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Changes in the Properties of Green Concrete Due to an Acidic Environment

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***Abstract*—The problem in this research is the negative environmental impact of cement production and the decrease in concrete durability due to acid rain. This research aims to create an equation for the relationship between concrete's mechanical properties and the concrete's age in an acidic environment. This equation is used to predict the quality of green concrete produced according to the mix design and to measure the reduction in strength of green concrete in an acidic environment. The method used is experimental research with wet-dry acid rain simulations (a mixture of sulfuric acid and nitric acid solutions) in the laboratory using rice husk ash (RHA) as a cement substitute. This research uses 5% and 10% of RHA variations of cement weight and immersion in pH3 and pH4 acid solutions. The results showed that adding 5% RHA increased the compressive and flexural strength of concrete, both in normal and acidic environments, with a significant increase in concrete life up to 120 days. However, the addition of 10% RHA showed decreased performance in acidic environments, although it still provided benefits under normal conditions. The potential environmental and sustainability benefits of using RHA as a cement substitute are significant, as it can reduce CO_2 emissions, overcome waste disposal problems, and increase the durability of green concrete in acidic environments. This finding provides an environmentally friendly and sustainable solution for the construction industry, especially in areas vulnerable to acidic environments (acid rain).**

***Keywords*—Green concrete; rice husk ash; compressive strength; flexural strength; acidic environment.**

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I. INTRODUCTION

Cement is one of the materials needed in the construction world to form concrete materials. In general, many buildings still use concrete as a material that is easy to form and has relatively cheap maintenance costs. The need for infrastructure such as housing always increases with increasing population. This causes the need for cement to increase, even though the manufacturing process causes environmental damage. Cement production produces significant CO_2 emissions, which contribute to climate change [1]–[5]. In addition, emissions of other air pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM) have also increased. Studies show that although there was an initial decline in SO_2 and NO_x emissions due to stringent air pollution standards, they rebounded as cement production increased [6]–[10]. Cement dust pollution can cause various diseases, such as chronic obstructive pulmonary disease, silicosis, endocrine disorders, and cancer (bioaccumulation of heavy metals such as nickel, cadmium, mercury, and arsenic). This pollution also affects the flora and fauna around the factory area [11], [12].

Cement substitute materials have been widely used to reduce negative environmental impacts, so the concrete produced is more environmentally friendly, known as green concrete [13], [14]. Green concrete is made from environmentally friendly waste, reducing CO_2 emissions and water use by up to 20%. Green concrete provides excellent thermal insulation and high levels of fire resistance, and it has significant potential in using waste materials to produce green concrete. Green concrete is defined as using waste materials and concrete with high sustainability that does not damage the environment in the production process [15], [16]. Various types of waste are used as substitute materials for cement, including slag [17]–[21], fly ash [22]–[25], silica fume [26]–[29]. This research showed improvements in concrete properties, including mechanical properties, microstructure, and durability, with substitution variations between 10% - 30% of the cement weight.

Rice husk ash (RHA) is an alternative material that has been widely researched and can be helpful in concrete mixtures. RHA and wood sawdust at 5% replacement were suitable sand substitutes for developing the required rigid pavement structure [30]. Using RHA and eggshells as partial cement replacements can reduce CO_2 emissions and address environmental problems related to waste disposal [31]. Due to its high pozzolanic properties, RHA can replace 10% to 20% of cement without sacrificing concrete performance [32], [33]. In sulfate attack tests, only concrete with 5.0% RHA performed better in aggressive environments [34], [35]. This is because water permeability decreases along with decreasing air content for all mixtures [36]. It was also found that the best replacement RHA proportion was 10% of the cement weight after 28 days of curing [37].

Nowadays, the majority of cities in industrial countries experience acid rain. Vietnam is one of the country's most vulnerable to acid rain in Asia. In Vietnam's Northern Mountains, acid rainwater has a negative impact on local agricultural ecosystems [38]. Increased frequency of acid rain affects the microbial communities of forest soils more than agricultural soils in Southern China. Acid rain is expected in this region and significantly impacts community stability and biodiversity conservation [39], [40]. The advantage of concrete over other materials is its durability. However, various studies have found that the acid rain phenomenon has an impact on reducing the durability of concrete [41]–[44]. Acid rain, as a corrosive liquid, easily reacts chemically with the concrete hydration process, reducing the mechanical properties of concrete and even causing collapse. If an acid attacks concrete, a neutralization reaction occurs between H+ in the acid and $Ca(OH)_2$ in the cement paste, which reduces its alkaline properties [45]–[47]. On the other hand, RHA containing silica will react with $Ca\ (OH)_2$ during cement hydration and form more C-S-H gel. This new gel contributes to improving the strength and durability properties of concrete [48]–[51].

Based on the description of the results of several previous studies, cement replacement materials should be applied in the construction world, especially in creating green concrete. For this reason, an accurate prediction of the quality of the concrete produced according to the mixed design for green concrete still needs to be made. Furthermore, if it is used in locations prone to acid rain, it is necessary to accurately predict the reduction in the strength of the green concrete. These two things are the research objectives carried out at the laboratory level. The method used is experimental research, simulating acid rain in the laboratory. Meanwhile, the cement replacement material used is RHA, which is available in large quantities. Indonesia is the third-largest rice-producing country in the world. According to the Food and Agriculture Organization (FAO), in 2011, Indonesia could produce 66 million metric tons of rice [52], [53]. The research results stated that around 5.45% of the rice volume produced by RHA [54]. This research did not use OPC cement as previous research conducted, but PCC cement. Different types of cement certainly have an influence, especially on the bond with RHA. Compressive and flexural strength tests will be carried out to formulate general equations regarding quality and strength reduction due to acid.

Suppose compressive and flexural strength equations for green concrete, along with strength reduction equations, are available. In that case, they can be used as a reference in making green concrete mix designs in areas that experience acid rain. Meanwhile, using RHA as a partial replacement for cement reduces pollution caused by cement production per year.

