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Research Article

A Study on the Abrasion Resistance of Hydraulic Structures with Different Repair Mortars

Getinet Melesse,[1] **Hibretu Kaske Kassa**,[2] **Minale Geta**,[2] **Tigist Simachew**,[2] **Tewodros Mamo**,[2] **Adal Mengesha**,[2] **and Tegegn Asale**[1]

[1]*Faculty of Civil Engineering, Arba Minch University, Arba Minch, Ethiopia*
[2]*Department of Civil Engineering, Debre Tabor University, South Gondar, Ethiopia*

Correspondence should be addressed to Getinet Melesse; getinet.melesse@amu.edu.et

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One of the main problems with hydraulic structures is that floating silt, gravel, ice sand, boulders, and other materials circulating over a concrete surface have an abrasive effect that causes hydraulic structures to abrade. Abrasion causes concrete to degrade, which could eventually expose the reinforcing to corrosion. In addition to section loss, reinforced concrete hydraulic structures' endurance may also be a problem. Repair mortars are used to restore surfaces that have been abraded. The suitability of various repair materials for use as a repair layer on concrete surfaces is examined in this study. In order to apply different repair mortars to concrete specimens and subject them to abrasive forces, this work employs an experimental methodology. The ASTM C 1138 standard was followed for testing the abrasion resistance of the samples repaired using repair mortars underwater. Both silica fume mortar and polymer-modified mortar were employed in the study as forms of repair mortar. For each type of repair mortar, three cylindrical concrete specimens were cast, along with control specimens. Hence, nine cylindrical concrete samples in total were employed in this study. In order to quantify the effect of abrasion and, consequently, to assess the efficacy of various repair materials, abrasion volume loss was measured. Important findings about each type of repair material's resistance to underwater abrasion are included in the study. The findings show that in terms of abrasion resistance underwater, the polymer-modified mortar performs better than the silica fume mortar.

1. Introduction

Abrasion erosion affects hydraulic structures, which complicates upkeep. Minor erosion due to abrasion may go unnoticed, but extreme erosion can significantly decrease the durability of concrete. Abrasion-erosion harm is brought on by the rolling and grinding action of water-borne particles such as sand, silt, gravel, and other solid refuse.

In a study [1], the optimal roughness index of the concrete surface for structural and nonstructural restoration was evaluated in order to assess the applicability of cement mortar modified with expansive admixture and fibers for the repair of hydraulic structures. Expansive admixture and polypropylene fibers were discovered to increase the cement mortar's adhesion properties and the roughness of the concrete surface that needed to be repaired. For the restoration of reinforced concrete in hydraulic structures (where frost-resistant mark F100 is required), it is thought that utilizing cement mortar modified with expansive admixture and a well-prepared concrete surface is the best option.

Reference [2] shows that throughout their useful lives, concrete structures are susceptible to both internal and external damaging forces. To maintain and increase the service life of the structures against destructive forces, it is crucial to prevent substantial damages through suitable concrete repairs. Slant shear tests were conducted on 168 samples over the course of two phases, and they looked at the variables affecting the bond strength. The effects of replacing a portion of cement with silica fume (SF) and two types of metakaolin (MA and MB) are examined in the first stage.

The best results were obtained with PCS-applied specimens, and only metakaolin type B could boost the bond strength. It was not advised to use BS as an interfacial adhesive in concrete repairs that were in contact with water. When applying pozzolan, the type of interfacial adhesive must also be considered along with the chemical components of the pozzolan.

An investigation [3, 4] showed that the effect of aggregate type, water-binder ratio, and maximum aggregate size on concrete's capacity to endure abrasion was examined using the underwater technique. The bottom slab repair concrete in the desilting channel was made using four different combination ratios. The results show that the abrasion resistance of concrete made using iron ore and/or iron sand is greater than that of concrete made with natural gravel and/or natural sand. In order to boost the concrete's resistance to abrasion while preserving its compressive strength, the water-binder ratio and maximum aggregate size were reduced. According to field test and laboratory data, a reasonable balance between aggregate strength, mortar strength, and the interfacial bonds between aggregate and mortar may significantly boost the abrasion resistance of concrete.

