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Research Article

First-Time Application of Underwater Live Concrete for Economic Retrofitting of Damaged Bridge Piers in Bangladesh

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This paper presents a comprehensive analysis of the use of underwater concrete (UWC) in the retrofitting restoration of bridge piers in Bangladesh. In Bangladesh, UWC is a comparatively new technology, and this investigation represents the first instance of its application in practice. This study's primary objective was to produce self-compacting, self-fresh concrete with minimal mass loss. To accomplish this objective, antiwashout admixture (AWA) was added to the concrete mix at varying weight percentages (0.1%, 0.2%, 0.3%, 0.4%, and –0.5%) to determine the optimal dosage of AWA that would result in the least amount of concrete washout. The slump and runoff resistance of the concrete mixture were evaluated, and it was observed that a certain percentage of AWA addition resulted in minimal cement mass loss. Furthermore, cost reduction was a major concern of this study, as it is essential to minimize project expenses. Thus, comparative cost analyses of various repair techniques were conducted to determine the most cost-effective approach for future underwater repairs.

1. Introduction

Bridges are a very important component of the transportation system. They are very costly to construct and repair, and there are many factors that may lead to the disintegration and deterioration of these structures [1]. The main building material of these robust structures is concrete. Globally, concrete is massively used due to its plethora of advantages, like flexibility of production and flexibility to be molded into different shapes, formulation simplicity, availability of raw materials, etc. [2]. Reinforced concrete is extensively employed to build bridges, jetties, breakwaters, and floating structures in coastal and underwater environments [3]. The success of concrete is largely related to its resistance to water without significant deterioration, making it an appropriate construction material for structures that control, retain, and distribute water [4]. Hence, the durability of concrete is significantly more important compared to any other material on Earth, provided that it is the second-most commonly used material on the planet, next to water. Therefore, maintaining the quality of concrete for construction is a very crucial factor, especially in the case of underwater and coastal structures, like piles, piers, jetties, bridges, etc. The environmental conditions underwater are more aggressive, unpredictable, and severe than those above water, so underwater concrete (UWC) structures are comparatively more vulnerable. These are caused by chloride content in water, sulfate attacks, abrasion erosion caused by slits, sand, and gravel, wetting and drying cycles, and the presence of waste and chemicals in water, and concrete is more susceptible to deterioration [4]. The formation of cracks in concrete increases the permeability of the concrete nearby, both underwater and in the splash zone. Thus, under seawater, chloride penetration is intensified in both depths and concentrations at the crack's proximal location, resulting in the formation of an anode at the reinforcing bars [5]. Therefore, these environmental factors will cause cracking, spalling, and corrosion, resulting in exorbitant costs. Extreme anomalous conditions and multifactor coupling exacerbate the underwater cracking phenomenon [6]. Consequently, large costs will be incurred for repairs, and the structural integrity and safety will deteriorate [7]. Cracks are more likely to jeopardize the safety and durability of UWC structures; as a result, it is important to identify and analyze crack damage to UWC structures [8].

The geographical characteristics of Bangladesh contribute to its abundant presence of rivers, waterways, and deltas. The aforementioned circumstances have resulted in a significant dependence on a complex system of bridges that not only enable daily transportation but also support commercial activities and emergency response services [9]. Over the course of several decades, a significant number of these essential infrastructural components have deteriorated to varying degrees. The rate of deterioration has been expedited by various factors, including insufficient initial engineering, the erosion of supporting banks, and the prevalent extreme weather conditions in the region, such as cyclones and seasonal flooding [10]. Furthermore, the cumulative effects of normal usage and occasional seismic events have resulted in the deterioration of certain bridge piers to a critical state. Unfortunately, the submerged condition of bridge piers frequently complicates the implementation of traditional techniques employed for their rehabilitation and retrofitting. According to Kennedy-Kuiper et al. [11], the implementation of standard repair tasks typically necessitates the presence of substantial dry conditions. Achieving such circumstances generally involves the costly practice of diverting or pumping water, hence introducing not only financial but also logistical complexities to the task at hand. Therefore, there is a pressing requirement for the development of more efficient, less intrusive, and cost-effective solutions. These solutions are not only crucial for maintaining the structural integrity of bridges but also for ensuring the safety of the people who depend on them.

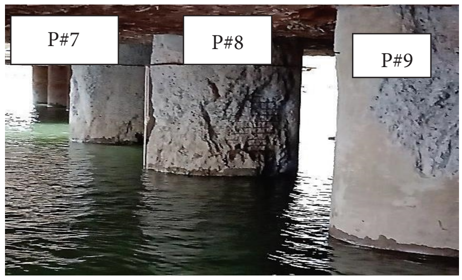
The application of UWC constitutes a notable progression within the field of civil engineering, specifically for endeavors that necessitate construction activities in submerged or partially submerged conditions. In contrast to conventional concrete, UWC is specifically designed and made for utilization in submerged environments. In order to maintain the structural integrity of the material, it utilizes specific admixtures and antiwashout substances, hence enabling it to be successfully poured under submerged conditions [12]. In the realm of bridge pier restoration and retrofitting, the utilization of UWC can provide a plethora of advantageous outcomes. First, it eliminates the necessity for costly and labor-intensive water diversion or drainage methods [13]. Additionally, the exceptional adhesive capabilities of this material render it highly suitable for adhering to preexisting structures, thereby minimizing the amount of preparatory work required for the previous surface. The great longevity of the product also results in a notable decrease in the frequency of necessary repair works, leading to long-term economic advantages [13].

Although the potential benefits of UWC are evident, its implementation in Bangladesh is still in its early stages. Significantly, a notable dearth of scholarly investigations exists regarding the performance of UWC systems within the distinctive environmental parameters of Bangladesh, encompassing its turbulent river currents, elevated sedimentation rates, and tropical climatic circumstances [14]. Furthermore, it is worth noting that the current corpus of knowledge lacks sufficient empirical evidence about the economic feasibility of employing UWC in extensive restoration initiatives inside underdeveloped nations [15]. Hence, the research's originality stems from its investigation into the utilization of UWC technology within the specific context of Bangladesh. The primary objective of this study is to address the notable deficiency in existing knowledge by offering empirical evidence on the performance and costs of the material in settings that are peculiar to Bangladesh. The capacity of UWC to provide a solution that is both sustainable and economically feasible has significant implications for infrastructure management, not only in Bangladesh but also in similar contexts worldwide.

In the current industry, UWC is one of the specialized varieties of high-performance concrete used to construct bridges, structures, and dams whose foundations are structured underwater [12]. Underwater placement of concrete for offshore and inshore construction work is a crucial challenge [16]. As a result, a series of precautions must be followed to ensure the efficiency and success of the underwater pouring technique [17]. The prerequisite for the successful placement of UWC is ensuring the proper method of UWC mix proportions and the proper technique of pouring concrete that can meet the international standards requirement for UWC [18]. The rheological and mechanical qualities of UWC have a direct impact on its performance. Therefore, the mechanical and rheological characteristics of UWC should be tailored to create a balance. The composition and rheological qualities of concrete determine its resistance to water diluting and segregation. Incorporating an antiwashout admixture (AWA) is one of the most effective strategies to reduce washout and segregation [19]. Coupling of AWA with a high-range water reduction agent, flowable and viscous concrete with a high level of fresh mixture stability can be accomplished [20]. The type of AWA has an immense impact on the strength of UWC because it consists of water-soluble polymers with a high absorption capacity, which affects the mixture's cohesion when submerged [21]. Many AWAs have been introduced in recent decades, and researchers are studying their behaviors and effects on UWC [16, 19]. The issue of the underwater structure disorder of the bridge is becoming increasingly apparent, which has seriously damaged the safe and reliable operation of the bridge structures [22] in Bangladesh; thus, it is vital to frequently inspect and repair the deteriorated underwater structures. In Bangladesh, UWC is a new technology, and there is still no practical elicitation of the UWC system except for this study.