II. Materials and Method

A. Materials

The material used is concrete with a quality of fc' 25 Mpa, a mixture of sand, gravel, cement, and water. Sand and gravel are sourced from Bili-Bili, with specifications according to ASTM C33/C33M. The cement used is Portland Composite Cement (PCC). Meanwhile, agricultural waste is used as a replacement material for cement, namely rice husk ash (Fig. 1), sourced from the free burning of rice husks without controlling temperature and burning time. Before use, rice husk ash (RHA) is filtered using filter No. 200 (Fig. 3).

Fig. 1 RHA as a partial cement replacement

The tools used in this study are as follows:

1) pH Meter: This tool controls the solution's acidity, measured by the pH level (Fig. 2).

Fig. 2 pH meter

2) Sieve No. 200: This tool filters RHA so that it is the same size as cement (Fig. 3).

Fig. 3 Sieve No. 200

*3) SEM and XRD T*ools test RHA characteristics (Fig. 4 & 5).

Fig. 4 SEM

Fig. 5 XRD

4) Universal Testing Machine: This tool is used for compression and flexural testing of specimens, obtaining mechanical property data (Fig. 6).

Fig. 6 Universal Testing Machine

B. Research Method

The concrete test specimen is cylindrical with a diameter of 150 mm and a height of 300 mm (Fig. 7) and a prism 150 mm x 150 mm x 600 mm (Fig. 8). Data collection was carried out by carrying out a series of concrete mechanical and microstructural tests. The mechanical properties test consists of a compression test (ASTM C39/C39M-21) and a flexural test (ASTM C293/C293M-16) using a Universal Testing Machine (UTM). Microstructural tests for RHA are scanning electron microscopy (SEM), energy dispersive X-ray (EDX), and X-ray powder diffraction (XRD) tests.

Fig. 7 Cylindrical specimens

Fig. 8 Prisms specimens

Table 1 shows the material needed for 1 m3 of concrete (ACI 211.1-91), namely PCC cement of 476 kg, sand, and gravel of 567 kg and 1071 kg, respectively. The water used is 220 kg. Test specimens were made with three variations, namely 0% RHA (without RHA), 5% RHA (5% of the weight of PCC cement), and 10% RHA (10% of the weight of PCC cement). The characteristics of the sand used in zone II are a specific gravity of 2.85, water absorption of 9.13%, fineness modulus of 2.55, and bulk density of 1.467 kg/l. The maximum grain of gravel used is 20 mm, specific gravity 2.24, water absorption 2.22%, and bulk density 1.447 kg/l. The cylinder contains 420 samples, with 140 samples each for the 0% RHA, 5% RHA, and 10% RHA groups. Pressure test examinations were carried out on three days, 7 days, 21 days, 28 days, 60 days, 90 days, and 120 days for 20 samples each. Next, the bending test was examined with variations in age of 28 days, 60 days, 90 days, and 120 days for ten samples each.

TABLE I

MIX PROPORTIONS OF CONCRETE (KG M^{-3})

Specimens	Cement PCC (kg)	RHA (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Water (kg)	Immersion Solution
0%RHA	476	0	567	1071	220	Normal
5%RHA	452.2	23.8	567	1071	220	Acid pH4
10%RHA	428.4	47.6	567	1071	220	Acid pH3

Next, the acid rain simulation is carried out by immersing (Fig. 9 & Fig. 10) in a solution of a mixture of sulfuric acid and nitric acid with a ratio of 7:3, with dry-wet cycles [55]. A test object without RHA is still made and soaked in normal water as a control test object. Variations in acid solutions were measured using a pH meter (Fig. 2) to create two solutions, pH4 and pH3.

Fig. 9 Cylinders immersion

Fig. 10 Prisms immersion

C. Research Variables

The independent variables are the percentage of RHA, namely 5% and 10% of the cement weight, and the soaking time (3, 7, 21, 28, 60, 90, and 120 days) in the solution (normal and acidic water). The normal water used is sourced from PDAM water. The acid solution is a mixture of sulfuric acid and nitric acid, acidity pH4 and pH3. Meanwhile, the dependent variable is the mechanical properties of compressive and flexural strength.

D. Data Analysis

Data analysis carried out in the research was used to find equations, ratios, and coefficients that can be used to apply green concrete in construction, especially in controlling concrete quality related to the compressive strength and flexural strength of green concrete. For this reason, data analysis was carried out in five stages, namely:

1) Standard Deviation Value: The standard deviation is obtained after obtaining the average compressive strength measurements in a normal environment, pH4 and pH3.

2) The Relationship Coefficient Between Compressive Strength and Concrete Age: Data analysis of mechanical test results is used to establish a relationship between compressive strength and concrete age with variations in the use of RHA. We will also pay attention to the effect of the length of soaking in pH4 and pH3 acid solutions.

3) Compressive Strength Ratio: Data analysis of mechanical test results is used to predict compressive strength at 28 days, 90 days, and 120 days.

4) Flexural Strength Ratio: Data analysis of mechanical test results is used to predict flexural strength at 28 days, 90 days, and 120 days.

5) Compressive Strength and Flexural Strength Coefficients: Data analysis of mechanical test results establishes a relationship between compressive and tensile strength.

III. Results and Discussion

A. Results

1) Rice Husk Ash (RHA) Characteristics: Figure 11 shows RHA filtered with filter No. 200. Meanwhile, Figure 12 shows the SEM results of the physical characteristics of RHA, namely the micro size, nanoporous, and irregular. The energy dispersive X-ray (EDX) method is used to view the chemical structural components of RHA, as illustrated in Figure 13. Furthermore, Figure 14 is the result of XRD, showing RHA in an amorphous condition.

