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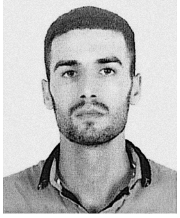
Experimental study on abrasion resistance of polished concrete in the water environment



With the aim of enhancing the overall durability and performance of concrete structures that are subject to water-related abrasion, this article explores the effects of hydraulic abrasion on polished and non-polished concrete surface using ASTM C1138 test. The results showed that the concrete surface improvement by polished surface with cement powder resulted in a 34% increase in the abrasion resistance of the concrete surface compared to the untreated concrete surface, concrete strength and surface treatment lead to improved abrasion resistance of concrete surfaces in abrasive hydraulic conditions.

Keywords: abrasion resistance, concrete, ASTM C1138, surface polishing, hydraulic structures.

Раззак А. В. Р., Алехин В. Н.
Экспериментальное исследование эрозионной стойкости полированного бетона в водной среде

С целью повышения общей долговечности и эксплуатационных характеристик бетонных конструкций, подверженных эрозии под воздействием воды, в статье исследуется влияние гидравлического эрозия на полированную и неполированную бетонную поверхность с использованием теста ASTM C1138. Результаты показали, что улучшение качества бетонной поверхности за счет полировки поверхности цементным порошком привело к повышению эрозионной стойкости бетонной поверхности на 34% по сравнению с необработанной бетонной поверхностью, прочность бетона и обработка поверхности повышают эрозионную стойкость бетонных поверхностей в абразивных гидравлических условиях.

Ключевые слова: эрозионная стойкость, бетон, ASTM C1138, полировка поверхностей, гидротехнические сооружения.

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Introduction

Hydraulic abrasion refers to the wear and degradation of concrete surfaces that are exposed to flowing water, particularly in areas where sediments are present [14; 24]. Hydraulic abrasion occurs widely in hydraulic structures such as dams, canals, water galleries, spillways, stilling basins and other structures exposed to water flow, such as bridge pillars [10; 11; 15; 18]. This phenomenon is caused by a combination of physical forces such as impact, grinding, initiated by particles like sand, gravel, and debris suspended in the water. As these particles collide with the concrete surface under hydrodynamic forces, gradual abrasion occurs leading to cracking over time [22; 25] (Figure 1). The process of abrasion of concrete under water can be described as the process of spreading small cracks, which leads to physical damage to the concrete [27]. The mechanisms behind hydraulic abrasion can be divided into cavitation and abrasive erosion [11; 19]. Cavitation happens when rapid pressure changes occur in fast-flowing water, resulting in the formation of vapor bubbles that collapse near concrete surfaces. This process can cause significant damage, leading to irregular surface deterioration characterized by deep pits. In contrast, abrasive erosion is caused by solid particles striking the concrete constantly as they move with the water flow; this type generally results in more even wear patterns [3; 14; 23; 25].

Several factors influence hydraulic abrasion, including the size and density of sediment particles, water velocity, flow characteristics, and the mechanical properties of the concrete itself such as its compressive strength and finishing techniques [1; 12; 19; 24]. Concrete mixtures that include specific aggregates or additives may show increased resistance to abrasion due to enhanced strength or better bonding among components [4; 8; 19]. Understanding these interactions is crucial for predicting how different concrete formulations will perform under specific hydraulic conditions [16]. The interaction between concrete and hydraulic conditions, especially in areas exposed to flowing water and sediment movement, creates a significant challenge for maintaining structural integrity [3; 12; 24].

Processes like abrasion and erosion can significantly reduce the lifespan of concrete surfaces, resulting in increased maintenance costs and potential failures in structural stability. Understanding the mechanisms behind these degradation processes is crucial for both new constructions and repair initiatives [8; 14; 16]. Factors such as mechanical degradation are

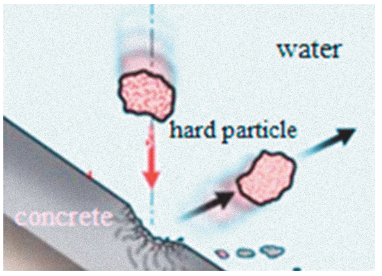

Figure 1. Effects of water-borne hard particles on the concrete surface. Author N. Ristić et al., 2017. Source: [25]

exacerbated by variables including water flow speed, sediment loads, and environmental conditions that promote abrasive wear [22; 24]. Incorporating additives like fly ash or steel fibers can enhance resistance to both mechanical stresses and chemical attacks [8–10; 20]. Ultimately, enhancing concrete durability in waterlogged environments not only improves the functionality of hydraulic structures but also supports sustainability goals by reducing resource waste through an extended service life and decreased repair requirements [15; 16; 22].

