

Effect of Water pH and Waterlogging Depth on the Physical and Mechanical Properties of Concrete Pavement

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ABSTRACT

This research examines the combined effect of waterlogging heights and water pH levels on the physical, mechanical, and microstructural properties of concrete pavements. A ready-mix concrete with a compressive strength of 25 MPa was used, with waterlogging heights varying between 0.5 cm and 5 cm and water pH ranging from pH = 2 to pH = 7. After 28 days of curing, testing was performed to measure compressive strength, water absorption, porosity, and microstructural analysis using Scanning Electron Microscope-Energy Dispersive X-Ray (SEM-EDX). It was found that concrete immersed in acidic water at low pH drastically lost its compressive strength at 12.53 MPa compared to concrete immersed in neutral water at 15.92 MPa compressive strength. Concrete immersed in acidic water also showed higher levels of porosity and absorption, indicative of the destruction of the concrete matrix through dissolution of the C-S-H gel and calcium carbonate. The SEM analysis and EDX revealed that concrete exposed to low pH water underwent dissolution of the primary cement phases, causing microstructural changes, and thus possible reduction of concrete durability and mechanical resistance. This provides a new insight into the importance of considering both the height of waterlogging and pH in the design of durable rigid pavement concrete in regions prone to acidic waterlogging.

Keywords-concrete; compressive strength; waterlogging; water pH; quality

I. INTRODUCTION

Pavement serves as a key factor in road construction, considering the safety and strength of a roadway. It can be classified as flexible and rigid. Specifically, rigid pavement, typically made of concrete, offers long durability under heavy

loading and requires only slight maintenance. Concrete is designed for high compressive strength and load distribution, making it an effective solution for highway construction.

However, the use of rigid pavements may be particularly challenging in areas with extreme environmental conditions,

like peatlands or swamps that are frequently waterlogged. The waterlogging condition with acidic pH can deteriorate concrete with harmful chemical reactions [1, 2]. Additionally, this phenomenon occurring during the concrete placement significantly affects its final quality. The waterlogging depth and high acidity can disrupt concrete hydration, damage its microstructure, and reduce its compressive strength and resistance to degradation. Furthermore, the sulfuric acid produced by the oxidation of pyrite minerals often found in peatlands may also contribute to the material's damage [3, 4]. Therefore, it is essential to investigate the waterlogging effects on the performance characteristics of rigid pavements, especially regarding the influence of pH and waterlogging depth.

Optimal curing techniques, like curing compounds or controlled moisture curing, can minimize humidity effects during the hydration process [5, 6]. Despite the various solutions that have been developed, more research is needed to fully understand how these environmental factors, such as waterlogging height and water pH, can influence compressive strength and durability of pavements.

Previous studies have examined the impact of waterlogging and pH on concrete properties, but each parameter has been studied individually [7, 8]. However, there is still lack of the microstructural changes induced in concrete upon being subjected to acidic waterlogging while curing, as well as the long-term effects of acidic-waterlogging in jeopardizing concrete integrity, particularly in the areas of swamps or peatlands. To address this gap, the current study explores the combined effect of waterlogging height and water pH on rigid pavement concrete, providing a novel perspective on how different environmental elements act together to affect concrete's durability and microstructure.

Peat water, commonly found in Kalimantan and Sumatra, has a very low pH [2], which can exacerbate the deterioration of rigid pavement concrete. Pyrite, a mineral abundant in peatlands, when oxidized, generates toxic acidic compounds, such as sulfuric acid, which can damage concrete structure [3]. This study uses sulfuric acid (H_2SO_4) as an artificial acid source to simulate waterlogging conditions in peatlands for investigation. By clarifying how acidic waterlogging influences compressive strength, absorption, porosity, and microstructure, essential information can be derived for designing durable pavement solutions in challenging environments.

II. MATERIALS AND METHODS

In this study, the concrete mixture is composed of fine aggregate, coarse aggregate, cement, water, and a retarder. The concrete designed for local roads should have a compressive strength of 25 MPa with curing through soaking. Table I presents the composition of the concrete mix, while Table II shows the characteristics of the materials. As for the retarder material, previous studies indicate that the use of retarder with a composition of 0.2% by weight of cement has proven to be the most optimal solution compared to other retarder compositions in increasing compressive strength [9].