According to [5], the effect of the fibers on the abrasion resistance of high volume fly ash (HVFA) concrete was investigated when variable percentages of class *F* fly ash and various amounts of fibers were used. These monofilament fibers are alkaline resistant, have a minimum thermal and electrical conductivity, are 12 mm long, and are composed entirely of virgin polyester. In this investigation, the Indian Standard Specifications IS 1237-1980 were used. In this study, the compressive strength and fiber content of the same batch of HVFA concrete from the same age were compared. According to test results, adding fibers to the HVFA concrete matrix improved abrasion resistance. According to test results, adding fibers to the HVFA concrete matrix improved abrasion resistance. The fibers are crack arresters that can increase tensile strength and postpone abrasion, despite the fact that their maximal abrasion resistance augmentation is just approximately 15%. This might be because these monofilament fibers are more flexible than conventional plastic fibers.

The design and evaluation of an experimental study on lime, naturally occurring hydraulic lime, and lime-cement mortars were explored [6]. Lightweight aggregate, expanded perlite, expanded glass granules, and zeolite were all employed in the study as complete replacements for quartz sand. The experiment produced mortars that had high porosity, low density, good mechanical qualities, and enhanced water vapour transport and absorption due to the use of light-weight aggregates in their composition. The development of mortars with outstanding salt resistance that were virtually independent of the type of binder was then made possible by lightweight aggregates. The use of lightweight aggregates and the addition of salt to mortars had the desired effect of increasing the amount of porous area and increasing the capacity to hold water vapor.

In [7], the usage of marginal aggregates in concrete abrasion was investigated. The findings supported ASTM C 1138 and demonstrated that concrete with strong aggregates and a low loose angle value was less susceptible to abrasion damage than concrete with weak aggregates and a high loose angle value. This study evaluated the abrasion resistance of two distinct types of concrete repair materials that comprise additives such as silica fume mortar and polymer-modified mortar. These materials will be used to restore water-borne particle-eroded concrete surfaces on many hydraulic buildings. We compare the abrasion resistance of designated repair materials in terms of abrasion mass loss, strength, abrasion depth, and volume loss. These repair materials are used to restore the concrete surfaces of many different types of hydraulic structures, which are abraded by water-borne particles.

When conducting various types of experiments on the abrasion resistance of concrete, various authors took into account the effects of variables including the water-cement ratio, aggregates, compressive strength, fly ash content, the effects of RCC, PCC, and SC, surface coating, repair materials, flow rate, impact angle, erodent size, sand content in water, crack width, flow direction, curing, finishing processes, and others.

To evaluate Type I portland cement concrete containing 30% Class *F* fly ash [8], four w/cm ratios of 0.50, 0.36, 0.32, and 0.28 were employed. They adopted a test protocol designed specifically to evaluate the concrete's resistance to abrasion under the pressure of a water-jet and sand impingement. A water jet traveling at 8 m/s and containing 400 kg/m^3 of sand immediately strikes a concrete surface, exerting 0.17 MPa of pressure and causing abrasion. The test results showed that abrasion resistance is inversely proportional to the w/cm ratio used in the study. As a result, the rate of concrete abrasion erosion increases along with an increase in w/cm. To assess the performance of various combinations of portland cement concrete (PCC), roller compacted concrete (RCC), and soil cement (SC) for abrasion resistance, the authors in [9, 10] conducted research. Similar types of aggregate were utilized for each type of concrete to enable accurate comparison. For mixture design, each material was subjected to the ASTM standard process. According to the ASTM C1138 or under water technique, abrasion tests were carried out. SC demonstrated the least abrasion resistance, but RCC demonstrated the least abrasion loss, indicating higher efficacy against abrasion. When compared to PCC, RCC demonstrated greater abrasion resistance, especially in the initial 36 hours.

According to [11, 12], concrete compositions with Class *F* fly ash up to 15% of the cement content demonstrated comparable abrasion resistance to concrete without fly ash. After 15%, abrasion resistance reduced as cement replacement increased, especially at low w/c ratios. In this study, Class *F* fly ash was used to replace 15%, 20%, 25%, and 30% of the cement in high strength concrete (HSC), and the test was carried out in accordance with ASTM C 1138. It was discovered that the abrasion resistance of the concrete samples decreased with increasing fly ash concentration when cement substitution by fly ash was greater than 15% and the compressive strength of the concrete samples was same.