Researches [2; 5; 10; 17], etc. on hydraulic abrasion includes laboratory testing methods like ASTM C1138, which simulate real-world scenarios in controlled environments. By evaluating how various concrete compositions withstand abrasives in tests, researchers can develop improved materials specifically designed for use in challenging hydraulic settings. Several researches have been conducted in the field of increasing abrasion resistance in the concrete of hydraulic structures due to flowing water.

Concrete abrasion in aquatic environments is influenced by hydraulic conditions, concrete characteristics, and operational factors [24]. Water dynamics and solid particles like sand or gravel significantly affect abrasion rates, with water energy impacting abrasion through cavitation and direct contact [11; 19; 25]. Concrete properties are crucial for assessing abrasion resistance, where compressive strength serves as a key indicator; higher strength generally enhances durability against abrasion forces [9; 15; 24]. The water-to-binder ratio (w/b) is also important, as lower ratios improve density and mechanical performance while reducing porosity, thus enhancing abrasion resistance [8; 14; 16; 20]. The quality and type of aggregates used can further influence results, with tougher aggregates providing better durability [1; 6; 24]. Innovations such as fiber reinforcement [8; 9; 17] and additives like fly ash [5; 19; 26] and silica fume [4; 8; 19] can bolster durability by strengthening microstructural integrity. Environmental factors, including temperature fluctuations and freeze-thaw cycles, can exacerbate wear over time [1]. A well-finished surface tends to experience less wear due to fewer imperfections that trap debris [1; 12]. A key advantage of polished concrete is its ability to prevent water intrusion and surface wear. The polishing densifies the concrete, sealing pores that typically allow liquid seepage, which is particularly beneficial in areas exposed to harsh chemicals or moisture [12]. There is not enough researches on the extent to which polishing the concrete surface affects its abrasion resistance, so it was necessary to conduct this research to assess the abrasion of polished concrete under water.

Figure 2. Materials used in the concrete mix. Author A. W. R. Razzaq

Table 1. Design compressive strength and proportions of the components of the concrete mixture. Author A. W. R. Razzaq

Mix ID	Cement kg/m³	Sand kg/m³	Gravel kg/m³	Water kg/m³	Design compressive strength 28 days MPa	Surface treatment
Low strength concrete (LSC)	380	795	1050	119	20	—
Low strength polished concrete (LSPC)	380	795	1050	119	20	Surface polishing
High strength concrete (HSC)	576	651	1050	128	45	—

Methodology

The method for evaluating the abrasion resistance of concrete, especially in hydraulic environments, employs standardized procedures to ensure consistency and reliability in the results. A commonly recognized standard used is ASTM C1138, which outlines the protocols for performing abrasion tests on concrete surfaces submerged in water [7]. The process begins with the preparation of concrete samples that are formed and cured under controlled conditions to achieve the desired compressive strength prior to testing. Once the specimens reach the specified age, they undergo hydrodynamic abrasion testing. During these evaluations, the concrete samples are placed in a watery setting where they are subjected to a stream of water mixed with abrasive materials, simulating actual hydraulic conditions. Typically, this setup involves a rotating drum or similar device that continuously wears down the surface of the concrete over a predetermined period. Measurements are carefully recorded at specific intervals usually at 0, 12, 23, 36, 48, 60 and 72 hours to assess the weight loss experienced by each specimen due to the abrasive forces [7]. This data allows for comparative analysis between different concrete mixtures or formulations. At the conclusion of the testing phase, statistical analyses are performed to evaluate the correlation between compressive strength and abrasion resistance.

