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Review of Erosion Causes and Important Factors on the Abrasion Resistance of Concrete

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Abstract

The long-term impact of waterborne solids may lead to the destruction of significant amounts of concrete in hydraulic structures, including spillways, dams, and culverts. Hydraulic structures' durability heavily depends on the concrete surface's resistance to mechanical erosion. Abrasion of the surface brought about by the continuous loss of material due to the impact of solid particles suspended in water is known as hydro-abrasion. Hydro-abrasive concrete wear frequently results in a reduction in the lifespan of the hydro-technical facility. Consequently, the facility needs repairs, causing it to be nonfunctional during the repair time and increasing expenses. This paper aims to provide a comprehensive overview of concrete erosion and its mechanisms, along with a brief discussion of the elements that significantly affect the abrasive wear rate. These elements include those related to hydraulic design standards, the properties of water-transported particles, and other factors related to the properties of concrete materials. Additionally, the research highlighted the laboratory testing methods for concrete's corrosion resistance. The research also found that concrete properties needed to be modified to enhance the abrasion resistance and increase compressive strength.

Keywords: Abrasion Resistance, Erosion, Hydraulic constructions

الخلاصة:

قد يؤدي التأثير طويل المدى للمواد الصلبة المنقولة بالمياه إلى تدمير كميات كبيرة من الخرسانة في الهياكل الهيدروليكية، بما في ذلك قنوات تصريف المياه والسدود والعبارات. تعتمد متانة الهياكل الهيدروليكية بشكل كبير على مقاومة السطح الخرساني للتآكل الميكانيكي. يُعرف تآكل السطح الناتج عن الفقد المستمر للمواد بسبب تأثير الجزيئات الصلبة العالقة في الماء باسم التآكل المائي. غالبًا ما يؤدي تآكل الخرسانة المائية الكاشطة إلى انخفاض في عمر المُنشأ الهيدروليكي. وبالتالي تحتاج المنشأة إلى إصلاحات، مما يجعلها غير قابلة للعمل أثناء فترة الإصلاح وزيادة الكلف. تهدف هذه الورقة إلى تقديم نظرة شاملة على تآكل الخرسانة وآلياته، بالإضافة إلى مناقشة موجزة للعناصر التي تؤثر بشكل كبير على معدل التآكل الكاشط. تشمل هذه العناصر تلك المتعلقة بمعايير التصميم الهيدروليكي، وخصائص الجسيمات المنقولة بالماء، وعوامل أخرى تتعلق بخصائص مواد الخرسانة. بالإضافة إلى ذلك، سلط البحث الضوء على طرق الاختبار المعملية لمقاومة تآكل الخرسانة. كما وجد البحث أن خصائص الخرسانة بحاجة إلى تعديل لتعزيز مقاومة التآكل وزيادة مقاومة الانضغاط.

1. INTRODUCTION

Erosion is a prominent problem in hydraulic construction, which involves the transportation of both liquids and solids. In order to control erosion, it is essential to examine three key factors: the solid surface, which causes the removal of substances from the surface, and a liquid medium that transports these particles [1, 2]. Because hydraulic systems include high-velocity flows, the concrete used in them should be withstand increased water and sediment pressure without wearing out. To increase the beneficial lifespan of hydraulic structures and provide safe and dependable continuous operation over extended periods, the concrete used should have great durability and abrasion-resistant characteristics. Various techniques are employed to enhance the wear resistance of concrete. Some of these methods include improving compressive strength or incorporating silica fume, fly ash, and reinforcement fibers into the concrete mix, which leads to improved mechanical properties and consequently enhances abrasion resistance [3, 4]. Essentially, the erosion rate is impacted by a set of elements that may be classified into two groups. Before to incorporating cementitious substances, it is essential to check the grade, the existence of fibers, w/c ratio, the hardness, size and shape of the aggregate, the types of cementitious components added, and the post-pour surface treatment of the concrete. The second group involves elements associated with environmental activity, like water speed, abrasive particle quality, and impact angle [5-7]. Many important hydraulic structures, like spillway aprons, culverts, and stilling basins, are prone to severe abrasion erosion damage [1], as illustrated in Figure 1.