Fig. 11 Rice husk ash filtration

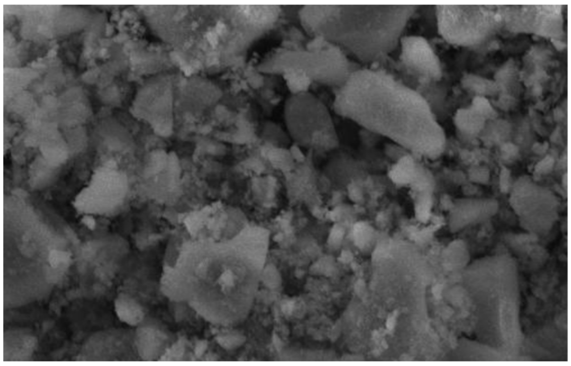

Fig. 12 SEM micrographs of RHA

Spectrum: test

Element	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Compound	norm. Comp. C [wt.%]	Error (3 Sigma) [wt.%]
Carbon	0.00	0.00	0.00		0.00	0.00
Oxygen	22.81	50.64	62.08		0.00	18.21
Silicon	20.02	44.45	31.04	SiO2	95.08	3.21
Nitrogen	2.21	4.92	6.88		4.92	5.19
Total:	45.04	100.00	100.00			

Fig. 13 Energy Dispersive X-ray (EDX) RHA

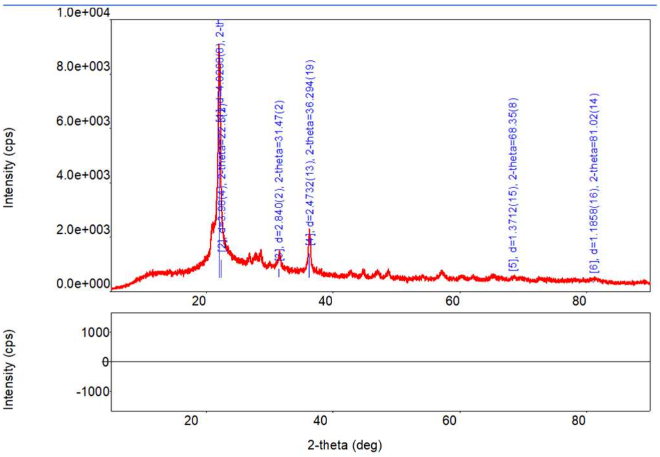

Fig. 14 XRD analysis of RHA

2) Compressive Strength Test: The average values of concrete compressive strength test results at various ages for samples treated in normal water are presented in Figure 15. Furthermore, Table II shows the standard deviation data values or data distribution for three groups of samples treated in normal water.

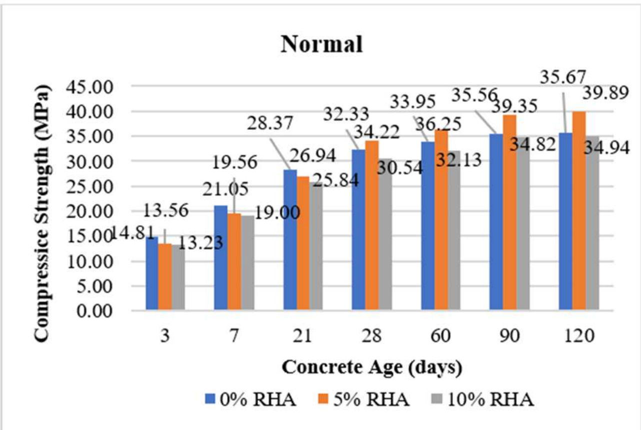

Fig. 15 Relationship between concrete age and compressive strength (normal condition)

Figure 15 shows the compressive strength values of concrete at various ages for variations in the percentage of RHA under normal conditions, which shows an interesting trend. This compressive strength data was measured at ages 3, 7, 21, 28, 60, 90, and 120 days for concrete with 0%, 5%, and 10% RHA. In concrete without the addition of RHA (0%), the compressive strength value increases as the age of the concrete increases, starting from 14.81 MPa at three days to 35.67 MPa at 120 days. Concrete with 5% RHA showed a significant increase in compressive strength, from 13.56 MPa at three days to 39.89 MPa at 120 days. This indicates that adding 5% RHA can substantially increase the compressive strength of concrete, especially at older ages. Concrete with 10% RHA also shows an increase in compressive strength over time, although the value is slightly lower than that of 5% RHA concrete. At the age of 3 days, the compressive strength of this concrete is 13.23 MPa and increases to 34.94 MPa at 120 days.

TABLE II
STANDARD DEVIATION VALUE OF CONCRETE COMPRESSIVE STRENGTH TEST RESULTS (NORMAL CONDITION)

Age (days)	Rice Husk Ash (RHA)		
	0%	5%	10%
3	1.70	1.94	1.90
7	1.89	2.40	2.23
21	2.16	1.69	2.42
28	2.33	2.61	3.03
60	2.64	2.24	2.59
90	1.87	2.39	2.02
120	1.52	1.92	2.13

The results of the standard deviation analysis show that the standard deviation value for samples soaked under normal conditions varies for the three data groups. The larger the standard deviation value, the less accurate the data. The study results in Table II show the most minor standard deviation at 0% RHA with the smallest value of 1.52. Meanwhile, samples with 5% RHA and 10% RHA showed larger standard deviation values. These results indicate that the presence of RHA in concrete further increases the risk of data deviation.

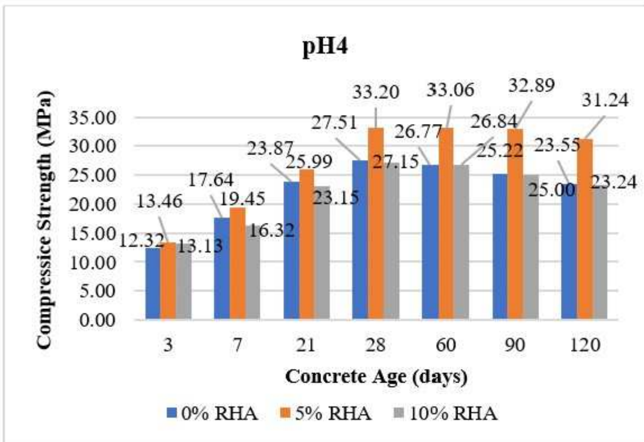

Fig. 16 Relationship between concrete age and compressive strength (pH4 immersion)

Based on the data given in the bar diagram in Figure 16, the influence of variations in the percentage of RHA on pH 4 can be observed at several time intervals, namely days 3, 7, 21, 28, 60, 90, and 120. At the beginning of testing (day 3), the compressive strength with 5% RHA showed the highest value (13.46) compared with the compressive strength of 0% RHA and 10% RHA. On day 7, the compressive strength with 5% RHA still showed the highest value (19.45), while the compressive strength of 0% RHA and 10% RHA had lower values. This trend continued until day 21, when the compressive strength of 5% RHA reached 25.99, higher than the compressive strength of 0% RHA (23.87) and 10% RHA (23.15). On the 28th day, the compressive strength with 5% RHA increased significantly to 33.20, while the compressive strength of 0% RHA and 10% RHA showed lower values. Until the 120th day, the compressive strength with 5% RHA remained the highest, although it decreased slightly to 31.24. On the other hand, the compressive strength of 0% RHA and 10% RHA continues to decrease consistently. This data shows that adding 5% RHA produces higher and more stable compressive strength than other variations.