This experimental research focuses on underwater abrasion testing of concrete surfaces. Surface abrasion is related to various surface and material parameters, the most effective of which is the type of concrete and its strength. Therefore, the effect of polishing the concrete surface on surface abrasion was evaluated by comparing three concrete mixtures: low strength concrete (LSC), low strength polished concrete (LSPC) and high strength concrete (HSC) and comparing the results.

Materials used

Locally available materials were used to prepare the concrete mix (sand, gravel, cement and water) (Figure 2), Portland cement type 42.5sr was used in the preparation of concrete mixtures as well as in polishing the concrete surface

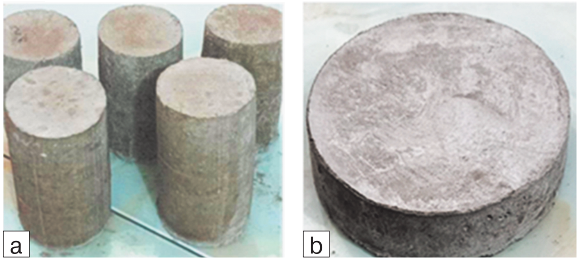

Figure 3. Concrete specimens for (a) compressive strength testing (b) abrasion testing. Photo A. W. R. Razzaq

of the low strength polished concrete (LSPC), which works to harden the concrete surface during the polishing process. while the used aggregates were well graded sand and crushed gravel with a maximum size of 19 mm. Ordinary water was used in the preparation of mixtures in this research, as well as it was used in the curing of concrete specimens.

Table 1 shows the details of the three concrete mixtures. Three concrete mixes have been designed, the first is a low strength concrete (LSC), the second is a low strength polished concrete (LSPC) and a high strength concrete (HSC). In this research the weights of concrete mix materials were calculated according to the method of the American Concrete Institute (ACI 211.1–91) [13]. Cement powder was used in the process of polishing the concrete surface (LSPC).

Specimens preparation

The surface abrasion was evaluated on three concrete mixtures with three concrete types, which are low strength concrete (LSC), low strength polished concrete (LSPC) and moderately high strength concrete (HSC). According to ASTM C1138 Standard [7], cement, sand, gravel and water were mixed from each mixture according to the mixing ratios shown in Table 1, 300 mm diameter and 100 mm depth cylindrical discs were cast. As for the preparation of low strength polished concrete (LSPC), As soon as the concrete starts to solidify, i. e. after the initial setting time of the concrete (1–4 hours), the surface is leveled and polished to make it smooth and perfectly flat by a rotating blade used to smooth and level the concrete with the addition of cement powder, which acts as a hardener, is sprayed on the concrete surface during the polishing process. These rotary blades have been passed several times over the surface, starting at a low speed and then gradually increasing the speed to ensure a perfectly polished surface with a smooth degree and high flatness, free of pores and cracks. One day after casting, the specimens' molds were taken off, and they were let to cure before being tested. All discs cured in water for 28 days to conduct the abrasion test using the abrasion testing machine. Five 15 cm (diameter) × 30 cm (height) cylindrical specimens were made from each mixture and tested for compressive strength testing in accordance with ASTM C39 [21] (Figure 3). One day after casting, the specimens' molds were taken off, and they were let to cure before being tested.

Abrasion testing procedure

The apparatus components are outlined as follows: a drill press; an agitation paddle; a cylindrical steel container, measuring 305 ± 6 mm (inside diameter) × 450 ± 25 mm (height), housing a disk-shaped concrete specimen; and 70 steel grinding balls of various size (Figure 4). The water in the container is circulated by the immersed agitation paddle powered by the drill press rotating at a speed of 1200 ± 100 rpm. The circulating water, in turn, moves the steel grinding balls on the concrete surface, producing the desired abrasion effects.