2. Problem Statement

Arial Kha Bridge was constructed at some time between 2017 and 2018. Subsequently, it was commissioned and set free for traffic at the end of 2019. After 1 year, it has been observed that some of the piles at Pier 7, which were supposed to be in the land, have been exposed due to erosion in the riverbed and bank. It was further observed that the surface concrete in those exposed piles that did not have the steel casing, unlike those in the middle of the river, is poor in quality with numerous pores and honeycombs, and in a few places, rebars were seen corroded to some degree (Figure 1). It was then



(a)

(b)

Figure 1: (a) and (b) Affected and exposed piles.

decided to extract cores from some of the piles and investigate the quality of the concrete at the greater depth of the pile from the surface toward the center. Subsequently, a local consultancy company, Design Den, was entrusted to carry out the work and submit a report on the extracted cores. There are eighteen piles in Pier 7 having a diameter of 1,500 mm each with 40 nos 32 mm rebars, leaving a space of about 85 mm between two successive rebars.

2.1. Possible Reasons Assumed for the Damage Caused. Several reasons were considered part of the investigation on the damage of the pile surface in this paper. The possible reasons that may cause the damage are described in the next section.

2.1.1. River Course Shifting. While designing the structural members of the bridge, shifting of the river course was not considered. The figure demonstrates how the riverbank was moved during each monsoon following the bridge's construction, exposing the piles from the waterbody. The piles of Piers 6–9 were originally intended to be land piles without permanent casings because the riverbank was located at Pier 5. The riverbank near Pier 6 was eroded and moved prior to the installation of Pier 7 piles, which increased the water content in the sand near the piles. After the 2020 monsoon, the land of Pier 7 washed away as the riverbank continued to move toward the Bhanga end. After that, the piles of Pier 7 were exposed, and defects were discovered on their exterior surface. The bridge and pier location of the bridge are shown in Figure 2.

2.1.2. Absence of Permanent Casing. During construction, the permanent casing was not used in Piers 7–9 as they were constructed over the land, and river erosion phenomena were not kept in consideration, although all the piles of the existing two-lane bridge were provided with permanent casings. The permanent steel casing was provided to Piers 1–6 but not to Piers 7–9. The defects started after the temporary casings were removed because nearby sand with a high water content blended with the outer concrete.

2.1.3. Contractor's Workmanship. Initially, it was assumed that the damage may have been due to defective workmanship from the contractor's end. Several initiatives were taken to justify the accuracy of the work executed by the contractor party. Those are described in the next section.

(1) Pile Diameter Check. After the piles were exposed, the diameter of the piles was checked to confirm whether they were constructed per the design diameter of 1.5 m. The average diameter of piles was found to be 1.6 m, which is more than the design diameter. Therefore, the diameter of the piles conformed to the design.

(2) Pile Integrity Test (PIT). After the construction of the piles, the PIT test was performed and found satisfactory. Though the PIT cannot be considered a precise method to determine the strength of the pile, further measure was taken to find out the strength of the exposed piles.

(3) Compressive Strength of Pile Concrete. The pile layout of Pier 7 can be seen in Figure 3. About 70-mm diameter cores were extracted following ASTM C 42 standard [23]. Cores were drilled radially towards the center of the pile with an approximate length of 600 mm. In most of the cases, the length of the obtained cores was nearly 600 mm, with few exceptions where the cutting barrel did not penetrate after a certain depth. In all cases, cores were divided into halves (300 + 300 mm) during the extraction procedure due to the limitation of the length of the cutting barrel and machine capacity. In a few cases, main rebars were trimmed off a few millimeters due to the fact that spacing between two rebars was seen as less than 70 mm. In some cases, it was observed that the concrete clear covers were more than the anticipated 75 mm, and the main rebars were located at a greater depth than expected. So, it was quite difficult to detect the rebar accurately with the help of a rebar scanner. Extracted cores were then properly designated and preserved for future investigation (Figure 4). A summary of the extracted cores is given in the following Table 1.

All the extracted cores were preserved in plastic bags following ASTM C42 standard [23]. Drilled cores were then carefully arranged in a cardboard box with cork sheet and transported to CRTS, KUET, for testing. Thirteen specimens were prepared for compressive strength tests following ASTM C 39 and ASTM C 42 Standards [23, 24]. The setup of the compressive strength test is given in Figure 5.

(4) Test Results of Extracted Cores. The design strength of the core extracted from the piles is 30 MPa. From the test results, it appears that the subsurface concrete (Figure 6) is of good quality and has sufficient strength. No individual test result falls below 75% of the design strength (f'_c) of 30 MPa according to ACI 301-16 [25]. Also, the average test strength is about 32.7 MPa, which is well above the design strength of

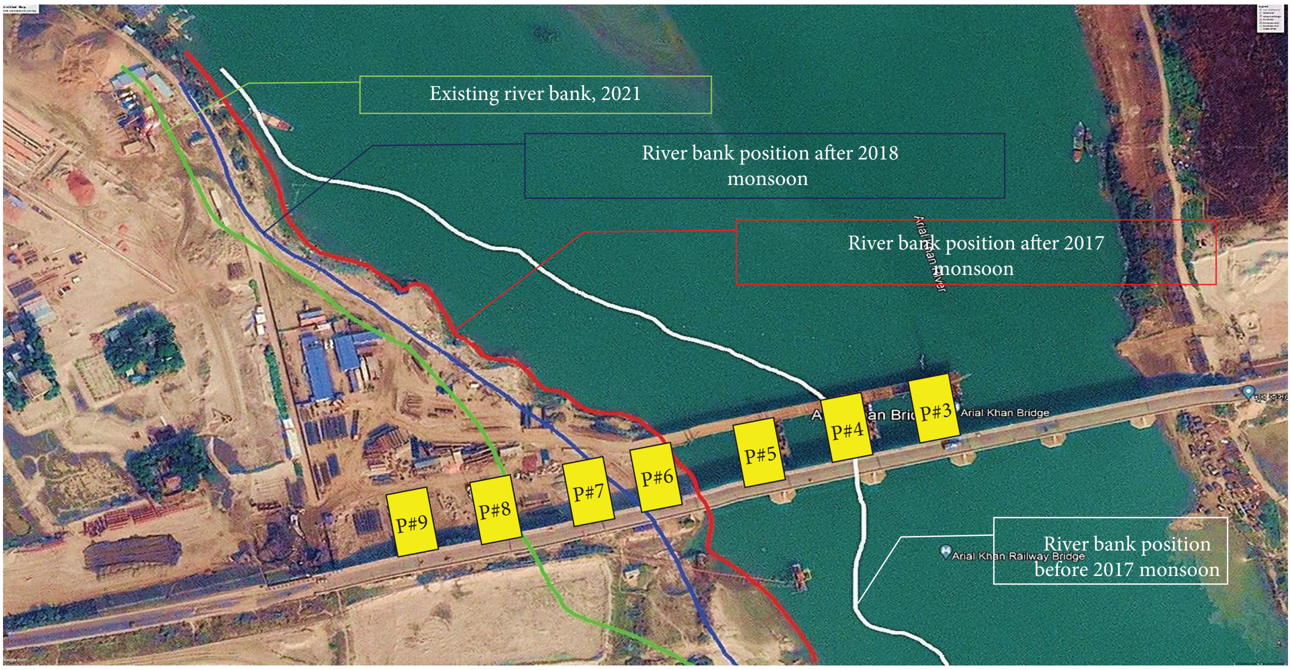


Figure 2: Bridge location in Google Maps and elevation of the bridge.