TABLE III
STANDARD DEVIATION VALUE OF CONCRETE COMPRESSIVE STRENGTH TEST RESULTS (PH4 IMMERSION)

Age (days)	Rice Husk Ash (RHA)		
	0%	5%	10%
3	2.90	3.02	4.82
7	1.83	1.43	2.42
21	1.06	2.49	2.45
28	2.33	2.61	3.89
60	2.64	2.95	3.96
90	1.87	2.20	3.06
120	1.44	1.68	2.47

The standard deviation values in the three sample groups with three treatments show varying numbers. Table III presents the diversity of data obtained in the 4% immersion treatment. The most extensive data diversity in the 0% RHA sample was 2.90, while the two groups of concrete with additional RHA showed a higher figure, 3.02 for the 5% RHA sample and 4.82 for the 10% RHA sample.

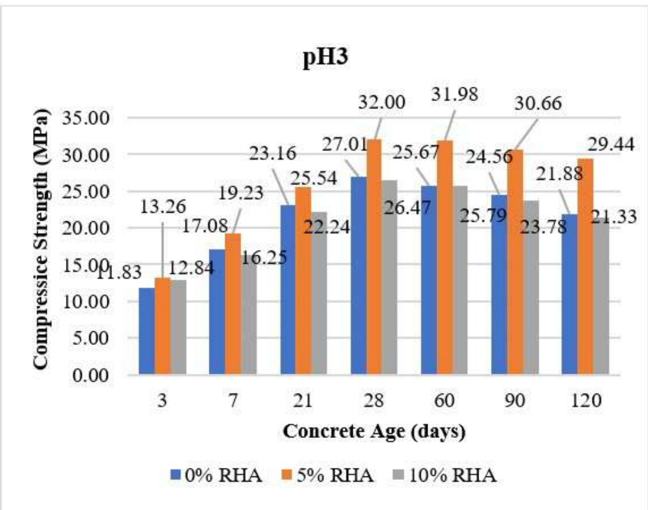

Fig. 17 Relationship between concrete age and compressive strength (pH3 immersion)

Figure 17 shows changes in the compressive strength of concrete in an environment with pH three, which shows significant variations based on the percentage of rice husk ash (RHA) added. On day 3, concrete with 5% RHA had the highest compressive strength of 13.25 MPa, followed by concrete with 10% RHA (12.84 MPa) and 0% RHA (11.83 MPa). On day 7, concrete with 5% RHA still showed the highest compressive strength (19.23 MPa), while concrete with 10% RHA and 0% RHA had compressive strengths of 16.25 MPa and 17.08 MPa, respectively. This trend continued until day 21, when concrete with 5% RHA reached a compressive strength of 25.54 MPa, higher than concrete with 10% RHA (22.24 MPa) and 0% RHA (23.16 MPa). On day 28, concrete with 5% RHA experienced a significant increase in compressive strength to 32.00 MPa, while concrete with 10% RHA and 0% RHA showed lower compressive strengths of 26.47 MPa and 27.01 MPa, respectively. After the 60th day, concrete with 5% RHA still showed the highest compressive strength (31.98 MPa), although it started to decrease slightly on the 90th day (30.66 MPa) and the 120th day (29.44 MPa). In contrast, 0% RHA and 10% RHA concrete showed a more consistent decrease in compressive strength from 25.67 MPa and 25.79 MPa on the 60th day to 21.88 MPa and 21.33 MPa on the 120th day. This data shows that adding 5% RHA positively increases the compressive strength of concrete in a pH three environment, maintaining higher and more stable strength compared to 0% RHA and 10% RHA concrete.

TABLE IV
STANDARD DEVIATION VALUE OF CONCRETE COMPRESSIVE STRENGTH TEST RESULTS (PH3 IMMERSION)

Age (days)	Rice Husk Ash (RHA)		
	0%	5%	10%
3	3.57	4.21	6.67
7	4.35	4.79	5.44
21	2.68	2.90	5.99
28	2.17	3.57	4.98
60	3.27	3.04	3.21
90	2.13	3.79	3.19
120	3.22	3.90	4.51

Soaking conditions with pH3 provide varying results. In Table IV, diversity figures were found between 2.13 and 4.35 in the 0% RHA sample, while in the 5% RHA sample, a higher figure was found, namely between 2.90 and 4.79. Even in a 10% RHA sample, the diversity value reached 6.67%.

3) Flexural Test: In a normal environment, as shown in Figure 18, concrete with various percentages of rice husk ash (RHA) shows an increase in flexural strength as the age of the concrete increases. Concrete with 5% RHA has the highest flexural strength, increasing from 3.45 MPa on the 28th day to 3.92 MPa on the 120th day. Concrete with 10% RHA also showed increased flexural strength, from 3.19 MPa on the 28th day to 3.61 MPa on the 120th day. Meanwhile, 0% RHA concrete had a lower increase, from 3.42 MPa on the 28th day to 3.65 MPa on the 120th day.