The ready-mix concrete mixture was placed into cylindrical molds with a diameter of 10 cm and a height of 20 cm. The

variations in waterlogging height included levels of 0 cm, 0.5 cm, 1 cm, 2 cm, 3 cm, 4 cm, and 5 cm, while variations in the pH of the waterlogging were applied, with values of 7, 6, 5, 4, 3, and 2. For clarity, 0 cm indicates no waterlogging, while 0.5-5 cm indicates the measured depth of standing water in the container. The waterlogging pH was adjusted by adding H_2SO_4 , and it was monitored using a pH-meter to ensure consistency throughout the study period.

Throughout the experiment, all test specimens were subjected to daily curing using the spray curing method for 28 days to maintain moisture, in accordance with ASTM C511 [10]. The processes of drying and hardening took place, and the specimens were then removed from the molds and underwent curing treatment. Afterwards, they were placed in containers, hardened, and remained there according to the applied treatments. A total of 111 test specimens were developed, as illustrated in Figure 1, consisting of 37 treatment variations, each with three replicates. All containers used to hold the test specimens were set up to maintain stable waterlogging height and pH levels.

TABLE I. COMPOSITION OF CONCRETE MIXTURE PER 1 m^3

Materials	Composition
Cement	490 kg
Fine aggregate	900 kg
Coarse aggregate	820 kg
Water	190 L
Retarder	0.98 L (0.2% of cement weight)

TABLE II. MATERIAL CHARACTERISTICS

Material	Fine aggregate	Coarse aggregate	Cement
Name	Barito sand	Katunun	Tonasa
Type	Mild sand	-	PCC
Grade zone	II	-	-
Specific gravity	2.64 g/cm^3	2.88 g/cm^3	3.019 g/cm^3
Water absorption	0.81%	0.73%	-
Moisture content	2.67%	-	-
Abrasion value	-	15.6%	-
Normal consistency	-	-	27.4%
Initial setting time	-	-	69 min
Final setting time	-	-	105 min



Fig. 1. Test specimens.

The nomenclature of the test specimens is presented in Table III. G_0 represents the control sample (no waterlogging), while G_x indicates the waterlogging height (0.5-5 cm) combined with different pH conditions.

Compressive strength, absorption, and porosity with microstructure study were the tests carried out to examine different characteristics of concrete when subjected to various waterlogging treatments and pH levels. The compressive strength testing was conducted on a compression testing machine following ASTM C39/C39M [11]. The testing of absorption and porosity were performed according to ASTM C642 [12]. The microstructural analysis was carried out employing SEM to visualize material morphology, whereas the chemical composition of the materials was analyzed deploying EDX [13].

TABLE III. NOMENCLATURE OF TEST SPECIMENS

Specimen code	Waterlogging height	pH
G_0	0 cm	-
$G_{0.5}$	0.5 cm	-
G_1	1 cm	7
G_2	2 cm	
G_3	3 cm	
G_4	4 cm	
G_5	5 cm	
$G_{0.5}$	0.5 cm	
G_1	1 cm	
G_2	2 cm	
G_3	3 cm	
G_4	4 cm	
G_5	5 cm	
$G_{0.5}$	0.5 cm	5
G_1	1 cm	
G_2	2 cm	
G_3	3 cm	
G_4	4 cm	
G_5	5 cm	
$G_{0.5}$	0.5 cm	4
G_1	1 cm	
G_2	2 cm	
G_3	3 cm	
G_4	4 cm	
G_5	5 cm	
$G_{0.5}$	0.5 cm	3
G_1	1 cm	
G_2	2 cm	
G_3	3 cm	
G_4	4 cm	
G_5	5 cm	
$G_{0.5}$	0.5 cm	2
G_1	1 cm	
G_2	2 cm	
G_3	3 cm	
G_4	4 cm	
G_5	5 cm	

III. RESULTS AND DISCUSSION

A. Compressive Strength Testing

The results of the compressive strength tests for rigid pavement under various pH conditions and waterlogging heights are presented in Table IV and Figure 2.

The specimen's compressive strength under dry conditions and with no pH variation (G_0) was equal to 23.25 MPa. At pH = 7, compressive strength falls to 23.14 MPa at a height of 0.5 cm of water ($G_{0.5}$), and drops further to 15.92 MPa at 5 cm of water (G_5). This demonstrates that the increasing heights of waterlogging correlate to a reduced compressive strength. This phenomenon can be attributed to water penetration into the material, making it over moist and probably susceptible to weathering, or a decrease in structural strength. This uniform decline is observed across all pH conditions, indicating that waterlogging has an adverse effect on the compressive strength of the material, irrespective of water pH [14]. This observation can be attributed to the increased hydrostatic pressure affecting the concrete microstructure [15]. Low pH water conditions can accelerate the breaking down of concrete due to harmful chemical reactions [16]. Moreover, water absorption is higher because of waterlogging leading to moisture influx that accelerates internal damage of concrete [17, 18].