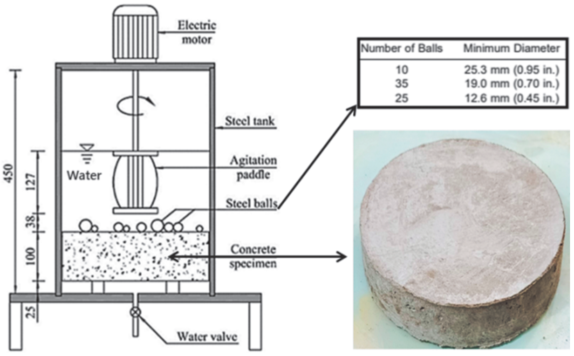

Figure 4. Underwater abrasion resistance test apparatus as per ASTM C1138. Source: [7]

After a 28-day curing time, all of the specimens (discs) were taken out of the curing tank and tested for abrasion resistance test in line with ASTM C 1138. The underwater friction abrasion tests every 12 hr. At the end of every 12 h of operation, the specimen was removed from the test container, the abraded material was flushed off, and the surface was dried. The specimen mass is determined and recorded in the air. Calculation of percentage abrasion weight loss every 12 hours. The abrasion test was conducted for the three mixtures at six steps each of 12 hours, totaling 72 abrasion testing hours. The following formula was used to calculate the percentage abrasion weight loss of each concrete specimen [2]:

$$Э = [(m_0 - m_t)/m_0]\ 100\%, \qquad (1)$$

where Э is percentage abrasion of the concrete specimen, m_0 is mass of the concrete specimen before abrasion test (kg), m_t is mass of the concrete specimen after abrasion test, for each 12 hr. testing interval (kg).

Results and discussion

After a 28-day curing time, all of the specimens were taken out of the curing tank and tested for compressive strength in line with ASTM C39 [21]. The compressive strength was tested at the three ages 28 days for all specimens. Three cylinders for each concrete type were used to estimate the compressive strength of concrete. The 28-day strength of the three mixtures are shown in Table 2. The specimens (discs) were tested for abrasion resistance test in line with ASTM C 1138 [7]. By the formula (1) the percentage abrasion weight loss was calculated of each concrete specimen, the results were obtained shown in the Table 2.

In Table 2 the results of mass losses with abrasion time for low strength concrete (LSC). For the test period of 72 hr., the low strength polished concrete LSPC specimens had low early abrasion mass losses and the rate of loss increased with time as shown in Figure 8. The concretes with surface treatments showed increased abrasion resistance compared to untreated concrete. The mass loss for low strength concrete (LSC) every 12 hours was 2.23%, 3.19%, 4.61%, 5.05%, 5.98%, 6.87%. While the mass loss for low strength polished concrete (LSPC) every 12 hours was 1.19%, 2.01%, 3.05%, 4.96%, 5.92%, 6.75%. The strength of the concrete surface was higher than that of the concrete body. The abrasion resistance of the concrete surface was largely controlled by the strength of the hardener (cement powder), while the abrasion resistance of the underlying concrete was controlled by the strengths of the matrix and aggregate (Figures 5, 6).

The mass losses of low strength concrete (LSC) surfaces were significantly higher than those of the low strength polished concrete (LSPC) surfaces shown in Figure 6. The mass losses of low strength concrete (LSC) surfaces after

Table 2. List of percentage abrasion weight loss with time of all specimens. Author A. W. R. Razzaq

Specimen	Percentage abrasion weight loss %							Compressive Strength after 28 days MPa
	0 hr.	12 hr.	24 hr.	36 hr.	48 hr.	60 hr.	72 hr.	
Low strength concrete (LSC)	0	2.23	3.19	4.61	5.05	5.98	6.87	24.8
Low strength polished concrete (LSPC)	0	1.19	2.01	3.05	4.96	5.92	6.75	26.2
High strength concrete (HSC)	0	0.94	1.98	2.79	3.33	4.11	4.97	50.3

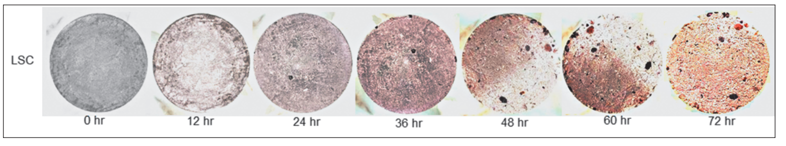

Figure 5. Various stages of abrasion on low strength concrete (LSC) specimen. Author A. W. R. Razzaq