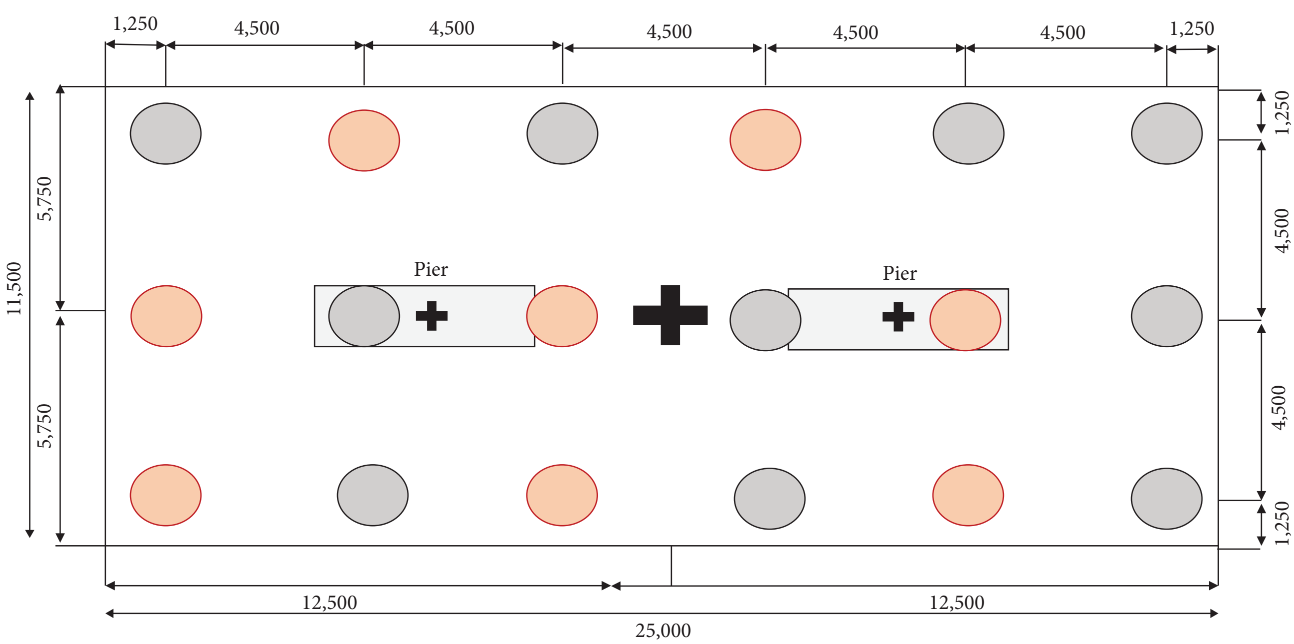


Figure 3: Pile layout of Pier 7.

30 MPa, where ACI code permits an average strength of 85% of design strength f'_c. However, the concrete at the surface of these piles appeared as potentially deficient in the required strength and needed to be removed. The extent and depth of removal depend on the condition of the concrete of a particular pile. It was recommended that the cover concrete over the 100 mm spirals be removed altogether. The removal length was from the bottom of the pile cap to a level that was deemed necessary by visual observation but not less than the riverbed. After scraping the cover concrete from the surface of the pile, the heavily corroded rebars were removed and replaced with new ones.

(5) Drilled Core Hole Repair Methodology. The hole caused by the core is filled with non-shrinkage mortar without slump and tamped with temping rod on every 10 cm. After the hole is filled, a solid tube is pressed into the hole and tightly tied to the pile body until the mortar is finally set before removing. The nonshrinkage mortar adopts MASTERFLOW®870

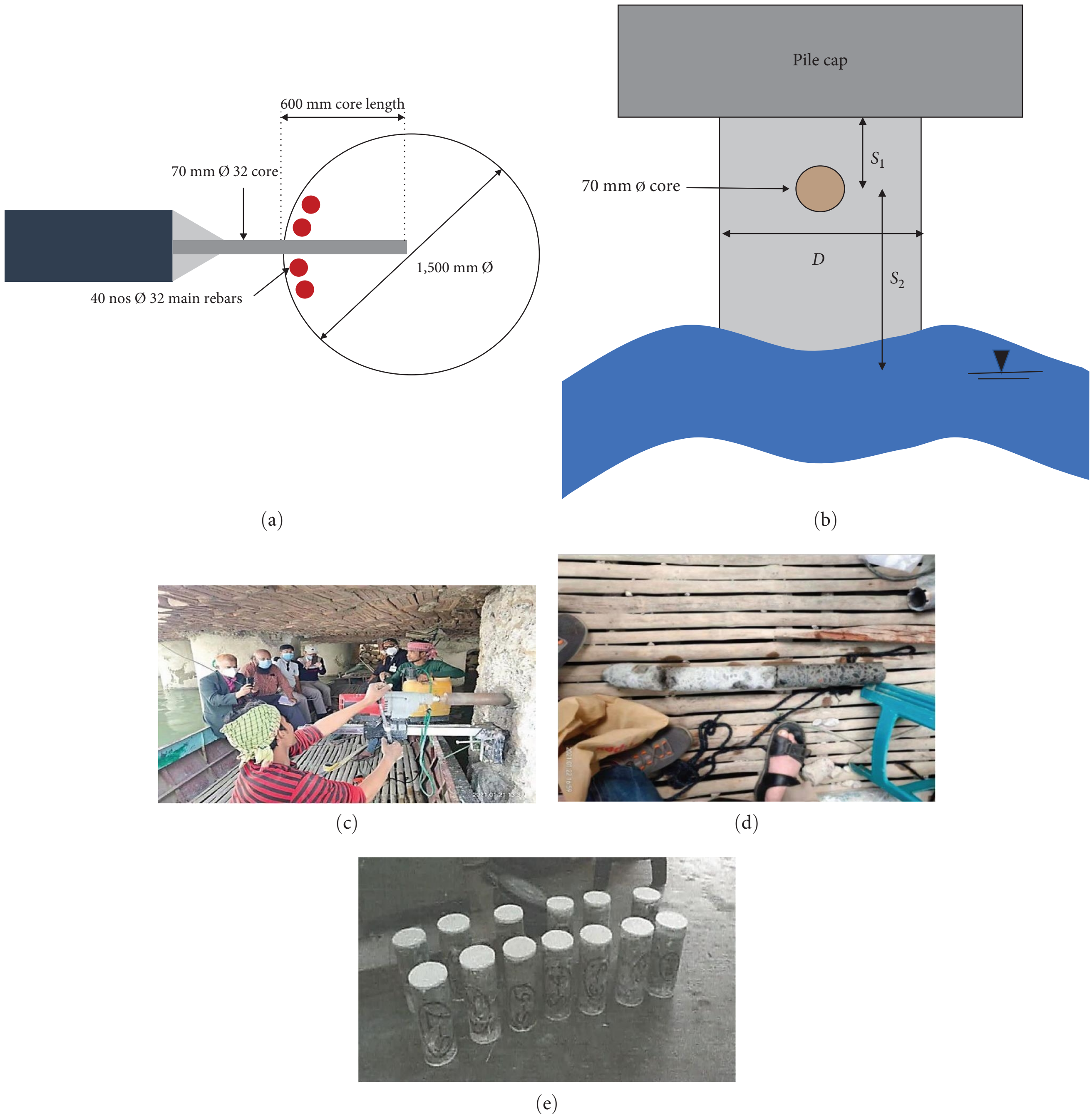


FIGURE 4: Sketch of (a) core extraction procedure, (b) location of core extraction, (c) core extraction in field, (d) extracted Ø70 mm core without cutting of the main rebar, and (e) prepared samples from extracted cores at CRTS lab in KUET.

produced by BASF. To repair the damaged spiral steel bar during core drilling, 2 nos 30 cm long Ø10 mm diameter pre-bent steel bar was welded to the damaged steel bar (welding length is 10 cm on both sides of the hole). The area of the newly placed rebar was then covered with the same material used for filling the cores.