Using the water-borne sand flow impact abrasion method, the authors in [13] examined the impact of erodent size and concentration on concrete abrasion. Fixed w/cm ratio of 0.36 and 45° impact angle were employed. The results of the tests showed that the rate of concrete abrasion increased from 100% to 217% and 367%, respectively, as the size of the erodent grew [14, 15]. The basic reason is that when the erodent size is tiny, the little particles can only plastically deform the surface rather than starting cracks. With the exception of repair materials, every parameter has already been the focus of at least three or four separate tests. The service life of the hydraulic structure may be increased if a proper repair mortar is applied to the concrete surface that has been abraded. The building may eventually approach the end of its useful life and need upkeep. It is crucial in this situation to choose repair materials with higher abrasion resistance. This is the reason why it was decided to investigate concrete restoration materials.

2. Material and Experimental Methods

2.1. Mix of Concrete. The abrasion test specimen models are prepared by using M25 mix design in a concrete casting laboratory according to IS 10262:2009 code standard [16]. A mixer is used to mix the ingredients during casting the concrete, and the casting is done on a vibrating table. The specimen must cure for 28 days in water and then be stored for 60 days before the abrasion test can begin, and the abrasion test was done according to the ASTM 1138 standard. In India, concrete with a cube compressive strength of 25 MPa is widely utilized for tunnel lining projects in hydropower projects [7]. No standards or regulations specify a minimum acceptable quantity for concrete abrasion resistance. In the absence of this, the study employs concrete with sound aggregates (L.A. abrasion value of less than 30%) and a cube compressive strength of 25 MPa as a reference line for acceptable concrete abrasion resistance. Only variable in this study is the type of repair mortar used. The concrete strength rating M25 was applied to each sample. The proportioning of the concrete mix is shown in Table 1. Both silica fume mortar and polymer-modified mortar were applied to the abraded surface and evaluated for abrasion resistance. The replacement mortars were all supplied by Sika India. Twelve cylindrical specimens altogether were cast to evaluate the concrete's resilience to abrasion.

2.2. Materials Properties. Normal water, fine and coarse aggregate, and ordinary portland cement of grade 53 were used to create each test example. In this research, only materials that complied with the applicable Indian Standard Codes [17] were employed. In this study, the fine aggregate was sand that adhered to IS 383:1970 standards, and the coarse aggregate was rough, while angular aggregate being with a maximum specified size of 20 mm [17]. All properties of repair mortar materials are shown in Table 2. According to the manufacturer, some of the characteristics of concrete coatings are described as follows.

Table 1: Mix proportion of concrete.

S. No.	Components used	(kg/m^3)
1	Cement with OPC 53 grade	315
2	Course aggregate which is crushed angular	1360
3	Fine aggregate (river sand)	755
4	Water (faucet water)	140

2.2.1. Polymer-Modified Mortar (Sika Top®-122). Polymers are primarily used to modify mortars (portland cement + water + sand aggregate) rather than concrete, which is a mixture of mortar plus bigger aggregates such as stone or gravel. Polymers decrease the water evaporation rate so that the crystal structure can grow during these critical early curing stages and can build up strength. This reduced evaporation of water is primarily important in thin applications where the surface area is exposed to high evaporation, based on the volume of the mortar, for durability and improved strength. In comparison to unmodified mortars, hardened, polymer-modified mortars have improved tensile strength, flexural strength, impact and abrasion resistance, water resistance, and chemical resistance. The purpose of the polymer in mortar is to limit microcrack propagation, increasing the overall toughness of the mortar.

2.3. Mixing, Casting, and Curing. The investigation used the following cast specimens: For tensile strength testing, twelve cubic specimens with widths of 150 mm and heights of 150 mm and nine cylindrical specimens with diameters of 305 mm and heights of 102 mm were used. Control repair mortar, silica fume mortar, and polymer-modified mortar are all available in them. The dimensions of cylindrical examples were selected in accordance with ASTM C1138M 12. A tilting-type blender was used in the lab to create the mixture. Before casting each example, the various components of the mix, including cement, sand, coarse aggregate, and water, were kept ready in the appropriate amounts.