Fig. 1 Abrasion of the concrete invert the Asahi SBT [8]

2. THE CAUSES OF EROSION

The term "abrasion" is frequently employed in hydraulic constructions to describe the breakdown of concrete surfaces that have been subjected to high-speed water containing sediment. The degree of surface degradation is heavily influenced by the water's transport capacity and the methods used to convey solid matter. There are basically three phases to the wear failure process. The first phase is pre-abrasion peeling, the severity of which may be greatly affected by the flow speed and the water's weight on the target surfaces. The second phase involves the formation of surface cracks in the concrete caused by impacts with waterborne particulates. As a result, wear is occurring in the third phase. The most important factors influencing abrasion-induced deterioration are the following: the amount, size, form, and hardness of waterborne particles, the flow's velocity on the focused surface, and the concrete products' characteristics [9, 10].

3. LITERATURE REVIEW

Generally, several parameters significantly influence the rate of abrasion erosion. They may be divided into two categories. Before adding cementitious materials, it is essential to identify the grade, the fiber content, the w/c ratio, the hardness, size, and shape of the used aggregate, the inclusion of cementitious substances, and the post-pour surface treatment of the concrete. The second group of factors includes environmental action- associated qualities, like impingement angle, water speed, and the qualities of abrasion particles.

Abid et al. [11] investigated self-compacting concrete's (SCC) resistance to abrasion. The underwater test that was performed according to the technique approved by ASTM C1138, was used for that analysis. The concrete was made in three distinct grades: 30, 40, and 50 MPa. The lowest-grade mixture included micro-steel fibers with content of 0.50, 0.75, and 1.0%, whereas the highest-grade mixture included 70 kg/m^3 of silica fume. Test findings showed that wear resistance increased significantly from days 7 to 28 more than that at days 7 to 90. As an example, in the first stage, the overall resistance for the 50 MPa category increased by 78% due to the maturation being extended to 90 days instead of 7 days. The use of fiber further enhanced SCC's abrasion resistance. At 90 days old, raising the fiber quantity from 0.50 to 0.75 and 1.0% resulted in a wear resistance increase of 8, 14, and 26%, respectively. Over time, the SCC grade greatly enhanced the material's resistance to erosion. With a concrete strength rise from 30 to 40 and 50 MPa at 90 days of age, the resistance to wear improved to 23.8% and 77.8%, respectively.

Horszczaruk [12] Performed an investigation to assess the wear and tear resistance of two kinds of high-strength concrete: conventional and fiber-reinforced concrete. The underwater test that was performed according to the technique approved by ASTM C1138, was used for that analysis. Three distinct dosages of fiber were applied: steel fibers ME 30/50 with a diameter of 0.50 mm and a length of 30 mm with an aspect ratio of 60; steel fibers ME

50/1.0 with a length of 50 mm and a diameter of 1.0 mm with an aspect ratio of 50; and polypropylene fibers (19 mm in length). For a more precise estimate of the variations in abrasion erosion resistance for the concrete specimens, the testing period was extended to ten intervals, each with 12 hours. After 120 hours of examination, the study showed that the highest wear depth was 3.27 mm, achieved with 50 mm of steel fibers added. However, when 30 mm of steel fibers were present, the wear depth was 2.89 mm at its lowest.
Shamsai et al. [13] examined the compressive and abrasion strengths of nano-silica concrete in this investigation and the impact of the water-cement ratio. Experimental concrete samples were made using w/c ratio of 0.33, 0.36, 0.40, 0.44, and 0.50 with 3% nano-silica. In all concrete samples, other design characteristics remained the same. Block samples of 15×15×15 cm^3 were tested for compressive strength at various ages. The wear resistance of the identical block specimens was assessed after 28 days. The compressive strength experiment demonstrated that a decrease in the water-cement ratio from 0.50 to 0.33 resulted in a 34.4% and 35.2% improvement in compressive strength, respectively. The abrasion resistance increased by 36.13% due to a decrease in the water-cement ratio from 0.50 to 0.33, according to the findings of the abrasion tests.

