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Abrasion Resistance of Ultra High Performance Concrete used in Dams – A review

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ABSTRACT

Abrasion erosion in concrete hydraulic structures is a common problem which reduces the service life of the structure. Ultra High Performance Concrete (UHPC) is a new class of concrete known for its superior durability, strength, and ductility, along with enhanced abrasion resistance compared to Normal Strength Concrete (NSC) and High Strength Concrete (HSC). The typical mix for UHPC includes cement, silica fume, fine sand, fibers, and a very low water-to-cement (w/c) ratio. While the abrasion resistance of UHPC has been investigated under various flow conditions, the impact of varying paste content and fiber dosage remains unclear in the literature. This study focuses on the abrasion resistance of UHPC with different fiber dosages while maintaining a constant paste content. The abrasion tests were conducted following ASTM C1138. The results indicate that abrasion resistance decreases as fiber content increases.

Keywords: Ultra High Performance Concrete (UHPC), Abrasion Resistance, Hydraulic Structures, Steel Fibers, Concrete Durability, Cavitation and Abrasion Erosion

Introduction

Erosion in Hydraulic Structures

Cavitation Erosion

High-speed water flowing over the concrete surface can create points where the water pressure decreases below the vapor pressure of water, which causes the formation of water bubbles and the sudden collapse of the water bubbles momentarily, if the bubbles are burst near the surface of concrete, the high impact forces cause the formation of microcracks and thus it progressively makes the concrete surface weaker with each impact.

Abrasion Erosion

Abrasion erosion happens due to the friction and impact forces generated by the water and particles of varying sizes often collectively called as debris. This action results in the surface concrete wearing away, allowing water to seep into the microcracks, which further leads to delamination of the concrete.

Ultra high Performance Concrete

Ultra-High Performance Concrete (UHPC) is an advanced form of high-performance concrete that exhibits exceptional strength, ductility, and durability. It has become one of the most trending topics in the industry. According to ASTM C1856, UHPC is a composite cementitious mixture with a compressive strength of more than 120 MPa, measured on cylinders with a diameter of 75 mm and a height of 150 mm. This concrete is typically composed of cement, fine-grained sand, silica fume, water, superplasticizer and steel fibers, with water-binder (w/b) ratios ranging from 0.15 to 0.25. UHPC offers enhanced durability and resistance to environmental degradation, as well as lower permeability due to its dense microstructure.

Abrasion resistance of NSC and HSC

Hydraulic structures like dams, canals, drainage tunnels, harbours, are constantly in contact with flowing water. The friction caused by the flowing water and particles it carries result in abrasion of the concrete surfaces. This gradually wears off the surface and makes the structure prone to other types of damage. It is estimated that 70% of the damage to hydraulic structures is due to high velocity water flow [5]. The influence of steel fibers on abrasion resistance is still not clearly understood because some studies show that resistance increases [8], whereas some show opposite effect [10,11]. Studies which show positive impacts of steel fiber inclusion attribute that to the angle of abrasive action w.r.t the sample surface and the formation of the shadow zone, also the ability of fiber to bridge across the micro-cracks which increases the energy required for fiber-mortar separation and micro-crack formation [9]. Some studies [10], [11] have observed the contrary, the claim being that fibers have low adhesion to Mortar which leads to further deterioration of concrete around fibers due to the vibration of these rigid steel fibers caused by the abrasive charges.

Abrasion Resistance of UHPC

Although some studies [6], [7] show that UHPC has better abrasion resistance than HSC and NSC due to its highly densified matrix and optimized microstructure. This study showed that the UHPC with fiber inclusion has more abrasion than UHPC without fiber.

Materials and Mix Proportions

OPC with a specific gravity of 3.15 was used as the primary binding material. Undensified silica fume served as a supplementary cementitious material (SCM) to enhance the density and durability of the concrete. Quartz sand, with a granular size distribution ranging from 150 µm to 600 µm, was utilized as fine aggregate, along with quartz powder to improve the packing density of the mixture. To achieve the desired workability, a high-range water-reducing admixture (superplasticizer) was incorporated. Steel fibers, each measuring 13 mm in length and having an aspect ratio of 65, were added to the mix. The water-to-binder (w/b) ratio was maintained at 0.20 to ensure optimal workability and mechanical properties.

The study involved three types of ultra-high-performance concrete (UHPC) mixtures, differentiated by varying dosages of steel fiber content (percentage by volume). For each type of mix, two cylinders with a diameter of 300 mm and a height of 100 mm, as well as three cubes measuring 100 mm on each side, were cast for testing. The mix designs were identified as Mix 0, Mix 0.5, and Mix 1, corresponding to fiber contents of 0%, 0.5%, and 1% by volume, respectively.

Table 1 Mix proportions and properties per m^3 of concrete

Sample	Mix 0	Mix 0.5	Mix 1
Cement (kg)	869.06	869.06	869.06
Silica Fume (kg)	173.81	173.81	173.81
Quartz Sand (kg)	938.32	938.32	938.32
Quartz Powder (kg)	234.58	234.58	234.58
Fiber Content (%)	0	0.5	1
Superplasticizer (%)	1.5	1.5	1.5
Water-binder (w/b) ratio	0.20	0.20	0.20
Compressive Strength (N/mm^2)	113.31	139.79	148.13

*Compression test conducted on cubes of size 100 mm.