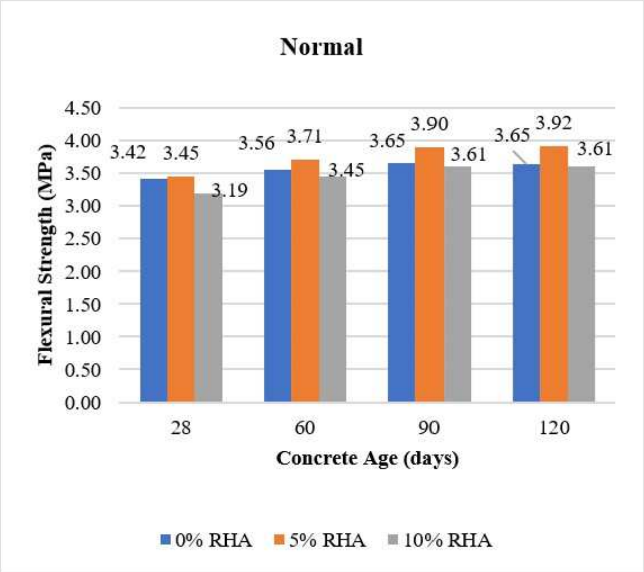

Fig. 18 Relationship between concrete age and flexural strength (normal condition)

In an environment with a pH of 4, concrete with 5% RHA again showed the best performance in terms of flexural strength (Figure 19). However, there was a slight decrease after reaching a peak on the 28th day with 3.29 MPa until it decreased to 2.99 MPa on the 120th day. Concrete with 10% RHA has a lower flexural strength, from 2.79 MPa on the 28th day to 2.54 MPa on the 120th day. 0% RHA concrete experienced a more significant decrease, from 2.95 MPa on the 28th day to 2.54 MPa on the 120th day.

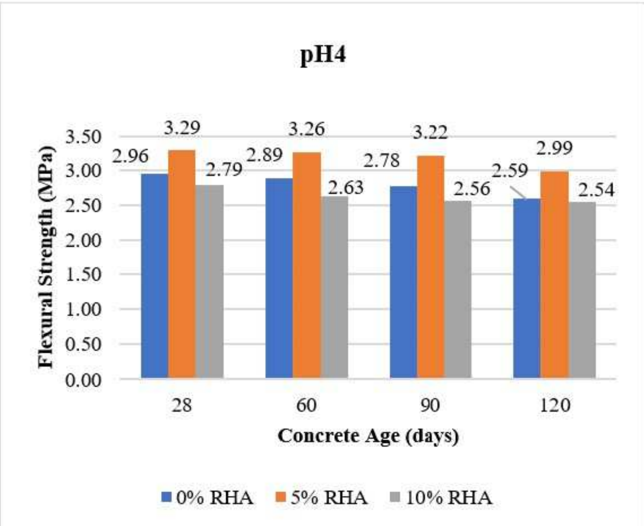

Fig. 19 Relationship between concrete age and flexural strength (pH4 immersion)

In an environment with pH 3, the decrease in flexural compressive strength is more visible in all RHA variations (Figure 20). Concrete with 5% RHA still showed the best performance, although it decreased from 3.23 MPa on the 28th day to 2.84 MPa on the 120th day. Concrete with 10% RHA decreased from 2.67 MPa on the 28th day to 2.30 MPa on the 120th day. 0% RHA concrete experienced the most significant decrease, from 2.82 MPa on the 28th day to 2.38 MPa on the 120th day.

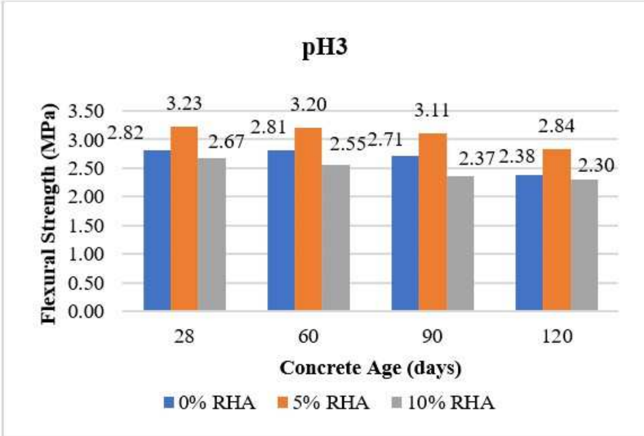

Fig. 20 Relationship between concrete age and flexural strength (pH3 immersion)

Based on the data presented in Figures 18, 19, and 20, adding 5% RHA to the concrete mixture consistently increases flexural strength in normal environments and environments with low pH (pH 4 and pH 3). Concrete with 5% RHA shows better resistance to more aggressive environmental conditions than concrete with 0% RHA and 10% RHA. Although all variations experience a decrease in flexural strength in low pH environments, concrete with 5% RHA still shows superior performance, making it the best choice for applications in acidic environmental conditions.

B. Discussion

1) Sample Standard Deviation Value: Table V shows the effect of immersion conditions and RHA concentration on sample deviation standards. Under normal soaking conditions, the diversity of the 0% and 5% RHA samples was relatively the same. Meanwhile, the maximum diversity value in the 10% sample was 3.03. Likewise, in the other two treatment groups. This indicates that a 10% RHA presentation has a higher risk of failure. Even in samples soaked at pH3, the diversity value exceeds 5%.

TABLE V
EFFECT OF IMMERSION CONDITIONS AND RHA CONCENTRATION ON SAMPLE STANDARD DEVIATION

Immersed	SD	Rice Husk Ash (RHA)		
		0%	5%	10%
Normal Condition	Max	2.64	2.61	3.03
	Min	1.52	1.61	1.90
pH4	Max	2.90	3.02	4.82
	Min	1.06	1.43	2.42
pH3	Max	4.35	4.79	6.67
	Min	2.13	2.90	3.19

The study of concrete characteristics generally involves calculating the standard deviation [56]. This statistical value is the researcher's confidence level in the sample being tested or the confidence interval [57]. The sample standard deviation shows the general characteristics or properties of the variables studied. The greater the standard deviation value, the more biased the sample presented is. Specifically, in the study of concrete characteristics, the standard deviation value contributes to the compressive strength characteristics of concrete. A smaller standard deviation value indicates a smaller sample failure rate. If the standard deviation value is large, it will reduce the compressive strength characteristics of the concrete [58].