(6) Conclusion from the Core Extraction. From Table 2, the average compressive strength found for the damaged piles is 32.7 MPa. The piles were designed with C30-grade concrete. Therefore, it is justified that there was no faulty or defective work done from the contractor's end.

2.2. Comprehensive Analysis of Pile Damage: Conclusive Explanations. Examining all the possible aspects of checking the strength of the pile, it can be concluded that the contractor made no compromise in the works. Pile strength was satisfactory. Therefore, the absence of permanent casing and river course shifting have been identified as the primary causes of pile surface deterioration.

2.3. Repair Methods. Wire meshing and shotcreting can be a good solution for the purpose of retrofitting. External jacketing can also be an alternative. Cathodic protection of

Table 1: Details of the extracted cores.

Si. no.	Pile no.	Core location		Extracted core length, *L* (mm)	Observed clear cover, *C* (mm)	Measured diameter of the pile, *D* (mm)
		From bottom of the pile cap, S1 (mm)	From top of water surface, S2 (mm)			
1.	P-1	660	620	540	120	–
2.	P-5	680	900	570	75	–
3.	P-3	380	1,330	540	110	1,592
4.	P-7	560	1,280	550	75	–
5.	P-9	470	900	186	180	–
6.	P-14	570	1,200	500	145	–
7.	P-11	540	1,150	250	80	1,640
8.	P-16	1,000	670	575	100	–

(a) (b)

Figure 5: (a) and (b) Compressive strength test machine and extracted core samples.

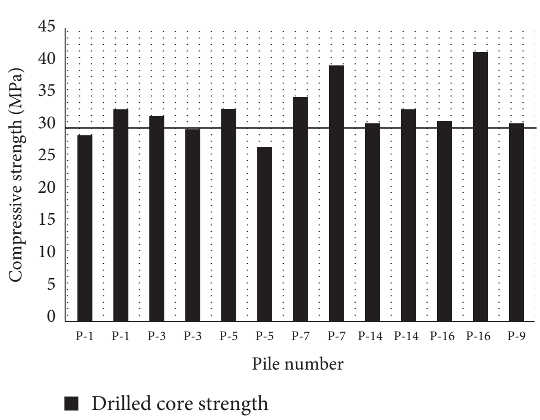


Figure 6: Bar chart of compressive strength with respect to pile number.

rebars, carbon fiber reinforced polymer wrapping with epoxy-based coating are some of the robust solutions but will be a little expensive, which is why these processes of reparation were not carried out. Therefore, for this project, the external jacketing process of retrofitting was used for strengthening the piles. The main challenge in this project was the concrete work. As the concreting will be done underwater, we needed to find a method that will be economical in cost as well as time, since there will only be 6 months to finish the necessary repair work before the monsoon. The two methods under discussion for executing the underwater concreting are described below.

2.3.1. Exposed Pile Head Cofferdam Process. Constructing a cellular cofferdam is done by driving sheet piles in a circular pattern and then repeating this process adjacent to the origin to form a series of circular cells. Each of these cells connects to one another and forms a tight seal that prevents water from entering. A cofferdam is an enclosure built within a waterbody to allow the enclosed area to be pumped out of water. This pumping creates a dry working environment so that the work can be carried out efficiently and safely. Cofferdam process application has some advantages, but technically, the disadvantages outweigh it. Cofferdam installation is very time-consuming and costly work. Installing sheet piles around the working place takes a lot of time, which lengthens the project duration and deteriorates the condition of the

Table 2: Extracted core details and strength.

Si. no.	Pile no.	Extracted core length (mm)	Finished core length (mm)	Recovery ratio	Core diameter (mm)	L/D	Load (kN)	Factored compressive strength (MPa psi)		Average compressive strength (MPa psi)
1	P-1	225	135	1.67	67.06	2.01	102.1	28.9	4,190	
2	P-1	280	136	2.06	67.49	2.02	117.8	32.9	4,770	
3	P-3	259	130	1.99	65.42	1.99	107.2	31.9	4,620	
4	P-3	277	131	2.11	65.29	2.01	99.8	29.8	4,320	
5	P-5	306	131	2.34	65.72	1.99	112.0	33.0	4,790	
6	P-5	260	131	1.98	65.45	2.00	91.0	27.1	3,920	
7	P-7	262	132	1.98	65.41	2.02	117.0	34.8	5,050	**32.7 (4,742.0)**
8	P-7	277	131	2.11	65.48	2.00	133.8	39.7	5,760	
9	P-14	212	131	1.62	65.3	2.01	102.9	30.7	4,450	
10	P-14	288	130	2.22	65.15	2.00	109.7	32.9	4,770	
11	P-16	282	130	2.17	65.6	1.98	105.0	31.1	4,500	
12	P-16	252	134	1.88	66.9	2.00	146.9	41.8	6,060	
13	P-9	186	134	1.39	67.62	1.98	110.2	30.7	4,450	

Bold value signifies the average value.

(a) (b)

Figure 7: (a) Braced cofferdam and (b) underwater concreting using the tremie method of concrete placement underwater.

structure where immediate action is required. Also, constructing a cofferdam needs a great amount of skilled manpower. Considering the number of skilled manpower, materials, and equipment needed to construct a cofferdam, it turns out to be costlier than other methods of constructing or repairing structures in water bodies.

2.3.2. Underwater Live Concreting. UWC using the tremie method is convenient for pouring large amounts of high-flowable concrete. Tremie pipe, the upper end connected to a hopper and lower end continuously submerged in fresh concrete, is used to place concrete at the exact location from a hopper at the surface. There are several methods to carry out underwater concreting, such as the tremie method, pumping methods, preplaced aggregate concrete, etc. The underwater concreting techniques are designed mostly to prevent cement washout. The underwater concreting method is less costly and consumes less time. It also requires less manpower. Underwater concreting allows construction and excavation in an adverse environment. The biggest challenge to execute underwater concreting is pouring concrete in moving water. If the water is moving, it can wash away the cement paste which is holding the sand and gravel together. If this issue can be handled properly, underwater concreting is more convenient to execute than the cofferdam method. Pictures of the braced cofferdam and tremie methods of underwater concreting are given in Figure 7.

2.3.3. Cost Comparison. To compare the costs for the reparation work, a cost analysis of the Cofferdam method and underwater live concreting was performed. Estimation of pile jacketing cost in the cofferdam method and summary cost of the underwater live concreting method is provided hereafter in Tables 3 and 4. From Tables 3 and 4, a significant difference between costs can be observed. From Table 3, underwater concreting costs close to 44 lac BDT or 4.4 million, whereas the cofferdam method in Table 4 shows costs over 5 crore BDT or 50 million, which is notably higher than the underwater concreting method. Considering from the economical perspective, underwater concreting is more economical as a repair method for underwater structures.

2.3.4. Selection of Repair Method. Analyzing the cost induced by both the cofferdam and underwater concreting methods, we decided to go for the underwater concreting method for repairing the damaged piles. The costs calculated for the

Table 3: Cost analysis of underwater concreting method.