Hamedi et al. [14] used the Messa testing apparatus to examine the materials' impact abrasion resistance. 18 samples were cast, representing three distinct mixes with design grades of 25, 35, and 55 MPa, and examined after seven and twenty-eight days. In addition to the original 45° paddle, two more paddles were manufactured and used, one with an angle of 30° and the other at 60°. At 28 days old, the findings showed that the concrete's wear resistance decreased by 11.9% and 49.9% for the 60° paddle, respectively, due to the rise in strength from 25 to 35 and 55 MPa. In addition, the device exhibited the least abrasive ability when the regular paddle was used, whereas the most abrasive ability may be obtained using the 60° paddle.

Ayoob et al. [15] investigated how self-compacting concrete was affected by water-impact abrasive erosion. The abrasion was assessed using the water jet test technique. The plate samples used consisted of six mixtures with 30, 40, and 50 MPa design strengths, including 0%, 0.5%, 0.75%, and 1.0% steel fiber concentrations. The findings show that abrasion losses may be decreased by about 17% by raising the strength from 30 to 40 MPa, and that the wear resistance may be improved by more than 23% by employing steel fibers with volumetric ratio of 0.75 and 1%. The highest improvement in wear resistance percentage was observed when the plain specimens' strengths were raised to 50 MPa, a 30% increase over the ordinary 30 MPa sample.

Ismaeil et al. [16] investigated concrete specimens that produced in three mixtures, each with a 25, 35, and 45 MPa compressive strength. After 7 days of curing, the samples were tested. It was also determined what impact the impingement angle had. The four inclination angles (0, 30, 45, and 60 °) with respect to the horizon were experimentally investigated. The experiments' results showed that a stream inclination angle of 60 degrees with respect to the horizon provides the minimum erosion rate, while a stream inclination angle of 45° results in the greatest abrasion depth.

Cheyad et al. [17] It has experimentally investigated the abrasion resistance of three different classes of normal concrete and geopolymer. Grades 20, 30, and 40 MPa were used. To perform the wear resistance evaluation (underwater technique), non-standard equipment that was a modification of ASTM C1138 was utilized. The abrasion test was carried out at 3, 7, and 28 days. Based on the testing findings, geopolymer concrete outperformed ordinary concrete in all three categories of abrasion resistance and reached its maximum strength at a very young age.

Abbas et al. [18] used 24 samples to experimentally test the abrasion resistance of both regular and green concrete. As a partial substitute for gravel, four distinct ratios of green and conventional concrete waste plastic were utilized: 0%, 30%, 60%, and 100%. The water jet test technique was employed for the evaluation. This study investigated the specimens at 3, 7, and 28-day ages. The evaluation used the water jet test method with two angles (45° and 90°) from the horizon. The findings demonstrated that the rate of abrasion was reduced with increasing plastic proportion with age.

4. LABORATORY TESTING FOR CONCRETE ABRASION RESISTANCE

Many standard and non-standard strategies have been developed in recent decades to assess concrete's wear resistance in various constructions, including hydraulic structures.

4.1 Standard ASTM abrasion tests

4.1.1 ASTM C1138 (underwater method)

The American Society for Testing and Materials (ASTM) C1138 [19] simulates the abrasive damage that may occur on concrete when exposed to waterborne particles like gravel, silt, sand etc. The usual duration of this test is 72 hours, separated into six periods of 12 hours each. Each period should record the sample mass. In this technique, the test equipment consists of a cylindrical steel tank with an internal diameter of 305 ± 6 mm and a height of 450 ± 25 mm, as seen in Figure 2. The electrical motor provided with the agitation paddle can spin it at a speed of 1200 ± 100 rpm. To simulate the abrasive substance, 70 iron balls with varying three diameters (12.7, 19, and 25.4 mm) are laid out across the surface of the specimen. The sample was a cylinder measuring 300 mm in diameter and 100 mm in height.

Fig. 2 The ASTM C1138/97 underwater abrasion test approach.

4.1.2 ASTM C418

This method [20] is typically employed to assess concrete's wear resistance using sandblasting. This approach clarifies how waterborne particles and abrasion weight loss during traffic cause abrasive damage to concrete surfaces.