The results of this study show that the standard deviation value of samples soaked at a low pH produces a larger standard deviation value. This value indicates that acidic conditions affect reducing the compressive strength characteristics. In other words, the acid attack caused more and more samples to be damaged.

2) Age Coefficient: Figure 21 shows the magnitude of each concrete age at 0% RHA, 5% RHA, and 15% RHA in a normal environment. The aging coefficient for concrete without RHA addition increased gradually from 0.46 at three days to 1.10 at 90 and 120 days. The aging coefficient also increases for concrete with 5% RHA, starting from 0.40 at three days to 1.17 at 120 days. Concrete with 10% RHA had a similar pattern, with the aging coefficient increasing from 0.43 at three days to 1.14 at 90 and 120 days.

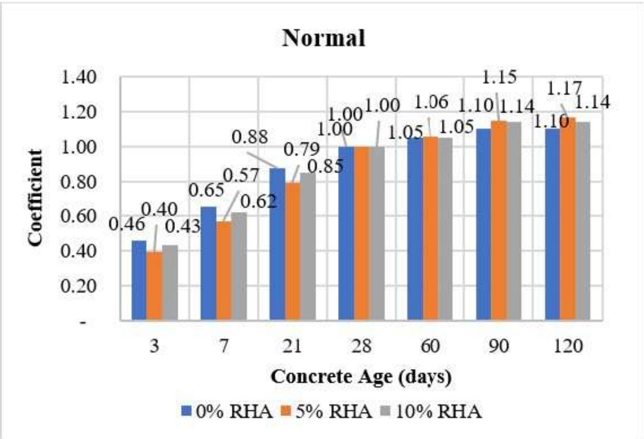

Fig. 21 Coefficient predicted compressive strength on various concrete age (normal)

Meanwhile, in Figure 22, where the environment is pH 4, concrete without RHA increases the aging coefficient from 0.45 at three days to 1 at 28 days, decreasing to 0.86 at 120 days. Concrete with 5% RHA increased from 0.41 at three days to 1 at 28 days, then slightly reduced to 0.94 at 120 days. Concrete with 10% RHA showed a somewhat different pattern, increasing from 0.48 at three days to 1 at 28 days, then decreasing to 0.86 at 120 days.

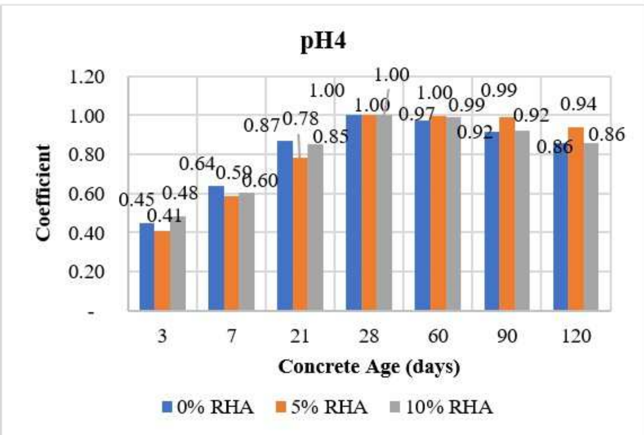

Fig. 22 Coefficient predicted compressive strength on various concrete ages (pH4)

Furthermore, in a pH 3 environment, concrete without RHA increased from 0.44 at 3 days to 1 at 28 days, then decreased significantly to 0.81 at 120 days (Figure 23). Concrete with 5% RHA increased from 0.41 at 3 days to 1 at 28 days and decreased slightly to 0.92 at 120 days. For concrete with 10% RHA, the aging coefficient increases from 0.49 at three days to 1 at 28 days, decreasing drastically to 0.81 at 120 days.

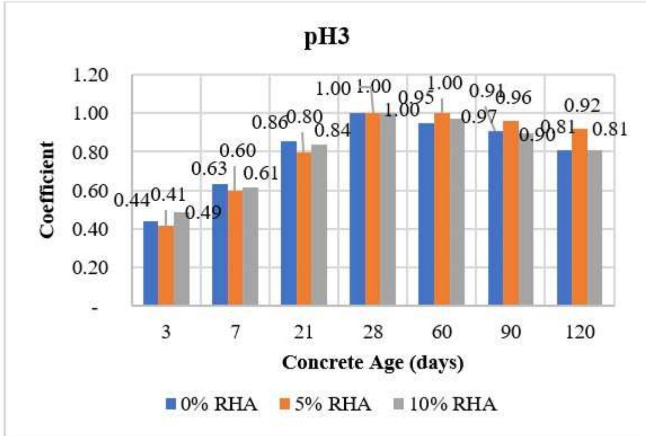

Fig. 23 Coefficient predicted compressive strength on various concrete ages (pH3)

Thus, it can be said that the addition of RHA to concrete increases the life coefficient under normal conditions, especially at levels of 5% and 10%. However, in low pH environments (pH 4 and pH 3), although the age coefficient increased up to 28 days, it tended to decrease, indicating the negative influence of the acidic environment on the strength of concrete over time. This decrease was more significant at higher RHA levels.

In specimens in a normal environment for RHA test objects, the coefficient values are low at 3, 7, 21, and 28 days compared to test objects with 0% RHA. Previous researchers also found this condition; at three days, the compressive strength at 5% RHA and 10% RHA decreased by 0.14% and 13.15%, respectively. Furthermore, at seven days, it decreased by 0.32% and 0.65%, respectively [59]. This result is caused by the pozzolanic activity of RHA, which takes longer to process, so the strength at ages under 28 days is low. On the other hand, at ages above 28 days, the strength development exceeds that of 0% RHA specimens [60]. The fine RHA particles help fill the voids in the paste so that more C-S-H is formed and increases the compressive strength of the concrete [61].

The equation that can be formed from the research data is the relationship between the age of concrete in days (x) and the age coefficient (y).