To ensure homogeneity, the color of the mixture and the amount of each ingredient were visually assessed. The slump cone test was used to gauge the new concrete's slump loss after mixing. Slump values between 50 and 75 mm were preserved throughout the development of the combos. All of the combos' bleeding and segregation were examined visually. There was neither bleeding nor segregation in any of the combos. Before being placed on a vibratory table with a speed range of 12000–400 rpm and an amplitude range of 0.055 mm for casting, molds were cleansed and oiled. After 24 hours, the specimen was taken from the molds and placed in water to cure until the testing day. The cubic specimens were then tested for compressive strength after curing, and the results were within the acceptable range, indicating that the material was safe against compressive strength.

Table 2: Properties of repair mortar materials.

S. No.	Type of repair mortar	Properties	Values	
(1)	Silica fume mortar	Compressive strength (at 28 days)	85 MPa	
		Flexural strength (at 28 days)	11 MPa	
		Hydraulic abrasion resistance index (at 28 days)	Abraroc	0.5–0.6
			Glass	1
			Granite	0.35–0.80
		Wear resistance Bohme	<6 $cm^3/50\ cm^2$	
(2)	Polymer-modified mortar	Compressive strength (at 28 days, +30°C)	55 MPa	
		Flexural strength (at 28 days, +30°C)	5 MPa	

2.4. Preparation of Specimens and Testing. After a 28-day curing time, all of the specimens were taken out of the curing tank and tested for cube compressive strength in a lab setting. All of the specimens passed the necessary limit. Throughout the study, the performance of all protective coatings against abrasion was tested using the underwater abrasion resistance technique [18]. The effectiveness of different protective coatings against abrasion was tested using a cylindrical specimen made of M25 concrete strength grade as a control specimen. The specimen surfaces were cleaned to remove dust and flattened to achieve an even surface to guarantee proper bonding when the protective coatings were applied. All other basic instructions from the manufacturer's product manual were followed when applying all repair mortars. Depending on the type of coating, all specimens were taken from the curing tank and put through an underwater abrasion resistance test in line with ASTM C 1138. Three test samples were examined for each result, and the average values were found. The mortars were only used as a repair mortar on the concrete's abraded surface on the tops of the concrete specimens. As a result, as shown in Figure 1, all repair materials were applied in accordance with the manufacturer's directions after first preparing the sample spacemen for mortar application [18]. In order to evaluate the abrasion resistance of concrete surfaces exposed to water particle abrasion on hydraulic structures such as spillway aprons, stilling basin slabs, culverts, and hydropower tunnels, the underwater abrasion resistance technique was developed in 1981. Figure 2 depicts a lab-fabricated test setup in addition to a schematic picture of the test apparatus. The apparatus consists of a drill press, an agitating paddle, steel grinding balls, and a cylindrical steel receptacle. The drill press's agitating paddle stirs the water in the cylindrical receptacle at a 1200 rpm speed. It causes the abrasive charge, made up of steel balls, to move around on the concrete specimen, causing abrasion effects on the surface. Each specimen was subjected to abrasive action for a total of 72 hours, as per ASTM C 1138 standard practice. At the end of every 12-hour interval, abrasion loss was measured and assessed. A vernier calliper was used to measure the specimen's diameter and height. The following formula was used to compute the abrasion loss of each concrete specimen:

$$V_t = \frac{(W_{\text{air}} - W_{\text{water}})}{G_W}, \quad (1)$$

where V_t = at the desired time, the volume of the concrete specimen in m^3, W_{Air} = at the specified time, the mass of the specimen in air in kg, W_{Water} = at the specified time, the mass of the specimen in water in kg, G_w = volume of the specimen before testing in m^3.

$$\text{VL}_t = V_i - \text{V}_t, \quad (2)$$

where VL_t = at the end of each time increment, the volume of material lost is calculated in m^3, V_i = in m^3, the volume of the specimen before testing.

Based on the volume of abraded material, the average depth of wear at the end of any time increase of testing.

$$\text{ADA}_t = \frac{\text{VL}_t}{A}, \quad (3)$$

where ADA_t = at the end of the test increment in question, average depth of abrasion in m,
A = area of top of specimen in m^2.

Various stages of abrasion action on the sample after every 12 hours and its abrasion loss for M25 control mortar, silica fume mortar, and polymer-modified mortar are shown in Figures 3–5, respectively.