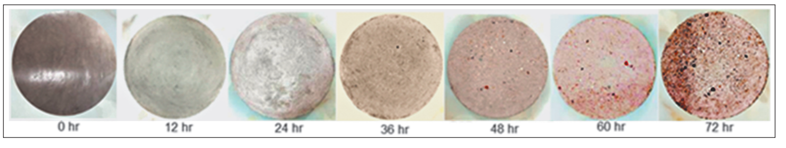

Figure 6. Various stages of abrasion on low strength polished concrete (LSPC) specimen. Author A. W. R. Razzaq

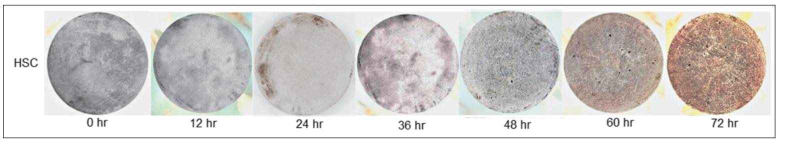

Figure 7. Various stages of abrasion on high strength concrete (HSC) specimen. Author A. W. R. Razzaq

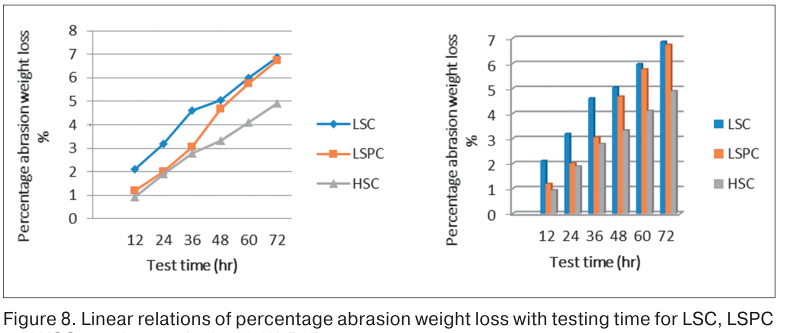

Figure 8. Linear relations of percentage abrasion weight loss with testing time for LSC, LSPC and HSC specimens. Author A. W. R. Razzaq

36 hours of abrasion test were around 4.61% and those of low strength polished concrete (LSPC) surfaces were only 3.05% (Table 2). The results thus confirmed that the surface treatment by polishing surface significantly improved the strength of concrete surface, this is consistent with the previously reported research [12]. The polishing of concrete surface resulted in the increased strength and reduced roughness which contributed to the reduced mass loss. This showed that the surface improvements with treatment were strong and increased the ability to resist abrasion by around 34%.

In Table 2 shows the comparisons of mass loss after a test time of 72 hr. for concretes with compressive strengths of low strength concrete (LSC) 24.8 MPa and high strength concrete (HSC) 50.3 MPa, the mass losses of specimens as a percentage of mass loss of corresponding original concrete specimens were 6.78, 4.97 respectively. For high strength concrete (HSC), the mass losses were relatively small and increased linearly with time (Figure 8). Concretes with high compressive strengths, the mass loss reduced with the increase in strength of concrete as expected. This is consistent with the previously reported researches [5; 12; 20]. When the concrete had a high compressive strength, the strength of surface concrete was also high and thus had the ability to resist abrasion as well (Figure 7).

We can comparison between LSC, LSPC and HSC. As depicted in the Figures 5–7, LSC specimen with the lowest strength 24.8 MPa, experienced the worst abrasion, while lower abrasion losses were recorded for the specimen HSC higher strength 50.3 MPa. From the figures, it is clear that the eroded regions were approximately more for the LSC specimens, steel balls were able to strip the thin layer from the exposed surfaces, where the coarse aggregates were visible. In contrast, fewer aggregates were stripped from the specimens with the greater strengths HSC. The eroded regions were more visible in the LSC specimens than in the HSC specimens.

It is obvious (Figure 8), the abrasion increases with the decrease of the concrete compressive strength. This trend is also clear by the comparison of the final surface abrasion pictures (Figures 5–7). The differences become clearer between the three concrete grades after the 72 hr. of abrasion testing. This result is directly attributed to the development of surface hardness with the increase of concrete strength, which absolutely results in better abrasion resistance.