TABLE IV. COMPRESSIVE STRENGTH TEST RESULTS

pH	Compressive strength (MPa)						
	G_0	$G_{0.5}$	G_1	G_2	G_3	G_4	G_5
-	23.25	-	-	-	-	-	-
7	-	23.14	20.38	18.90	18.47	17.20	15.92
6	-	22.51	19.75	18.68	18.26	16.77	14.23
5	-	21.87	19.53	18.47	17.62	16.56	14.01
4	-	21.66	19.11	18.47	17.20	15.50	13.80
3	-	21.02	19.11	18.26	16.99	15.29	13.59
2	-	19.96	18.90	17.41	16.77	15.07	12.53

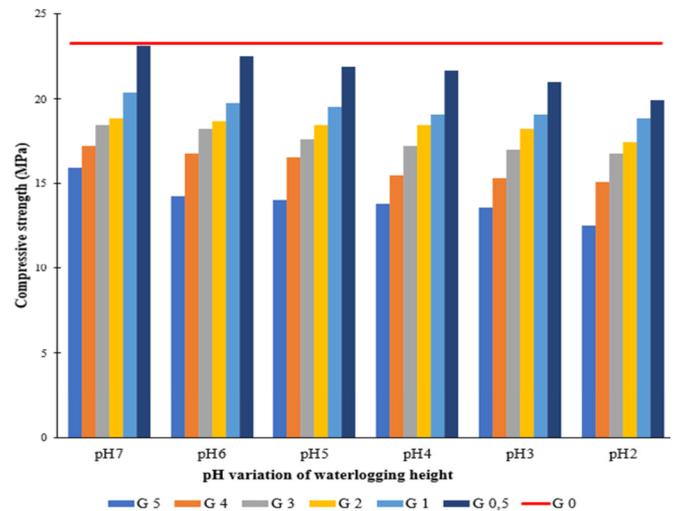


Fig. 2. The effect of waterlogging height and water pH on compressive strength.

Additional materials, including rice husk ash or fly ash, can enhance concrete's resistance to acidic waterlogging [19], making them alternative solutions to conventional concrete. The reducing compressive strength was consistent with previous studies, which reported the increase in moisture absorption of concrete due to waterlogging, resulting in microstructural damage [18]. The effect of low pH can further enhance concrete degradation through chemical reactions [20]. The percentage decrease in concrete compressive strength due

to waterlogging height and water pH is illustrated in Figures 3 and 4.

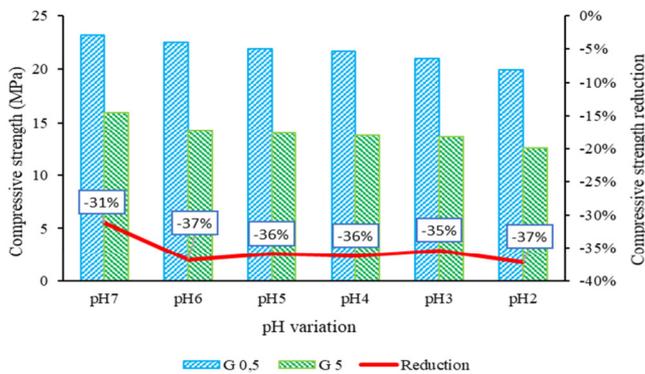


Fig. 3. The percentage reduction of compressive strength due to waterlogging height drop.

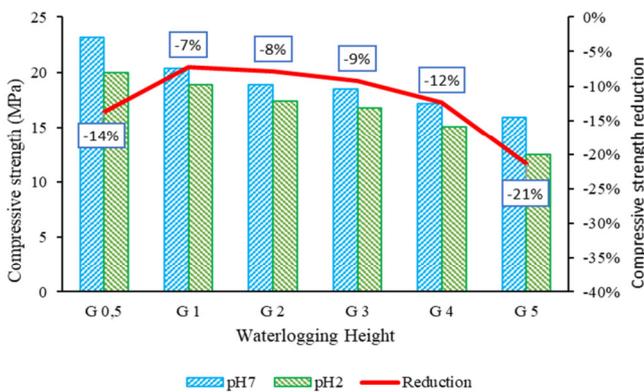


Fig. 4. The percentage reduction of compressive strength due to pH waterlogging drop.