3. Results and Discussion

Using an underwater abrasion resistance test in line with ASTM C 1138, the abrasion resistance of all repair mortars was assessed in terms of material loss and average abrasion depth. The test results are shown in Table 3 for exposure times varying from 0 to 72 hours. The best abrasion-resistant mortar of the repair mortars examined in this research, as determined by laboratory test results, had an overall reduction in abrasion loss of 64%. However, polymer-modified mortar, which decreased abrasion loss by 16%, outperformed silica fume mortar in terms of abrasion resistance. A more thorough analysis of the different repair mortars' rates of abrasion loss over time can be found in Figures 6 and 7.

For instance, during the first 12 hours of testing, abrasion loss rates for M25 repair mortar and silica fume mortar were roughly similar, but after a thin upper layer of silica fume mortar was abraded, it started to deviate. The precision of the correctly conducted test range between test results from the three samples should not be higher than 46.2% of their mean, in accordance with ASTM C1138M-12. The

(a) (b)

Figure 1: (a) Grinded samples to apply repair mortars; (b) demolished samples to have good bond strength with repair mortars.

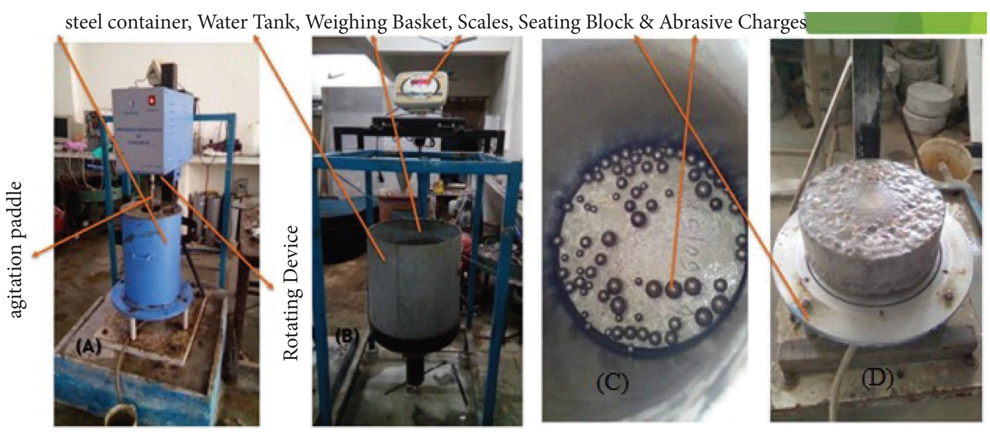

Figure 2: (A, C) Underwater abrasion resistance machine as per ASTM C1138; (B, D) the weighing machine for measuring the weight of samples in air and water.

measurement performed here is within the allowed range; the precision is between b/n 5 and 36.23%. The only change that occurs during abrasion is the decrease in depth; the average diameter of nearly all specimens used was 305 mm.

On hydraulic structures, the most commonly used commercially available repair mortars were silica fume and polymer-modified mortar. That is why it is chosen to test them for abrasion resistance underwater. So to validate the result, [19] is referred, who studied the performance of conventional, polymer-modified, steel-fiber, epoxy, and silica-fume mortars in a high-velocity water flow. The results of a comparative investigation to determine the mechanical characteristics, adhesion, and accelerated ageing of four repair systems are presented in this work. Epoxy and silica-fume mortar were the two solutions that performed better. Steel fibers are suitable for use as an intermediate layer for underwater repair due to their high adhesion to the substrate and mechanical performance. After ageing and underwater abrasion tests, this system showed obvious corrosion at the steel fibers on the surface, which should be evaluated before being employed on exposed spillway slab surfaces.