4.1.3 ASTM C779

This testing technique encompasses three distinct approaches to determining the relative resistance to wear of horizontal concrete surfaces. Different procedures are used to test the surface characteristics of concrete, which are affected by mixing proportions, finishing, and surface processing. These procedures range in shape and degree of abrasion force. Portable equipment relies on these three techniques, making it excellent for laboratory and experimental work. Techniques A, B, and C are the revolving disc, dressing wheel, and ball-bearing methods, respectively [21].

4.1.4 ASTM C944

A test approach [22] provides a method for evaluating the ability of mortar and concrete to withstand abrasion. This technique applies to both cast and cored samples. This test is essentially the same as the dressing wheel (process B) of the ASTM C779 test technique. Concrete bridges and roads under heavy traffic loads are better evaluated using the ASTM C944 technique.

4.1.5 Böhme disc method

This technique is conventional and compliant with European Specification EN 13892-3. This method is utilized to evaluate the concrete's mechanical abrasion resistance. A cube-shaped specimen measuring 71 ± 1.5 mm in length is used for testing purposes. The examination, which is confined and positioned in the way of the Böhme circular processor, offers a consistent surface wear drive. It must undergo sixteen complete rotations and be exposed to a load of 294 N. Every cycle has 22 rotations. Before each test and after every four cycles, the test specimen should be weighted [23, 24].

4.2 Non-Standard ASTM abrasion tests

4.2.1 Water-jet test method

Taiwanese researchers [9, 25] developed this method as a non-standard testing procedure. The computed abrasion resistance of concrete is negatively affected by sand and water impingement. The instrument has a rectangular nozzle with measurements of 10×200 mm, designed to simulate the flow over a spillway. During the examination, it is positioned at a 45-degree angle above the specimen to ensure the shear force and impact are optimal. The second component of the device consists of a chamber that measures (2500×1800×1500) mm. In the final section, test samples of concrete plates measuring 200×200×50 mm are subjected to a water flow with varying quantities and velocities of sand. Fig. 3 below illustrates the device's design.

Fig. 3 Water-jet test machine

4.2.2 A proposed abrasion device

It is a new apparatus that was proposed by Messa et al. [26] This apparatus is a modified version of the standard underwater testing method (ASTM 1138) [19]. The abrasive steel balls were swapped out for 950 grams of silica sand, whose bulk density is 650 kg/m3, to simulate the abrasive state in hydraulic systems more accurately. The details of this device are illustrated in Fig. 4 It consists of the following components: The first part is a cylindrical tank that measures 350 mm by 450 mm to hold the mixture of water and sand, as well as the specimen. The second section is an agitation paddle, a circular shaft used to stir the water and sand mixture. It is composed of stainless steel. The final section is an electrical motor with three horsepower and a revolving speed of 600 rpm that is utilized to rotate the paddle at the necessary speed.

Fig. 4 Modified ASTM 1138 test

5. FACTORES AFFECTING THE RISISTANCE OF CONCRETE TO ABRASION EROSION

5.1 The Impingement Angle's Influence

The effect of impact angle on abrasion-induced concrete loss was examined by Liu et al. [27] In that evaluation, the water jet approach was applied. The results show that among the four impact angles (60°, 30°, and 45°), the 90° angle causes the most abrasion damage, with a diminishing tendency at lower angles when taking into account varying water-cement ratios.

Hamedi et al. [14] utilized the Messa instrument test technique to examine the inclination flow angle of abrasive harm in ordinary Portland cement (OPC). Three paddle angles were used (30°, 45°, and 60°). The data obtained showed that a 60º agitation paddle created the most abrasion action, while a 45º regular paddle created the least. Using a 30º paddle instead of a conventional one increased abrasion damage by 43.9% and a 60º paddle by 75% at 28 days of age.

5.2 Impact of abrasive solids properties

The kind of particles that roll and strike the concrete surface when the hydraulic structure is operating is a major component in controlling wear damage. Liu et al. [27] used a water jet technique to examine how the concentration and size of sand affected the rate of hydraulic concrete abrasion. The experiment used four distinct sand concentrations (0, 110, 230, and 340 kg/m^3) and four distinct mean sand diameters (0.6, 1.2, 2.5, and 5 mm). The results indicated that erosion rates were 10, 17, and 23 times greater at 0.6, 1.2, 2.5, and 5 mm in water with 110 kg/m^3 of sand at an effect angle of 45°. Damage to concrete surfaces from erosion and abrasion is negligible in the absence of sand concentration.