Si. no.	Item	Unit	Amount
	Arial Kha Bridge		
	Pile surface repairing cost at Pier 7		
1	Direct cost		
a.	Material cost		
1	MASTERFLOW 870	Bag	50.00
2	Cement	Bag	450.00
3	Coarse sand	cft	714.00
4	Stone	t	67.00
5	10 mm rebar	t	2.50
6	6 mm rebar	t	1.00
7	Admixture	kg	900.00
8	Grouting cement	kg	700.00
b.	Equipment cost		
1	Concrete mixer mMachine	Nos	1.00
2	Boat	Nos	4.00
3	Generator	Nos	3.00
4	Formwork	kg	3360.00
5	Fuel for the equipment	Liter	750.00
6	Other related equipment	Nos	
c.	Manpower		
1	Chinese technical person	Person	2.00
2	Engineer	Person	2.00
3	Water diver	Person	7.00
4	Skilled labor	Person	6.00
5	Unskilled labor	Person	10.00
6	Subtotal (a + b + c)		7,029.50
2	Overhead cost		4,381,976.00
	Total (1 + 2)		4,389,005.50

cofferdam and underwater concreting method were 100 and 4.4 million, respectively. A very significant difference between the methods can be observed here. While executing any infrastructural project, cost analysis is a vital factor to be considered. The techniques used to complete a project in the field conforming to design standards while taking the economy into consideration are crucial. We chose to use the underwater live concreting method for the repair work after carefully considering all the factors, including the cost.

3. Field Implementation Details

After taking the decision of the repair method to be implemented in the field, we first prepared the concrete mix design that will be used as the UWC. The concrete class for the drilled cores from the damaged piles is of C-30 grade. Therefore, using C-30 grade for live concreting the damaged piles under pile cap 7 after retrofitting was initially decided. However, employing C-40 grade for live concrete was decided upon after taking washout, dispersal, and self-compaction of concrete mixture underwater into consideration. As a safety measure for the life period of the piles, it was decided to use concrete of a higher class. Prior to completing the mix design, properties of the materials to be used in the concrete were determined. In the section below, material attributes are described.

3.1. Material Properties

3.1.1. Coarse Aggregate. Stone chips were used as coarse aggregate in this project. A local company produced the stone chips as per the following sizes from the grading given in Figure 8. Sieve analysis was done following the international standard ASTM C 136 [26]. The source of the stone chips is Pakur (India).

3.1.2. Fine Aggregate. Sieve analysis and grain size distribution of sand were done following ASTM C136 standard [26]. Sylhet sand having a fineness modulus of 2.53 was used for the mix design, which is better in quality than local sand. The gradation curve of the fine aggregate is given in Figure 9. Besides fineness modulus, other physical properties, such as various categories of specific gravity and absorption percentage of fine aggregate, were also determined and summarized in Table 5.

Moreover, dry-rodded unit weight and relative density/specific gravity of the stone chips were determined as per standard ASTM C29 and ASTM C127, respectively [27, 28]. The values are tabulated in Table 5.

3.1.3. Admixture. PCA®–I concrete superplasticizer is a polycarboxylate polymer-based composite admixture. It is a liquid substance that has the characteristics of high-range water reduction, excellent slump, retention, and strengthening. It is especially suitable for producing high-durability, self-compacting, high-compressive-strength, and high-workability concrete. Besides, it has low alkali content with no chloride ions and is non-corrosive to steel bars. PCA®–I Concrete superplasticizer is formulated to comply with the following specification for concrete admixture: ASTM C494/C494M [29]. Figure 10 picturizes the admixture used in this study.

For obtaining the optimum amount of admixture, various tests, such as antidispersal, antiwashout, self-compaction, and plasticity were, done. Moreover, the pH of the water before and after the application of admixture was also determined to check whether the admixture changes pH of water significantly. Descriptions of the tests are stated below.

(1) Antidispersal Test. This test was done to determine the performance of the concrete underwater. In water medium, any liquid or semiliquid material tends to disperse. After applying the admixture to the concrete, the standard test for antidispersal was carried out both in field and laboratory conditions. Antidispersing agent for underwater nondispersing concrete is a new type of admixture made of a variety of special organic polymer materials and active carriers based on the characteristics of UWC. It improves the viscosity of the solution between the polymer chain and cement. The admixture can give the UWC excellent construction performance and good mechanical properties. The process of antidispersal test at the laboratory and at the site are shown in Figure 11.

(2) Antiwashout Test. The antiwashout test was done using the CRD-C61 standard [30]. The calculation of determining weight loss is stated below as per the standard.

Table 4: Cost analysis of cofferdam method

Estimation of pile jacketing cost at Pier 7 (cofferdam method)						
Si. no.	Item	Unit	Quantity	Unit price (Tk.)	Total cost (Tk.)	Remarks
Section-I: cofferdam construction						
I-A	Materials					considering the work to be completed within 6 months and the steel materials are used on a rental basis
1	Sheet pile rent (400 mm)	Ton	142.12	14,040.00	1,995,319.17	
2	H-beam rent (450 mm)	Ton	12.38	10,800.00	133,754.54	
I-B	Equipment					
1	Berge (02 pcs)—600 ton	Month	6	600,000.00	4,800,000.00	
2	Mud pump (20 HP)	Nos	2	40,000.00	80,000.00	
I-C	Construction cost					
1	Driving of sheet piles and construction of cofferdam		154.50143	93,525.00	14,449,746.24	
	Subtotal (I)				21,458,819.95	
Section-II: pile jacketing work						
II-A	Materials					
1	MASTERFLOW-870	Bag	122	1,725.00	219,000.00	135,000.00
2	Cement	Bag	720	485.00	350,200.00	30,000.00
3	Coarse sand	cft	1100	67.00	73,700.00	367,500.00
4	5–10 mm stone	t	59	4,400.00	261,360.00	63,750.00
5	10 mm rebar	t	2.75	73,000.00	218,724.00	70,000.00
6	6 mm rebar	t	0.65	68,000.00	60,550.00	1,696,505.00
7	Super plasticizer	kg	1150	75.00	86,250.00	95,710.00
8	other related materials cost	Nos			253,520.00	
	Subtotal (II-A)				1,523,304.00	
II-B	Equipment summary					
1	Concrete mixture machine-1	Nos	1	4.50	30,000.00	135,000.00
2	Concrete mixture machine-2	Nos	1	1.00	30,000.00	30,000.00
3	Generator	Nos	3	4.25	30,000.00	367,500.00
4	Welding machine	Nos	2	4.25	7,500.00	63,750.00
5	Air compressor	Nos	2	4.25	7,500.00	70,000.00
7	Formwork	kg	9,190	68,000.00	180.00	1,696,505.00
8	Fuel for the equipment	Liter	1,420	75.00	66.00	95,710.00
	other related equipment	Nos			253,520.00	
	Subtotal (II-B)				2,708,465.00	
II-C	Manpower summary					
1	Chinese site manager	Person	1	6.00	390,000.00	2,340,000.00
2	Chinese concrete specialist	Person	1	6.00	390,000.00	2,340,000.00
3	Project coordinator	Person	1	6.00	150,000.00	900,000.00
4	Engineer	Person	1	6.00	55,000.00	330,000.00
5	Purchase officer	Person	1	6.00	55,000.00	330,000.00
6	Lab engineer	Person	1	6.00	50,000.00	300,000.00
7	Lab helper	Person	1	6.00	25,000.00	150,000.00
8	Foreman	Person	1	6.00	25,000.00	150,000.00
9	Skilled labor	Person	8	5.50	20,000.00	880,000.00
10	Unskilled labor	Person	8	4.50	18,000.00	6,488,000.00
	Subtotal (II-C)				1,178,000.00	
II-D	Test costs					
1	Drilled core test				415,000.00	
2	Compressive strength test machine cost				100,000.00	
	Subtotal (II-D)				515,000.00	
	Subtotal (II)				13,114,769.00	

Table 4: Continued.