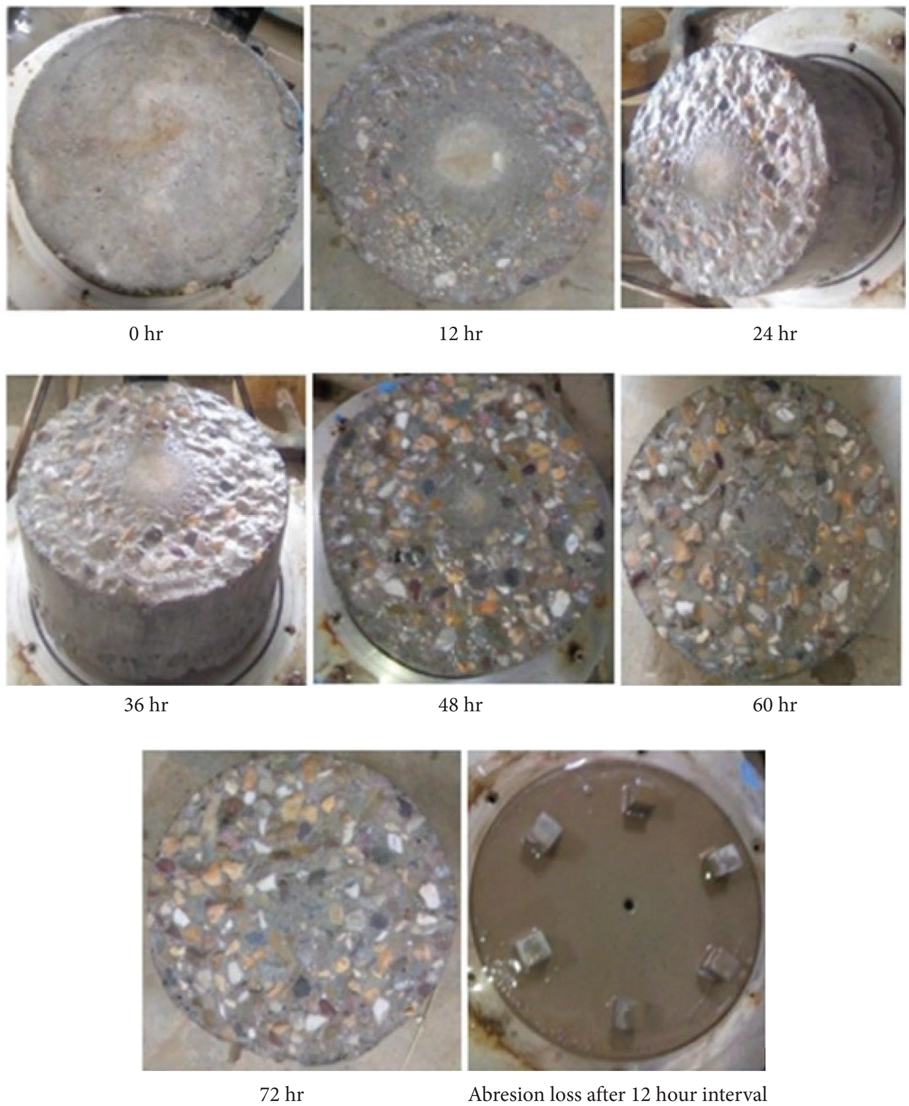

Figure 3: Various stages of abrasion action on the sample after every 12 hours and its abrasion loss for control specimen of M25 control mortar.