It is clear that the effect of waterlogging height is more pronounced on the compressive strength reduction compared to pH changes. The average reduction due to waterlogging height is approximately 35%, while the average reduction due to pH variations is only 12%. In terms of waterlogging height, as shown in Figure 3, the greatest reduction appears at pH = 6 and pH = 2, indicating that high water levels accelerate material degradation, especially under acidic conditions. Considering pH variations, as evidenced in Figure 4, the largest decline is recorded for G₅, showing that materials are more vulnerable to low pH under high waterlogging conditions. Thus, the interaction between waterlogging height and water pH is critical; the higher the water level is, the greater is the pH influence on the rate of the chemical reactions that lead to the reduction in concrete strength [21].

B. Physical and Mechanical Properties of Specimens

The visual changes of the test specimens after 28 days of treatment are portrayed in Figure 5. After 28-day curing, the G₀ specimen (Figure 5(a)) remained almost at its initial condition, while G₅ with pH = 7 (Figure 5(b)) exhibited minimal changes, as neutral conditions do not make significant chemical reactions. However, Figures 5(c) and 5(d), displayed noticeable degradation. The acidic environment accelerated corrosive

reactions, such as the dissolution of calcium hydroxide and the formation of corrosive products, leading to surface damage, including cracking and swelling. These behaviors highlight the increasing difficulty of the material to resist in acidic environments.

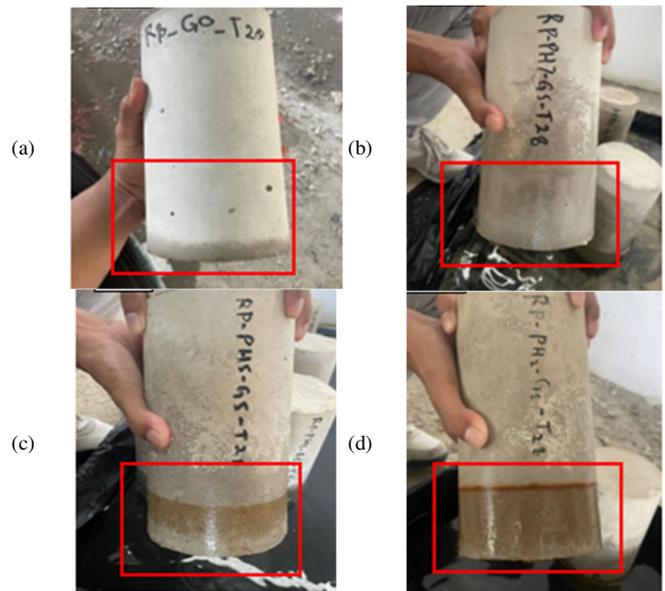


Fig. 5. Visual changes of test specimens: (a) G₀, (b) pH=7-G₅, (c) pH=5-G₅, and (d) pH=2-G₅.

The results of the compressive strength, absorption, and porosity tests for the test specimens G₀, and G₅ at pH = 7, pH = 5, and pH = 2 are presented in Table V and Figure 6. In the dry state, the material attained a compressive strength of the highest value amounting to 23.25 MPa and absorption of 10.83. The compressive strength was found to be 15.92 MPa for neutral pH = 7, while porosity increased slightly up to 19.96%, indicating a slight change to the pore network. During acidic waterlogging (pH = 2), compressive strength further declined due mainly to chemical degradation, while porosity was slightly reduced to 17.84% owing to change in pore structure as corrosion took place. Absorption is also decreased to a small value under acidic conditions (9.93%), indicating the alteration of the pore spaces of the material. These results suggest that more corrosive environments (acidic pH) tend to decrease compressive strength, and so further increase the ability of the materials to absorb and retain liquids, thereby increasing structural damage. The lowering of compressive strength due to low-pH waterlogging is mainly attributed to the chemical reactions that promote the interaction of the acidic environment with concrete, therefore reducing the quantity of calcium hydroxide in the concrete matrix. Acidic environments also promote the deconstruction of microstructures in concrete, raising porosity against compressive strength [22]. Moreover, aggressive reactions at low pH that accelerate the penetration of liquids have been shown to magnify the structural damage caused to the concrete [23]. These findings are consistent with those of recent studies on the impact of aggressive environments on concrete microstructure [22]. It is still essential, though, to use additives, like fly ash or pozzolan, to

reduce porosity and improve the durability of concrete in extreme environments.