Estimation of pile jacketing cost at Pier 7 (cofferdam method)						
Si. no.	Item	Unit	Quantity	Unit price (Tk.)	Total cost (Tk.)	Remarks
III	Miscellaneous					
1	Transportation by local vehicle	Nos	1	70,000.00	490,000.00	
2	Air ticket for foreigner	Nos	2	150,000.00	600,000.00	
3	House and food				642,000.00	
4	Refreshment				100,000.00	
	Subtotal (III)				1,832,000.00	
IV	Direct cost A = (subtotal (I + II + III))				36,405,588.95	
	Overheads 10% based on "A, C"				3,640,559.00	
	Profit 10% based on "A, D"				3,640,559.00	
	Total excluding VAT and AIT (B = C + D)				43,686,707.00	
	AIT				3,512,411.00	
	VAT				3,014,383.00	
	Total cost including taxes (BDT)				50,213,501.00	

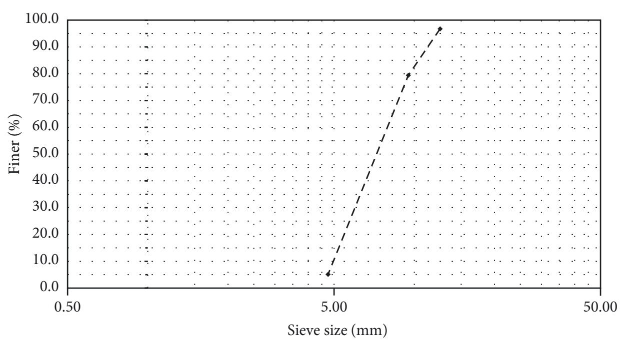


Figure 8: Gradation curve of coarse aggregate.

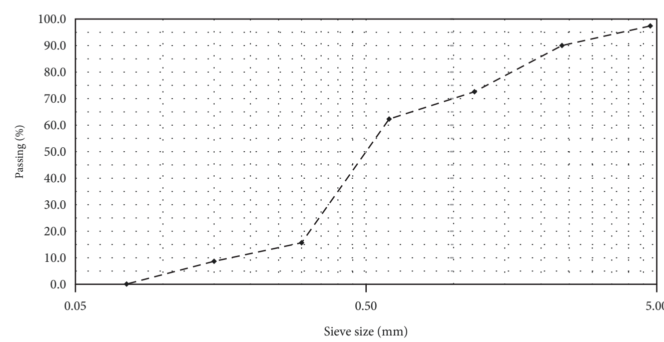


Figure 9: Gradation curve of fine aggregate.

Table 5: Physical properties of coarse and fine aggregate.

Si. no.	Test name	Unit	Aggregate type	
			Coarse	Fine
1.	Avg. dry rodded unit weight of aggregate	g/cc	1.672	—
2.	Avg. specific gravity (oven dry)	—	2.854	2.585
3.	Avg. specific gravity (SSD)	—	2.872	2.624
4.	Avg. apparent specific gravity	—	2.907	2.690
5.	Avg. absorption	%	0.64	1.52
6.	Fineness modulus	—	—	2.53

$$D = \frac{Mi - Mf}{Mi} \times 100, \quad (1)$$

where D = washout (%), Mi = mass of sample before test (g), Mf = mass of sample after test (g).

The amount of cement washout using different percentages of AWA was determined. As the concreting will be done underwater, it must be ensured that the concrete will not washout in large volumes and has quick self-compaction capability. Heniegal et al. [31] replaced 0.1%–0.5% cement by AWA to observe the effect on cement weight loss and, therefore, the amount of cement washout. He concluded that, with an increase in AWA dosage, weight loss generally decreased. For this, we incorporated 0.1%–0.5% AWA to check the weight loss trend and found that the lowest cement loss was recorded for 0.5% AWA inclusion; slump found was 230 mm, which is also a good value to be worked with. Table 6 summarizes the test values of different parameters that were determined to obtain the optimum amount of AWA agent to be used in underwater concreting.

Figure 12 illustrates the correlation between concrete slump values and cement runoff resistance. The figure demonstrates that there exists a connection between these two factors. As the

Figure 10: Admixture used in the concrete.

(a) (b) (c)

(d) (e)

Figure 11: (a) and (b) Antidispersal test at laboratory, (c), (d), and (e) at field.

Table 6: pH, weight loss, and slump of UWC in various AWA dosages.

AWA dosages (%)	pH	Weight loss (%)	Runoff resistance (%)	Slump (mm)
0.0	7.005	10.1	89.9	210
0.1	7.004	8.2	91.8	190
0.2	7.002	7.5	92.5	170
0.3	7.001	5.1	94.9	150
0.4	6.998	4.8	95.2	140
0.5	6.995	3.2	96.8	130

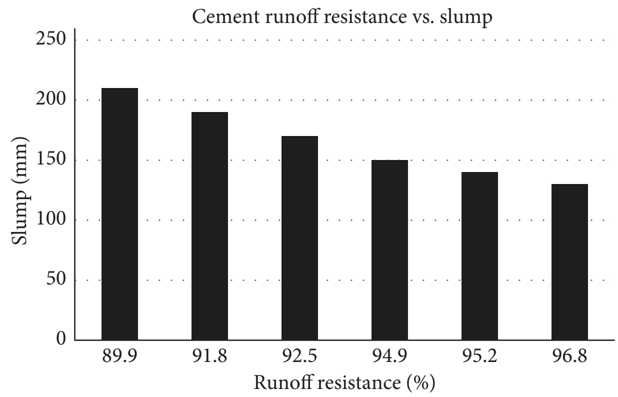


Figure 12: Analysis of cement runoff resistance vs. slump curve.

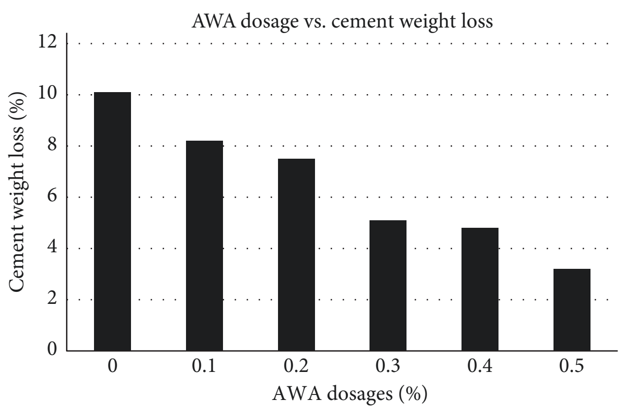


Figure 13: Relation between cement weight loss with respect to varying AWA dosages.

runoff resistance of cement increases, the slump value of concrete increases as well. This implies that the more resistant the cement is to runoff or washout, the stiffer the concrete becomes, leading to a higher slump value. Since cement serves as the binding agent for the various components of concrete, a greater runoff of cement leads to a reduction in the cohesion among these components. Consequently, the concrete's consistency becomes softer, exhibiting a decreased slump value.

In Figure 13, it is evident that as the dosage of AWA increases, there is a gradual reduction in cement weight loss. This reduction is most significant at the highest AWA dosage, highlighting a direct correlation between increased AWA usage and decreased cement weight loss. This positive effect can be attributed to the chemical constituents of AWA, which play a crucial role in enhancing the cohesion of the cement–concrete paste and thereby minimizing weight loss.