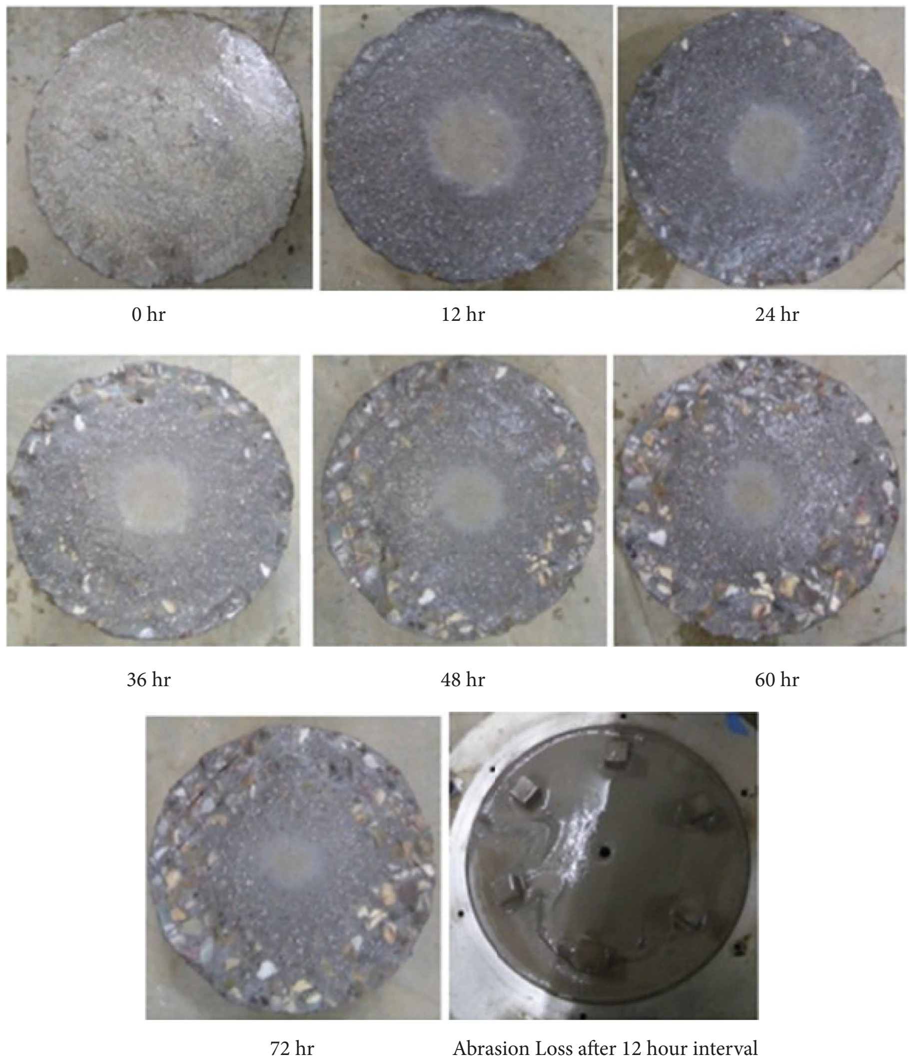

Figure 4: Various stages of abrasion action on sample after every 12 hours and its abrasion loss for silica fume mortar.

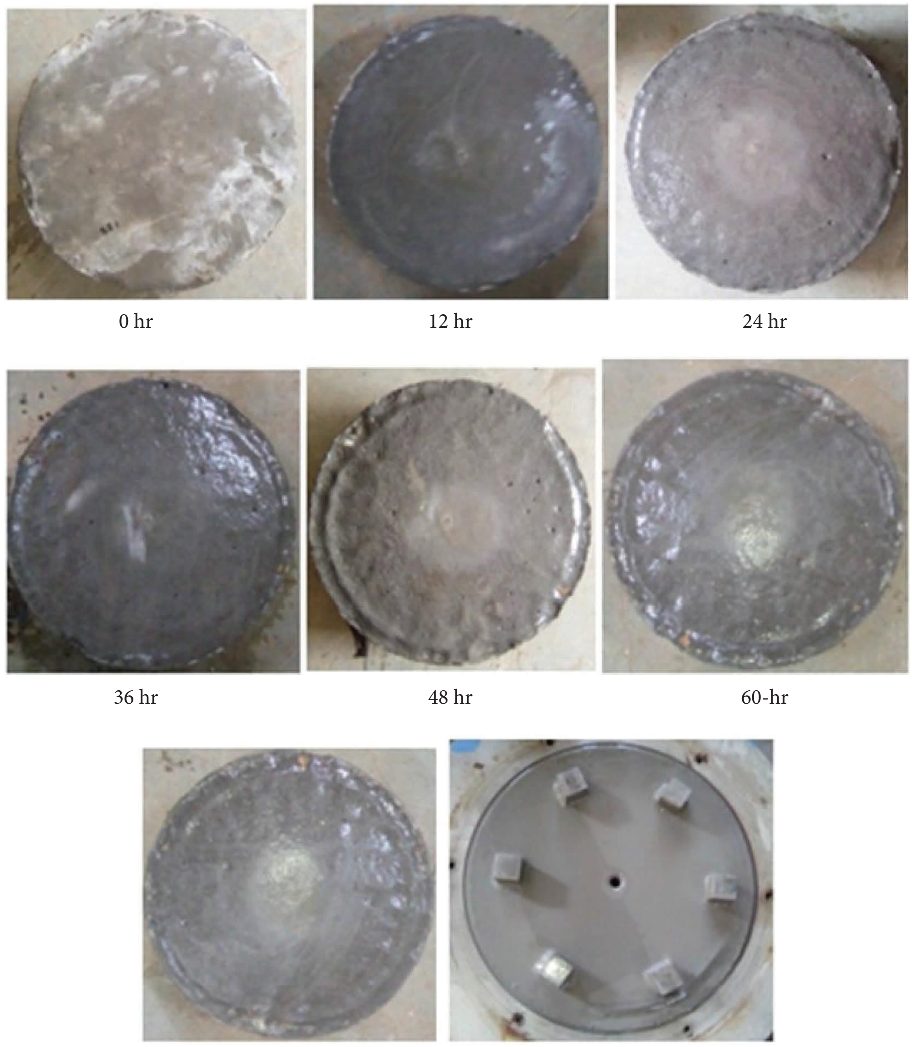

Figure 5: Various stages of abrasion action on sample after every 12 hours and its abrasion loss for polymer-modified mortar.