Based on the results obtained, polished concrete led to a delay in abrasion in the aqueous environment compared to unpolished concrete with the same components, at 12 hours, 24 hours and 36 hours, the percentage abrasion weight loss in low strength polished concrete (LSPC) were 1.19, 2.01, 3.05, which is close to the abrasion in high strength concrete (HSC) 0.94, 1.98, 2.79 for the same test duration, while at 48 hours, 60 hours and 72 hours the percentage abrasion weight loss of low strength polished concrete (LSPC) were 4.96, 5.92, 6.75, which is close to the percentage abrasion weight loss of low strength concrete (LSC) 5.05, 5.98, 6.87 for the same test duration, The reason is that when the concrete surface was polished and cement powder was added as a hardener, this process leveled the surface, reduced pores and permeability, and made the surface have a smooth and even texture (Figure 9), when testing, the Iron Balls slid over the smooth surface of the poured concrete, causing less corrosive damage compared to unpolished concrete, which has pores and a rather rough surface.

But the high-strength concrete had a greater abrasion resistance than the polished concrete due to the components of the concrete mix, where the abrasion of the concrete depends on the components of the concrete mix and the strength of the concrete. We conclude that polished concrete is an effective solution for abrasion resistance, the abrasion resistance increases from the use of coatings with polishing for the concrete surface, perhaps comparable to the abrasion resistance of high-strength concrete.

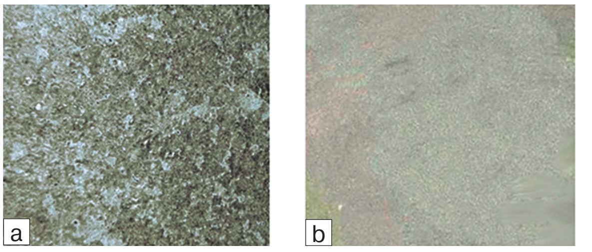

Figure 9. Concrete surface texture (a) non-polished (b) polished. Photo A. W. R. Razzaq

Conclusion

The study revealed crucial insights into the factors affecting the abrasion resistance of concrete in hydraulic environments. The ASTM C1138 was utilized to carry out abrasion experimental evaluations. Within the limitations of the variables and test procedures used in this study, cylindrical specimens were evaluated to assess the abrasion resistance of three different kinds of specimens (low strength concrete (LSC), low strength polished concrete (LSPC) and high strength concrete (HSC)). Within the scope of this study, the following can be summarized as the main conclusions:

1 With respect to the loss in weight of specimens underwater in the abrasion test, abrasion is more in the case of LSC as compared to the loss in weight of LSPC, which is in great concurrence with the experimental results of the previously conducted study. Concrete surface improvement by polished surface with cement powder resulted in a 34% increase in the abrasion resistance of the concrete surface compared to the untreated concrete surface. The untreated concrete surface had voids or pores at the surface zone whereas the concrete polishing surface was dense and non-porous. When compared to low strength concrete (LSC), low strength polished concrete (LSPC) exhibited noticeably lower surface abrasion losses, which reflects the better anti-abrasion resistance when the concrete surface is polished during construction or repairs.

2 The study also emphasized that the strength of concrete plays a crucial role in increasing abrasion resistance. This result emphasizes the importance of careful overall selection during the design of the mixture to improve durability. Optimizing material selection and mixing ratios for concrete and additives with surface treatments can greatly improve the long-term resilience of concrete structures in abrasive hydraulic conditions.

3 For all abrasion specimens, the abrasion test results conducted in this study in addition to literature results showed that the abrasion deterioration increased as testing time increased. However, it was found that the time rate of this deterioration was dependent on the age, strength grade and type of the tested concrete specimens.

4 Polished concrete has shown to be exceptionally effective in various application scenarios, particularly in hydraulic environments. Its natural durability and resistance to abrasion make it a preferred choice for structures that are exposed to both water and abrasive substances. A notable example is found in hydropower facilities, where polished surfaces significantly minimize wear caused by sediment-laden flows while maintaining structural integrity. The smooth finish also helps reduce drag on the water flowing over these surfaces, thereby improving operational efficiency. Another area where polished concrete excels is in industrial settings marked by heavy foot traffic or machinery operation. The abrasion-resistant nature of polished surfaces leads to lower maintenance requirements and fewer repairs over time, positioning it as a cost-effective option for factories and warehouses.

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