TABLE VI
EQUATION OF THE RELATION BETWEEN AGE OF CONCRETE AND AGE COEFFICIENT (NORMAL CONDITION)

Sample	Regression	R Square
0%RHA	$y = -9E\text{-}05x^2 + 0.0151x + 0.5309$	0.8834
5%RHA	$y = -1E\text{-}04x^2 + 0.0171x + 0.4450$	0.9190
10%RHA	$y = -9E\text{-}05x^2 + 0.0159x + 0.4976$	0.9054

For typical environments, the concrete age coefficient increases as the age of the concrete increases. The R^2 value shows this model has a reasonably strong correlation (88.34%) with the data. Meanwhile, adding 5% RHA slightly increases the concrete life coefficient compared to 0% RHA. A higher R^2 value (91.9%) indicates a robust correlation to the data. Furthermore, adding 10% RHA gave similar results to 5% RHA, with a slight increase in the concrete life coefficient. The R^2 value (90.54%) still shows a robust correlation.

TABLE VII
EQUATION OF THE RELATION BETWEEN AGE OF CONCRETE AND AGE COEFFICIENT (PH4 IMMERSION)

Sample	Regression	R Square
0%RHA	$y = -0.0001x^2 + 0.0146x + 0.5328$	0.7591
5%RHA	$y = -0.0001x^2 + 0.0163x + 0.4648$	0.8460
10%RHA	$y = -0.0001x^2 + 0.0148x + 0.5273$	0.8041

For pH4, the concrete life coefficient decreases slightly compared to normal environments. The R^2 value (75.91%) shows a fairly good correlation. Adding 5% RHA in a pH4 environment increases the life coefficient of concrete. The R^2 value (84.6%) shows a stronger correlation than 0% RHA. The addition of 10% RHA showed a slight increase in the concrete life coefficient compared to 5% RHA. The R^2 value (80.41%) shows a good correlation.

TABLE VIII
EQUATION OF THE RELATION BETWEEN AGE OF CONCRETE AND AGE COEFFICIENT (PH3 IMMERSION)

Sample	Regression	R Square
0%RHA	$y = -0.0001x^2 + 0.0149x + 0.5214$	0.7567
5%RHA	$y = -0.0001x^2 + 0.0158x + 0.4810$	0.8241
10%RHA	$y = -0.0001x^2 + 0.0147x + 0.5313$	0.7965

The concrete age coefficient is lower in the pH3 environment compared to normal and pH4 environments. The R^2 value (75.67%) shows a fairly good correlation. Adding 5% RHA in a pH3 environment increases the concrete life coefficient, with the R^2 value (82.41%) showing a good correlation. The addition of 10% RHA shows an increase in the concrete life coefficient compared to 5% RHA. The R^2 value (79.65%) shows a good correlation. The polynomial equation shows how variations in concrete age and RHA percentage affect the concrete life coefficient under various environmental conditions. A high R^2 value indicates that this model accurately describes existing data.

3) Compressive Strength Ratio: The graph in Figure 24 shows that in a normal environment, concrete with 5% RHA experiences an increase in compressive strength as time increases. On days 3 and 7, the compressive strength ratio was 0.92 and 0.93, meaning concrete with RHA had a slightly lower compressive strength than concrete without RHA. However, after 28 days, the compressive strength ratio of concrete with 5% RHA increased to 1.06 and continued to increase until it reached 1.12 on the 120th day. For concrete with 10% RHA, the compressive strength ratio was relatively lower at the beginning of the test (0.89 on day 3) and increased to 0.98 on day 120.

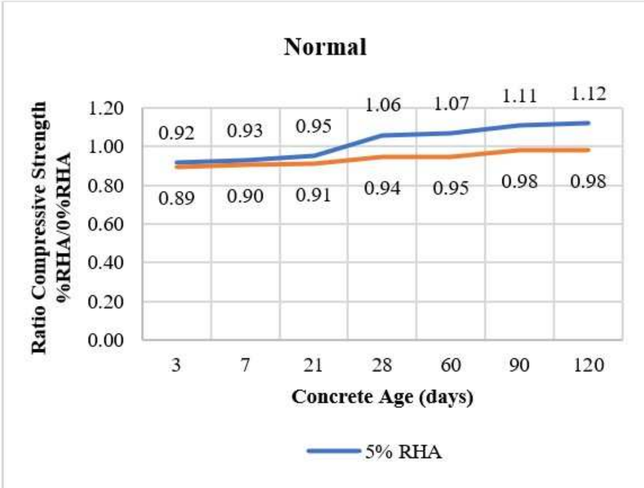

Fig. 24 Compressive strength ratio (normal environment)

The graph in Figure 25 shows that in a pH4 environment, concrete with 5% RHA experienced a significant increase in compressive strength compared to concrete without RHA. On the 3rd day, the compressive strength ratio was 1.09 and continued to increase until it reached 1.33 on the 120th day. This shows concrete with 5% RHA performs much better in a pH4 environment. Concrete with 10% RHA also showed an increase in compressive strength at the beginning of the test, with a ratio of 1.07 on day 3. However, this ratio experienced fluctuations and decreased slightly to 0.99 on day 120.

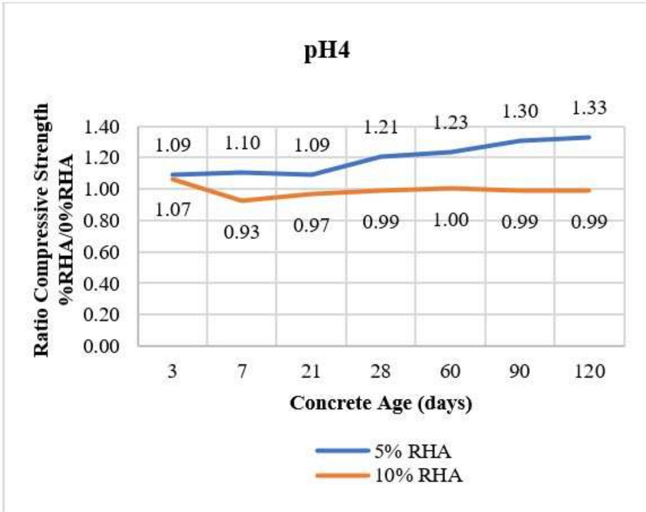

Fig. 25 Ratio compressive strength (pH4)

The graph in Figure 26 shows that in a pH3 environment, concrete with 5% RHA shows a significant increase in compressive strength, similar to a pH4 environment. The compressive strength ratio on day 3 was 1.12 and continued to increase until it reached 1.35 on day 120. This shows that concrete with 5% RHA is very effective in increasing compressive strength in a pH3 environment. Concrete with 10% RHA had a lower compressive strength ratio at the beginning of the test (1.09 on day 3) and experienced a slight decrease to 0.98 on day 120.