Table 3: Results of an ASTM C 1138 underwater abrasion test on coatings.

	Time (hours)	0	12	24	36	48	60	72
Volume of material lost (m^3)	M25 repair mortar	0	0.00007	0.00017	0.00024	0.00033	0.00041	0.00045
	Silica fume mortar	0	0.00007	0.00014	0.0002	0.00027	0.00032	0.00038
	Polymer modified mortar	0	0.00003	0.00006	0.00009	0.00011	0.00014	0.00017
Average depth of abrasion (mm)	M25 repair mortar	0	1.54	2.88	4.01	5.21	6.34	7.08
	Silica fume mortar	0	0.24	0.72	1.38	1.89	2.49	3.49
	Polymer-modified mortar	0	0.22	0.68	1.34	1.81	2.48	2.81

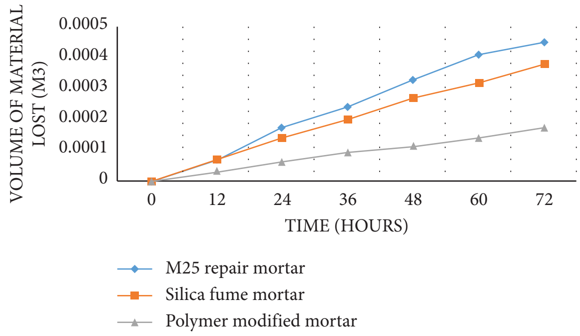

FIGURE 6: Variation in measured abrasion volume loss of different repair mortars.

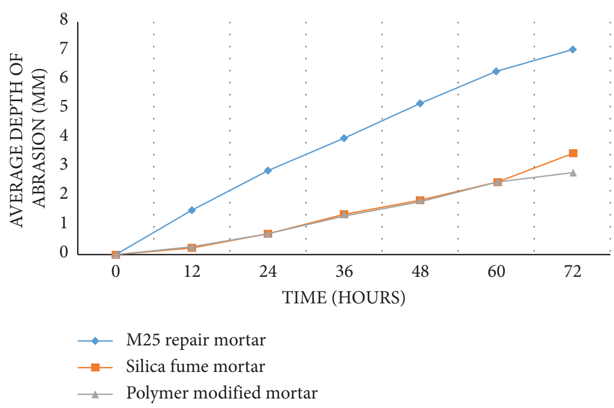

FIGURE 7: Varied concrete coverings have different measured abrasion average depths.

4. Conclusion

Nine cylindrical specimens were evaluated using ASTM C 1138 to assess the abrasion resistance of two different kinds of repair mortars and control specimens (silica fume mortar, polymer-modified mortar, and M25 repair mortars). Within the scope of this study, the following conclusions were made: with respect to the loss in weight of samples underwater in the abrasion test, abrasion is more in the case of M25 concrete control mortar as compared to the loss in weight of silica fume and polymer-modified mortar on hydraulic structure, which is in great concurrence with the experimental results of the previously conducted study. Again, when we compare the abrasion loss in weight of silica fume and polymer-modified mortar, polymer-modified mortar is better at resisting abrasion than silica fume mortar. Similarly, the loss in thickness and volume is more for the control specimen as compared to silica fume and polymer-modified mortar. In the case of repair mortar, using polymer-modified mortar is much better against abrasion resistance on the hydraulic structure than silica fume mortar, which is different from experimental results of the study for validation.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

The preprint of this manuscript is also available at https://ssrn.com/abstract=3995411.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Hibret Kaske Kassa, Getinet Melesse, and Tigist Simachew. The first draft of the manuscript was written by Hibretu Kaske Kassa, and all authors commented on previous versions of the manuscript. Then, Adal Mengesha, Minale Geta, Tewodros Mamo, Getinet Melesse, and Tegegn Asale were involved in revising the comments given by the editorial board. All authors read and approved the final manuscript.

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