5.3 Impact of water on cementation material proportion

Rahmanzadeh et al. [28] utilized the Water Sand Blast technique, which depends on the ASTM-C778 requirement, to assess the abrasion force test on cube specimens of 150 × 150 × 150 mm during 28 days of age. According to the findings, the abrasion depth increased when the water-cement proportion was raised. Gradually, the abrasion depth increased from 0.3 to 0.46 as the ratio of water to cement increased. As demonstrated in Figure 5.

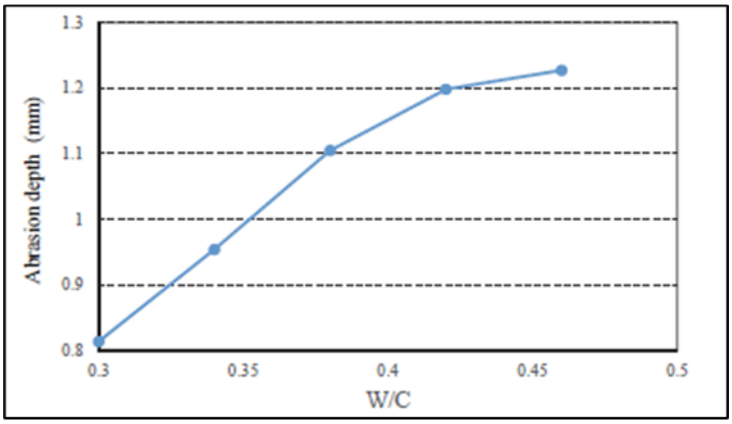

Fig.5 Impact of the w/c ratio on the depth of abrasion [28]

5.4 Compressive strength's impact

One of the most important considerations is compressive strength. It greatly affects the abrasion resistance of the concrete's surface. Yen Tsong et al. [29] investigated how compressive strength impacts abrasion resistance in concrete. The findings showed that independent of the fly ash concentration, the resistance to abrasion damage in concrete improved with increasing compressive strength and a decreasing w/c ratio.

5.5 The Influence of Fibers

Bodnárová et al. [30] investigated the water jet approach's ability to test concrete's resistance to water erosion. The investigations were conducted on two concrete types: one without added fibers, and another with polypropylene and steel fibers. The stream rate was 0.0011 m^3/min, and the water weight was 80 MPa. Upon impact with a water jet, the concrete showed no indications of cracking, and the steel fibers stayed securely embedded within the bond grid.

Zarrabi et al. [31] performed an experimental investigation on the impact of hydraulic parameters on abrasion damage in hydraulic constructions made of fiber-reinforced concrete. The waterborne sand apparatus was used to examine the damage from the abrasion. The three mixtures that were cast were benchmark concrete (BM) without fiber, steel fiber concrete (SFC) with a concentration of about 1%, and polyester fiber concrete (PFC) with varying dosages of (0.2, 0.4, and 0.6%). Fibers are a good addition to hydraulic structures because abrasion opens micro-cracks continuously, and fibers can bind cracks and stop them from spreading. The results demonstrate that both polyester and steel fibers enhance abrasion resistance. The consumption of polyester fibers at 0.6% enhances the most abrasion resistance.

5.6 Fly Ash's Influence

The use of fly ash in concrete dates back many decades. At first, it was used to reduce hydration heat and cracking at an early age. Recently, it has gained significance as a component in high-strength concrete. Yen et al. [29] examined how fly ash class F affects erosion wear in high-strength concrete. Underwater methods which fulfill the requirements of ASTM C1138 were employed to carry out the study. Various quantities of fly ash were used to create five distinct types of samples. Fly ash from Class F was utilized to partially substitute cement in five distinct formats: 0, 15, 20, 25, and 30%. The findings of the experiments demonstrated that the abrasion resistance for the 0% and 15% compensations was almost the same for 28 and 91 days, respectively. However, for the identical test period, the abrasion resistance declined by 22%, 32%, and 55% for compensation rates of 20%, 25%, and 30%, respectively. Liu et al. [9] examined the concrete's erosion resistance. In this test, cylindrical concrete specimens with a diameter of 100 mm and a height of 50 mm were subjected to a direct, vertical water jet and sand particles. According to the author's reasoning, using fly ash in concrete produces better abrasion resistance than ordinary concrete. Nevertheless, other mixtures, including fume seethe, demonstrated far higher abrasion resistance than fly ash.