TABLE V. RESULTS OF COMPRESSIVE STRENGTH, ABSORPTION, AND POROSITY TESTING

Specimen	Absorption (%)	Porosity (%)	Compressive strength (MPa)
G ₀	10.83	19.58	23.25
pH = 7-G ₅	10.64	19.96	15.92
pH = 5-G ₅	11.73	21.53	14.01
pH = 2-G ₅	12.36	22.42	12.53

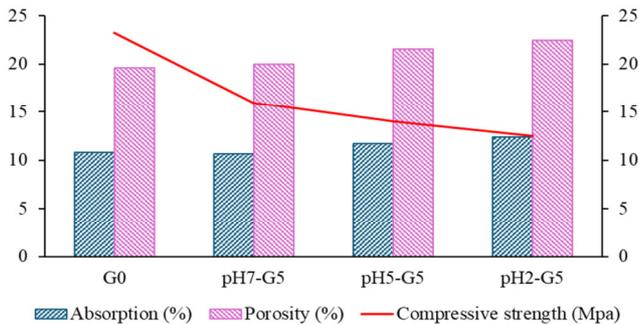


Fig. 6. Physical and mechanical properties of specimens.

C. Scanning Electron Microscope-Energy Dispersive X-Ray Testing

The results of the SEM tests are presented in Figures 7-9, while the results of EDX tests are presented in Figures 10-12, and Table VI.

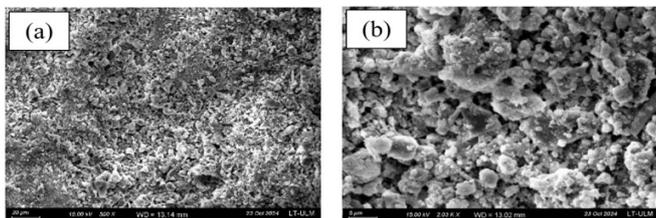


Fig. 7. SEM images for G₀ specimens with magnification (a) 500x (b) 2000x.

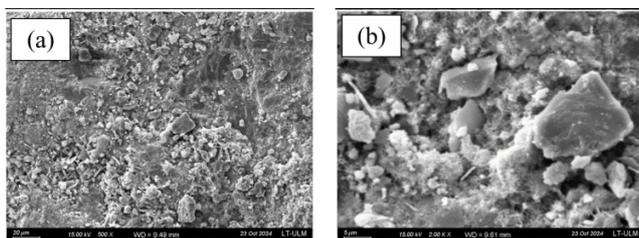


Fig. 8. SEM images for pH = 7-G₅ specimens with magnification (a) 500x, (b) 2000x.

Research has shown that acidic environments, particularly those involving sulfuric acid, can cause severe degradation of concrete through the dissolution of C-S-H gel and calcium carbonate [24]. Furthermore, the effect of neutral pH water causes slow carbonation, lowering the density binding gel [25]. Thus, concrete without liquid exposure maintains a denser and

more homogeneous microstructure, demonstrating that a liquid-free environment is optimal for maintaining the mechanical strength of concrete [26]. Furthermore, the importance of C-S-H gel stability in maintaining concrete strength is highlighted, as this phase is highly susceptible to acid attacks [27]. The observed increase in Fe at pH = 2 in the EDX analysis supports that acidic environments enhance the corrosion of iron within the concrete matrix [28]. These findings have significant practical implications for concrete applications in areas at risk of acidic waterlogging.

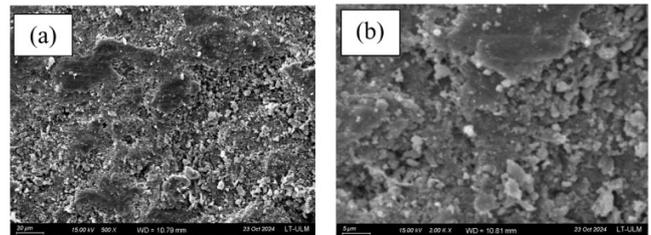


Fig. 9. SEM images for pH = 2-G₅ specimens with magnification (a) 500x, (b) 2000x.

