhibits an average abrasion rate higher by 55.7 and 58.5% as compared with the Portland cement types of CEM I 42.5R and 52.5R, respectively.
2. Silica fume has noticeable positive effect on abrasion resistance, where the abrasion rate reduced by 66 and 83% due to the addition of 47 and 70 kg/m³ silica fume, respectively.
3. Self-compacting concrete has higher effective abrasion resistance with lower abrasion rate compared to vibrated concrete with a higher compressive strength.
4. The inclusion of fibers considerably enhances the concrete abrasion resistance. Furthermore, the addition of 19 mm PP fibers was found to have the greatest influence on abrasion loss decrement among the reviewed types of fibers.
5. The w/c ratio of the mixture and its compressive strength and tensile strength have dependent influence on the improvement of the abrasion resistance. Generally, their effects are governed directly by the other factors. However, it can be said that within certain and restricted circumstances,
the decrease of w/c and the increase of compressive strength or tensile strength leads to lower abrasion rates.

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