(3) pH Value Check. Before and after the admixture was mixed, the pH of the water was measured to observe if there had been any changes, both in the field and the lab. It was found that there was negligible change in pH value even after adding admixture in the concrete (Table 6). Before the addition of the admixture, pH of water was found 7.000, which then increased to 7.001 after mixing admixture. Therefore, it can be concluded that the admixture has an insignificant

Figure 14: Check for pH value after the addition of admixture.

Table 7: Physical properties of cement with standard.

Physical properties	Value	Method
Fineness	99.6%	ASTM C184
Normal consistency	26.0%	ASTM C187 [32]
Initial setting time	175 min	ASTM C191 [33]
Final setting time	270 min	
Specific gravity	3.15	ASTM C188 [34]

Table 8: Physical properties of reinforcement.

Physical properties	Value	Method
Tensile strength	555.0 MPa (yield) 656.0 MPa (ultimate)	ASTM A 615 [35]
Bend/rebend	Satisfactory	
Unit weight	1,566.0 g/cc	

effect on the pH of water. Figure 14 shows the action taken to measure pH value in site.

3.1.4. Cement. The mix design incorporated the cement of a local brand. For the concrete work, premier cement type I (ordinary Portland cement) was chosen. The physical properties of premier cement are tabulated in Table 7.

3.1.5. Reinforcement. Reinforcement used in the retrofitting work was locally supplied. Local brand BSRM XTREME B500W CWR reinforcement was procured for using as the retrofitting mesh. The physical properties of BSRM rebar are provided in Table 8.

4. Mix Design

The cores extracted from the damaged piles are C-30 grade concrete. Therefore, it was initially decided to use C-30 grade for live-concreting the damaged piles under pile cap-07 after retrofitting. However, the decision to use C-40 grade for live concreting was made after considering washout, dispersion, and self-compaction of concrete mixture underwater. At first, the mix proportion for C-40 grade concrete was done incorporating 2.8% plasticizer and 2.0% antidispersing agent, tabulated in Table 8. Later, AWA (0.1%, 0.2%, 0.3%, 0.4%, and –0.5%) was added considering the washout phenomenon of concrete underwater and adjusted with the mix design of C-40 grade concrete. The water–cement ratio was kept at 0.39 throughout the design. After finalizing the proportions

Table 9: Crushing strength of concrete cylinder in 28 days.

Si. no.	AWA (%)	Cement weight loss (%)	Slump (mm)	Cylinder crushing strength (28 days) (MPa)
1.	0.0	10.1	210	32.1
2.	0.1	8.2	190	35.5
3.	0.2	7.5	170	37.2
4.	0.3	5.1	150	42.6
5.	0.4	4.8	140	39.2
6.	0.5	3.2	130	37.4

of all the materials for the concrete mix design of the C-40 strength category, several trial mix designs were conducted with varying AWA dosages to obtain the optimum AWA dosage level. The concrete cubes were prepared as per the proposed mix design and immersed in water. The crushing strength of the concrete cylinder (28 days) is shown in Table 9.

The data in the table reveal that as the AWA dosage increases in concrete, the amount of cement washout decreases, reaching a low of 3.2% for the highest AWA dosage applied. While the trend shows a decline in cement washout, the concrete's compressive strength progressively rises with respect to AWA dosages up to an application of 0.3% of AWA. However, further increases in AWA dosages lead to a decline in concrete strength. This phenomenon could be attributed to the chemical properties of AWA incorporated into the concrete. As the proportion of AWA increases, an adverse interaction takes place within the concrete due to the complete chemical composition of both cement and AWA. Cement and an enhanced amount of AWA react in a way that ultimately leads to a reduction in the strength of the concrete. Therefore, an increase in AWA dosage does indeed correlate with reduced cement mass loss, and the concrete's strength experiences improvement up to a certain AWA percentage usage, which is 0.3%. As preserving concrete strength is imperative, the optimal AWA dosage is finalized to be 0.3% of the cement content to be executed in the field. Moreover, the slump value (150 mm) found for 0.3% AWA application is also good enough for better workability while implementing the underwater concreting work of the project. A graphical analysis of compressive strength with respect to AWA dosages is presented in Figure 15.

From the graph of Figure 15, it can be observed that the compressive strength of the concrete increases steadily with mild upward fluctuations and reaches a peak of 42.6 MPa strength, corresponding to 0.3% of AWA dosage. However, after reaching the peak at 0.3% of AWA dosage, it has been depicted that the strength of the concrete plummets with a further increase in the percentage of AWA. Thus, it is evident from the graph that though the addition of AWA increases the strength of concrete, after reaching an optimum amount the situation alters.

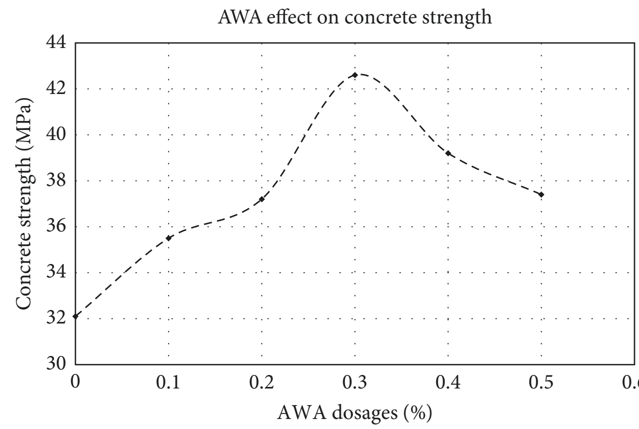


Figure 15: Relation of concrete compressive strength with varying AWA dosages.

5. Execution of Underwater Concreting

5.1. Reinforcement Details. The details of the reinforcement mesh are demonstrated in Figure 16. Forty nos 10 mm rebar were used as the main (vertical) reinforcement. As spiral or shear reinforcement, 10 mm diameter rebar at 150 mm spacing was used above the water surface, and 6 mm diameter rebar at 100 mm spacing was provided from the water surface to the bottom of the main bar. A 3 mm thick steel plate was used as a permanent casing surrounding the pile. In between the steel casing and reinforcement mesh, the C40 concrete was poured.

5.2. Rebar Lashing. As positioning rebar, a circle of 10 mm diameter rebar was positioned 20 cm below the pile cap and 20 cm above the river bed throughout the circumferential direction. The main bar of the appropriate length is prepared in advance and placed one by one over the positioning bar. The main bar consists of rebar with a diameter of 10 mm and is welded and attached to the top positioning bar. Divers tied the bottom main bar to the bottom positioning bar by adjusting the distance between the main bars (same as the pile main bars), ensuring the verticality of the main bar. Then, spiral reinforcement of 10 mm diameter rebar was arranged over the main reinforcement at a spacing of 15 cm up to the water level, and spiral tendons of 6 mm diameter were tied to the exterior of the main rebar at a spacing of 10 cm starting at the water's surface and ending at the bottom of the main bar. Figure 17 shows the rebar placement around the pile surface.

5.3. Production and Processing of Permanent Casing. The formwork consists of semicircular, 3 mm thick iron sheet formwork with a diameter of 1.8 m and a height of 1.2 m.