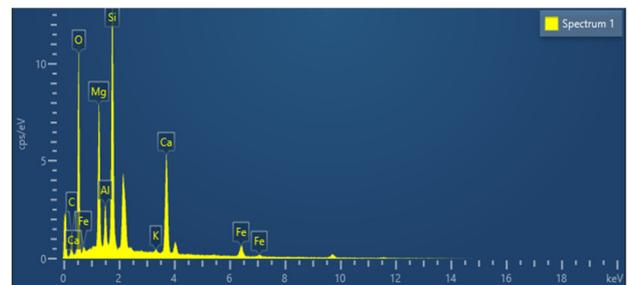


Fig. 10. EDX test results for specimen without waterlogging.

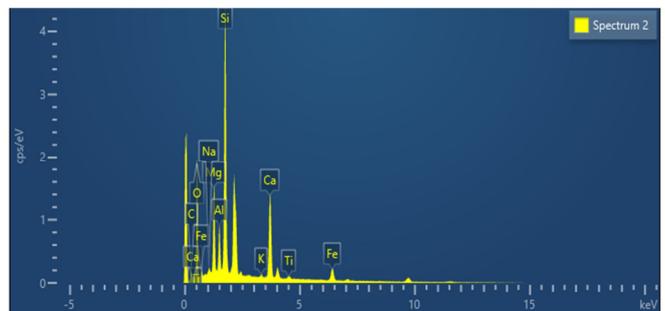


Fig. 11. EDX results for specimen in pH = 7 waterlogging (5 cm height).

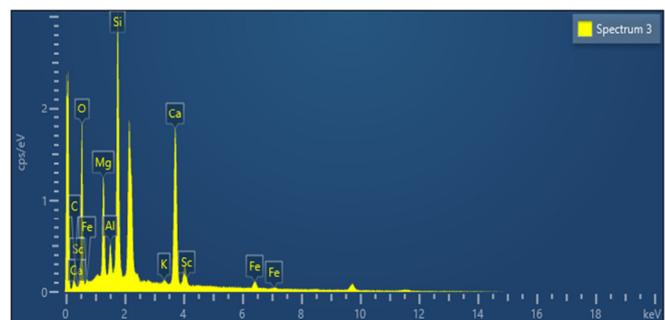


Fig. 12. EDX results for specimen in pH = 2 waterlogging (5 cm height).

TABLE VI. EDX TESTING RESULTS

Element	Atomic %		
	G ₀	G _s	
		pH = 7	pH = 2
C	25.56	24.84	24.27
O	50.94	50.34	45.9
Na	-	-	0.41
Mg	6.31	4.47	5.23
Al	1.59	1.19	2.27
Si	8.62	9.2	12.86
K	0.15	0.16	0.19
Ca	5.33	8.65	6.2
Sc	-	0.15	-
Ti	-	-	0.26
Fe	1.5	1	2.4

IV. CONCLUSION

This study focused on the simultaneous effects of different waterlogging heights and water pH on the physical and mechanical properties of concrete giving insight into the deterioration mechanisms that affect pavement performance over time. A 28-day curing period took place for 111 specimens, where compressive strength, absorption, and porosity with microstructure study were tested. The findings revealed that an increase in waterlogging height reduces compressive strength across pH conditions, especially under low pH values. Moreover, acidic waterlogging caused severe microstructural damages, evidenced by the dissolution of C-S-H gel and calcium hydroxide, as shown through the SEM-EDX analysis. These outcomes align with those of prior studies that highlight the vulnerability of concrete to acid-induced deterioration and the need for enhanced durability strategies. It is essential to consider the use of additives, like fly ash or pozzolan, to reduce porosity and improve the durability of concrete in extreme environments. Overall, designing concrete mixtures to withstand both prolonged waterlogging and acidic environments is essential in flood-prone regions or areas with low pH groundwater.

V. RECOMMENDATION

Future research should evaluate the long-term effects of waterlogging on concrete strength, extending beyond the 28-day period to capture potential late-stage deterioration under acidic environments. This will provide a more comprehensive understanding of the combined impact of waterlogging depth and water acidity, especially regarding compressive strength and microstructural changes over time. Furthermore, the use of additive materials, such as fly ash or slag, should be further explored to enhance concrete's resistance to the degradation caused by acidic environments. Investigations into hybrid solutions may also offer innovative avenues for strengthening concrete against low pH waterlogging conditions.

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