Experimental Setup

The experiment was conducted according to under water method ASTM C1138 [12]. 'Underwater method' by ASTM C1138 can simulate the abrasive action of gravel particles like silt, sand, gravel, and other solids. This test method covers a procedure for determining the relative resistance of concrete to abrasion under water. In a steel tank, the cylindrical sample of height 100 mm and dia 300 mm are placed in the container. The agitation paddle rotates at a speed of 1200 rpm. Since UHPC has high abrasion resistance, the testing duration has been extended to 120 hours to better differentiate between volume losses of different UHPC mixes. The measurements were taken at 24 hour intervals. To study the volume loss caused by abrasion, calculations were made as per the ASTM C1138 and the results are shown in Figure 6.

Figure 2. Test Setup according to ASTM C1138 [4]

Test results and discussion

The Abrasion test results show that mixes with increasing fiber content had more volume loss compared to Mix with no fiber. This observation is supported by a few studies [10,11], although some have observed the opposite [9,13,14]. The observations made in this study can be attributed to the high rigidity of the steel fibers which create grooves in the cement matrix upon impact of the abrasive steel balls [12], this causes the formation of microcracks at the fiber paste interface, which further propagates the cracks causing delamination of the fiber and loosening of the cement matrix. Although the shadow zone has been formed as shown in Figure 3, the fibers do not protect the shadow zone for a longer time and eventually the mortart surrounding the matriz gets abraded. This type of abrasion testing casues impact forces and shear forces along the surface of the sample. The shear forces are the dominant forces in this typoe of testing, studies [5,10,11] have shown that at shallow abrasion angles, fiber cutting, pull out and delamination are observed which confirmed in this study.

Also since the Abrasion test setup runs at 1200 rpm, the impact forces due to the saltation of the steel balls causes indentation at the edges of the concrete samples. Those indentations are also observed by [13], although those are not as prominent as observed in this research, this confirms that the velocity of the abrasive particles accelerates the abrasion damage on concrete [8], [10].

Figure 3. Indentations caused by high speed steel balls

a)

b)

c)

Figure 5. a) Fiber delamination, b) Fiber crushing, c) Fiber pull out

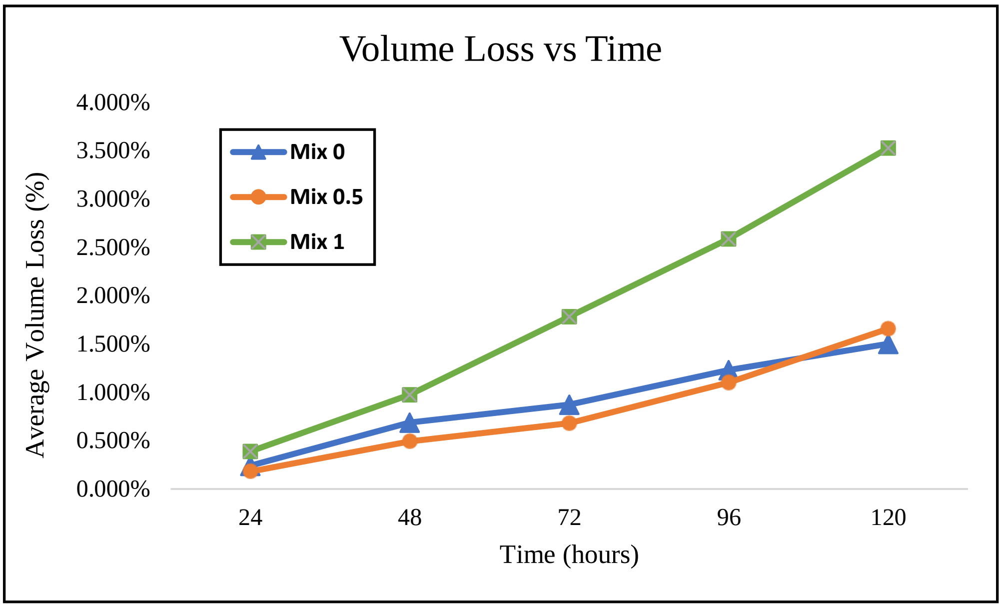

Figure 6. Volume loss of the tested specimens with varying fiber dosage

Conclusion

The following conclusions are made in the abrasion resistance tests performed on UHPC samples with different fiber contents (0%, 0.5%, and 1%):

- Mix 0 showed the highest abrasion resistance with the least amount of volume loss, suggesting that a mix lacking of fibers offer better abrasion resistance.
- Despite having the maximum compressive strength, Mix 1 had the highest volume loss and the lowest abrasion resistance. This is probably because of the fibers' rigidity, which caused microcracks to form at the fiber-mortar interface.
- Mix 0.5 initially showed better abrasion resistance than both Mix 0 and Mix 1, but its performance declined over time due to deterioration around the fibers caused by their vibration.
- The so called "shadow zones" were observed around the impact areas, where fibers acted as a shield and contributed to better resistance to abrasion.

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