5.7 Silica fume's impact

Eren et al. [32] conducted a study on the impact of adding silica fume to enhance the abrasion resistance of concrete. For this test, specialized machinery was created. To the mix, three distinct doses of silica fume were added: 0, 5, and 10% by volume of concrete. The experimental findings showed that adding silica fume to the concrete improved its surface resistance to wear. There was a noticeable improvement in wear resistance of 15% and 17% with 5% and 10% silica fume, respectively. There was a noticeable improvement in wear resistance of 15% and 17% with 5% and 10% silica fume, respectively.

6. CONCLUSIONS

The structure of the study first discusses the principles of abrasion-erosion in concrete, along with findings from various cementitious composites and brittle materials, as well as the elements that impact them.

1- As the samples age, the abrasion weight loss often reduces. This will directly reference the anticipated change in surface hardness, which will lead to an improvement in sample quality.

2- Several factors, including the compressive and tensile strengths, the type of cement used, the aggregate quality, the modulus of elasticity of concrete, the proportion of w/c, treatment of surfaces and upkeep, all contribute to the concrete's ability to resist abrasion. Furthermore, additives such as polymers, minerals, and fibers play a significant role.

3- Incorporating the fibers into the concrete increases its resistance to abrasion. Of the fiber types studied, 19-mm PP fibers were shown to have the most effect on reducing abrasion loss.

4- Geopolymer concrete achieves its maximum strength at an early age, suggesting it is an ideal material for hydraulic systems. Structures that undergo maintenance may still operate well in emergencies, since an age of three days significantly enhances abrasion resistance.

5- Based on the literature review of previous studies and standards, the ASTM C1138 abrasion test for concrete provides an ideal qualitative instrument to assess the abrasion of surfaces exposed to waterborne particles over hydraulic structures. However, this test does not account for the effects of falling water and waterborne particles originating from higher elevations. Nevertheless, there may exist extensive literature on a nonstandard test technique, such as the water jet test, which determines the concrete's wearing resistance due to the impact of water and sand.