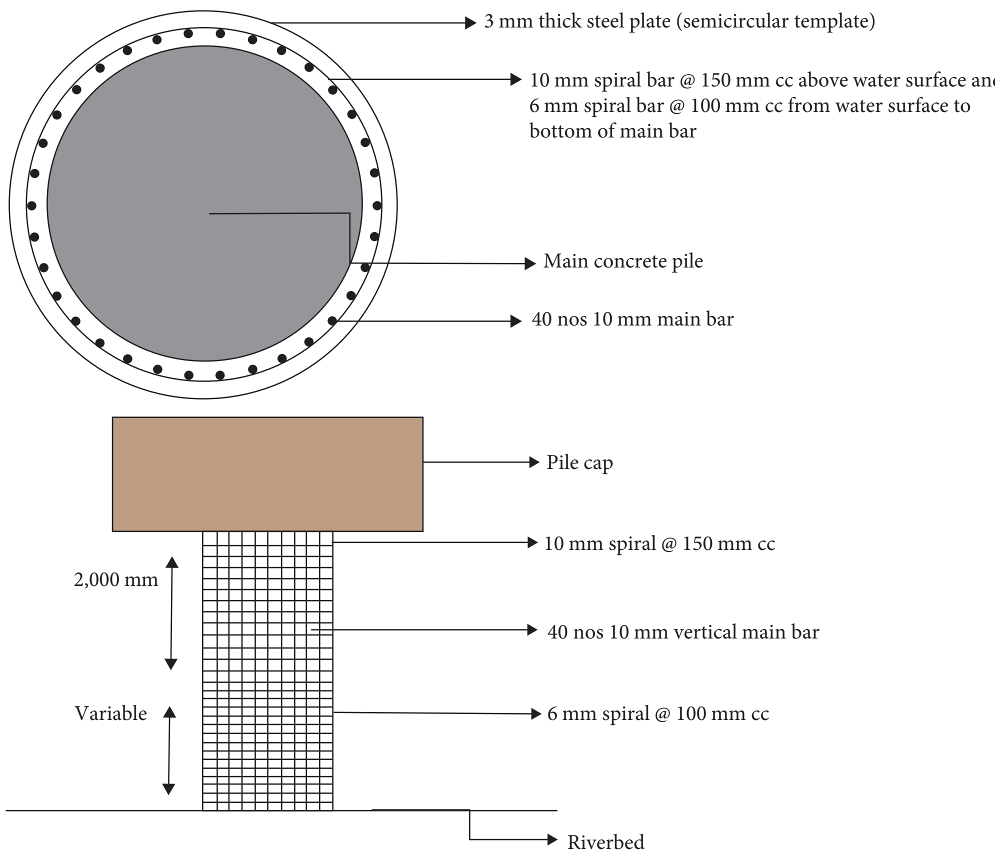


Figure 16: Reinforcement details of pile retrofitting.

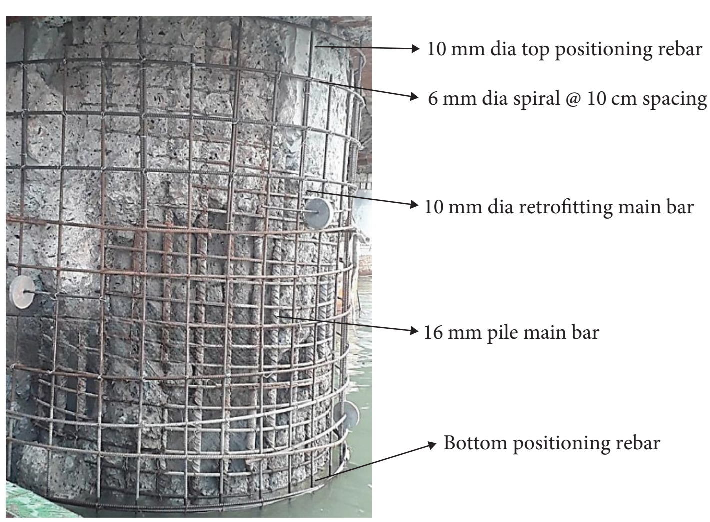


Figure 17: Reinforcement arrangement for retrofitting of the pile.

The exterior is strengthened with 20 mm steel hoops spaced 50 cm apart. The two templates are overlapped by 10 cm and secured with two 20 mm steel hoops on the exterior. Using the inverted assembly process, the formwork is inverted-pulled onto the top of the pile. The assembly is completed on the surface of the water, each section is completed and lowered individually, and the first part of the formwork is placed in the river bed. After construction is finished, the iron template will not be destroyed. It will be incorporated into the concrete as part of the protection and stability of the pile. Specifications of the permanent casing and the placement process are picturized in Figure 18.

5.4. C-40 Underwater Nondispersible Concrete Pouring. Sobute's underwater nondispersible concrete antidispersant

(a) (b) (c)

(d)

Figure 18: (a)–(c) Placement of permanent casing process and (d) iron permanent casing dimension.

(a) (b)

Figure 19: (a) and (b) Field slump test of concrete mix.

was used in concrete to impart UWC with superior workability and enhanced mechanical properties. It significantly improves the rheology of concrete and facilitates with vibration-free molding and self-leveling. A small self-falling mixer is used for mixing when casting, and the mixture is manually poured into the template. To avoid mold expansion, the pouring speed is controlled at 50 cm/hr. Pouring of concrete was performed in layers in varied heights (having layer thicknesses of 1.0 m each) to avoid segregation. When a section of formwork (1.2 m high) is lowered, concrete is immediately poured into the formwork to a height 10 cm below the formwork's top level. This process is repeated until a height less than 20 cm from the bottom of the pile cap is reached. Finally, the top 20 cm high area at the bottom of the pile cap is filled manually with non-shrink grout (MASTERFLOW® 870) concrete (without slump).

5.5. Slump Test. For each trial and final concreting work, slump was obtained. Slump was found to be around 150 mm while executing the final concreting work. Figures 19(a) and 19(b) show slump test carried out in field.

(a) (b)

Figure 20: Piles after completion of retrofitting.

6. Completion of Underwater Concreting

After underwater concreting in between retrofitting and the steel casing formwork, the casings were not removed and placed as permanent formwork. This is to provide extra protection to the pile concrete surface against erosion and surface damage due to water contact and tidal waves. Figure 20 shows the final look of the piles after completion of all the necessary repair works and retrofitting.

7. Conclusion

In Bangladesh, structures above the water level are where the retrofitting method for structural repairs of concrete is most commonly used. For the first time in the construction history of Bangladesh, underwater retrofitting and underwater live concreting were carried out in the Arial Kha River bridge piles. It is a huge achievement for the construction sector of Bangladesh. For minimal concrete washout, trials of concrete mix design were carried out changing the dosages of AWA. From the analysis, it is found that for 0.3% addition of AWA resulted in the maximum concrete strength, which also satisfies the desirable target strength of concrete. Also, underwater concreting was found more economical than other conventional methods for carrying out underwater reparation works. This finding can be used to perform future underwater construction and repair projects in Bangladesh. Therefore, it can be concluded that using AWA on concrete in appropriate amounts, underwater concreting can replace the cofferdam method for reparation works, which will save both time and cost for any project.

8. Recommendation for Future Application

(1) Piles, especially when constructed using permanent casing, are those substructures whose quality of perfect concreting is difficult to be monitored thoroughly. In order to ensure quality workmanship throughout, care must be taken.

(2) The environment should always be taken into account when designing large bridges from the perspective of potential river course alterations. An environmental impact assessment must be performed before commencing any development project works. River training works and viaduct adjustments must be made from that viewpoint if deemed necessary.

(3) Monitoring system for underwater substructures of bridges to be emphasized. Equipment with advanced technology, such as an underwater camera, may be used.

(4) Last but not least, since Bangladesh is a country of rivers and canals and has numerous major and minor bridges for transportation connectivity, the requirement to retrofit their piles and pile caps necessitates using regular budget funds. Hence, underwater live concreting can be employed in a planned way to achieve economy. A thorough study is necessary to portray how much savings might be made. In this paper, a comparative cost estimate is already devised.

Data Availability

All data are attached in the manuscript. If any further data are required, we can provide those.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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