REFERENCES

1. Committee, A., *210, Erosion of concrete in hydraulic structure (ACI 210R–03)*. 2003, American Concrete Institute, plUSA.
2. Atiş, C.D., *High volume fly ash abrasion resistant concrete.* Journal of Materials in Civil Engineering, 2002. **14**(3): p. 274-277.
3. Liu, Y.-W., *Improving the abrasion resistance of hydraulic-concrete containing surface crack by adding silica fume.* Construction and Building Materials, 2007. **21**(5): p. 972-977.
4. Kryžanowski, A., et al., *Abrasion resistance of concrete in hydraulic structures.* ACI materials journal, 2009. **106**(4): p. 349-356.
5. Kryžanowski, A., et al., *Testing of concrete abrasion resistance in hydraulic structures on the Lower Sava River.* Strojniški vestnik-Journal of Mechanical Engineering, 2012. **58**(4): p. 245-254.
6. Horszczaruk, E. and P. Brzozowski. *Use of a 3D scanner for imaging concrete sample surfaces abraded with the ASTM C 1138 method*. in *Proc., Creative Construction Conf*. 2018.
7. Hasan, M.S., et al., *Measurement of abrasion on concrete surfaces with 3D scanning technology.* Journal of Materials in Civil Engineering, 2019. **31**(10): p. 04019207.
8. Auel, C., R.M. Boes, and T. Sumi, *Abrasion prediction at Asahi sediment bypass tunnel based on Ishibashi's formula.* Journal of applied water engineering and research, 2018. **6**(2): p. 125-138.
9. Liu, Y.-W., T. Yen, and T.-H. Hsu, *Abrasion erosion of concrete by water-borne sand.* Cement and concrete research, 2006. **36**(10): p. 1814-1820.
10. Dandapat, R. and A. Deb, *A probability based model for the erosive wear of concrete by sediment bearing water.* Wear, 2016. **350**: p. 166-181.
11. Abid, S.R., et al., *Underwater abrasion of steel fiber-reinforced self-compacting concrete.* Case Studies in Construction Materials, 2019. **11**: p. e00299.
12. Horszczaruk, E., *Hydro-abrasive erosion of high performance fiber-reinforced concrete.* Wear, 2009. **267**(1-4): p. 110-115.
13. Shamsai, A., et al., *The effect of water-cement ratio in compressive and abrasion strength of the nano silica concretes.* World Applied Sciences Journal, 2012. **17**(4): p. 540-545.
14. Hamedi, M.H., et al. *The evaluation of the abrasion damage in hydraulic structures using the modified test method*. in *IOP Conference Series: Materials Science and Engineering*. 2021. IOP Publishing.
15. Ayoob, N., et al., *Water-impact abrasion of self-compacting concrete.* Magazine of civil engineering, 2020(4 (96)): p. 60-69.
16. Ismaeil, R.H., et al., *Experimental study on erosion depth in hydraulic structures.* Materials Today: Proceedings, 2021. **42**: p. 2340-2345.
17. Cheyad, S.M., A.N. Hilo, and T.S. Al-Gasham, *Comparing the abrasion resistance of conventional concrete and geopolymer samples.* Materials Today: Proceedings, 2022. **56**: p. 1832-1839.
18. Abbas, M.Q., A.N. Hilo, and T.S. Al-Gasham, *Comparing The Abrasion Resistance of Conventional Concrete and Green Concrete Samples.* Wasit Journal of Engineering Sciences, 2023. **11**(3): p. 83-95.
19. ASTM, *Standard test method for abrasion resistance of concrete (underwater method)*. 1997, The American Society for Testing and Materials Philadelphia, PA, USA.
20. ASTM, C., *418, Standard Test Method for Abrasion Resistance of Concrete by Sandblasting.* Philadelphia, PA: American Society of Testing and Materials, 2005.
21. Standard, A., *Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces.* 2012.
22. ASTM, C., *944-99. Standard Specification for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method.* Philadelphia, PA: American Society for Testing and Materials, 1999.
23. Çolak, A., *Effects of chrome oxide and limestone filler on the wear characteristics of paste and concretes made with white Portland cement.* Construction and Building Materials, 2008. **22**(11): p. 2276-2280.
24. Horszczaruk, E., *Abrasion resistance of high-performance hydraulic concrete with polypropylene fibers.* Tribologia, 2012(1): p. 63-72.
25. Topličić-Ćurčić, G., et al., *Hydro-abrasive resistance and mechanical properties of rubberized concrete.* 2014.
26. Messa, G.V., et al., *A combined CFD-experimental method for abrasive erosion testing of concrete.* Journal of hydrology and hydromechanics, 2018. **66**(1): p. 121-128.

27. Liu, Y.-W., S.-W. Cho, and T.-H. Hsu, *Impact abrasion of hydraulic structures concrete.* Journal of marine science and technology, 2012. **20**(3): p. 2.
28. Rahmani, K., B. Rahmanzadeh, and S. Piroti, *Experimental study of the effect of water-cement ratio on compressive strength, abrasion resistance, porosity and permeability of Nano silica concrete.* Frattura ed Integrità Strutturale, 2018. **12**(44): p. 16-24.
29. Yen, T., et al., *Influence of class F fly ash on the abrasion–erosion resistance of high-strength concrete.* Construction and Building Materials, 2007. **21**(2): p. 458-463.
30. Bodnárová, L., et al., *Flow Erosion Resistance of Concrete-Interaction of High-Speed Water Jet and Concrete.* Solid State Phenomena, 2019. **296**: p. 215-220.
31. Zarrabi, N., M.N. Moghim, and M.R. Eftekhar, *Effect of hydraulic parameters on abrasion erosion of fiber reinforced concrete in hydraulic structures.* Construction and Building Materials, 2021. **267**: p. 120966.
32. Eren, Ö., K. Marar, and T. Çelik, *Effects of silica fume and steel fibers on some mechanical properties of high-strength fiber-reinforced concrete.* Journal of Testing and Evaluation, 1999. **27**(6): p. 380-387.