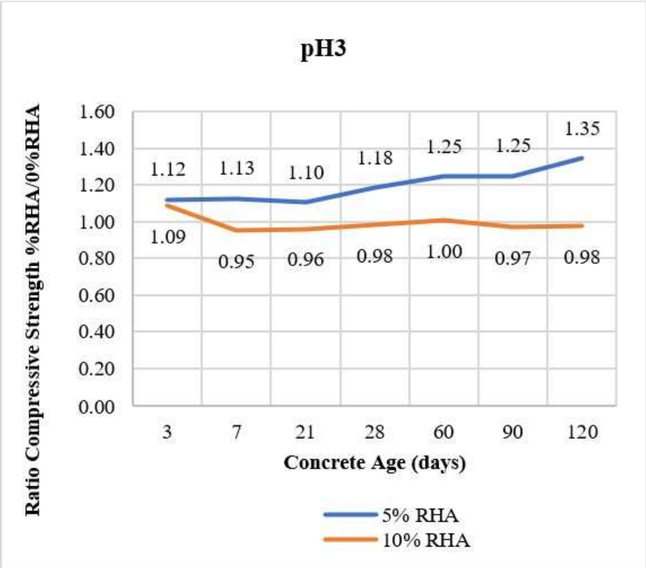

Fig. 26 Ratio compressive strength (pH3)

Overall, using 5% RHA in concrete significantly increases compressive strength in various environmental conditions, especially in environments with lower pH (pH4 and pH3). Meanwhile, using 10% RHA showed a more moderate and fluctuating increase in compressive strength. The equation that can be formed from research data is the relationship between concrete age in days (x) and compressive strength ratio (y).

TABLE IX
EQUATION OF THE RELATION BETWEEN AGE OF CONCRETE AND COMPRESSIVE STRENGTH RATIO

Immersed	RHA	Regression	R Square
Normal Condition	5%	y = 0.0386x + 0.8662	0.9271
	10%	y = 0.0160x + 0.8727	0.9525
pH4	5%	y = 0.0448x + 1.0146	0.9135
	10%	y = -0.0025x + 0.9998	0.0171
pH3	5%	y = 0.0380x + 1.0443	0.8583
	10%	y = -0.009x + 1.0254	0.1835

For typical environments, the linear equation for using 0% RHA, 5% RHA, and 10% RHA with R^2 close to 1 show that this model has a reasonably strong correlation with the data. Increasing the age of concrete will increase the resulting compressive strength. Meanwhile, for acidic environments (pH4 and pH3), only 5% RHA was used, which had a high R^2 value (91.35%), showing a robust correlation with the data. This does not happen when using 10%; the R^2 values are very low (0.0171 and 0.1835), indicating a very weak correlation.

The decrease in concrete strength due to acidic conditions has received special attention from researchers. Zhang [62] found that acid rain, as a natural phenomenon, has a negative impact on the quality of concrete. Next, Yoshida & Higashiyama [63] explained that concrete samples placed in an environment with pH 1 to 5 experienced damage due to sulfur and nitric acid attacks. This damage begins with cracks between the aggregate and matrix, characterized by increased porosity. As a result, air quickly enters the concrete body and worsens the bond between the materials [44], [50]. Several studies have stated that acid in the concrete environment causes cracks between the concrete matrix of varying sizes. On a micro level, damage begins with the formation of hairline cracks in the concrete matrix.

Furthermore, at a macro level, the damage takes the form of loosening the bonds between the aggregate and the cement matrix [64][65]. The mechanism of concrete damage in an acidic environment begins with holes in the concrete surface. The lower the pH of the immersion water, the faster the increase in damage, which is indicated by a decrease in concrete mass [66].

4) Flexural Strength Ratio: Figure 27 shows that concrete with 5% RHA experiences an increase in flexural strength in a normal environment compared to concrete without RHA as time increases. On the 28th day, the flexural strength ratio was 1.01 and increased to 1.07 on the 120th day. This shows that using 5% RHA can increase the flexural strength of concrete in normal environments. For concrete with 10% RHA, the flexural strength ratio was slightly lower, starting from 0.93 on the 28th day and increasing slightly to 0.99 on the 120th day.

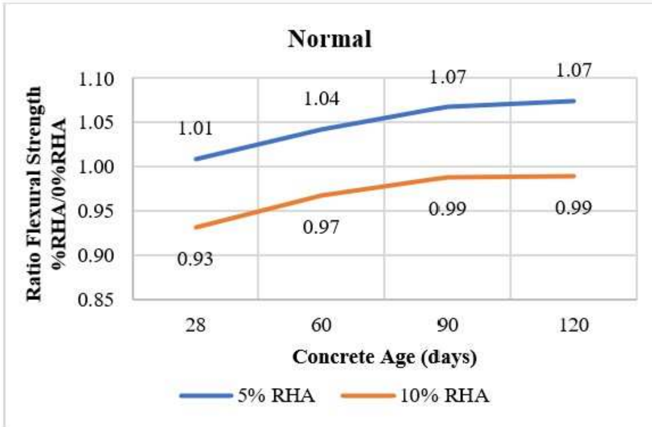

Fig. 27 Ratio flexural strength (normal)

Figure 28 shows that in a pH4 environment, concrete with 5% RHA significantly increases flexural strength compared to concrete without RHA. On the 28th day, the flexural strength ratio was 1.11 and increased to 1.15 on the 120th day. This shows that concrete with 5% RHA is more flexible in a pH4 environment. Meanwhile, concrete with 10% RHA has a lower flexural strength ratio, starting from 0.94 on the 28th day and fluctuating until it reaches 0.98 on the 120th day.

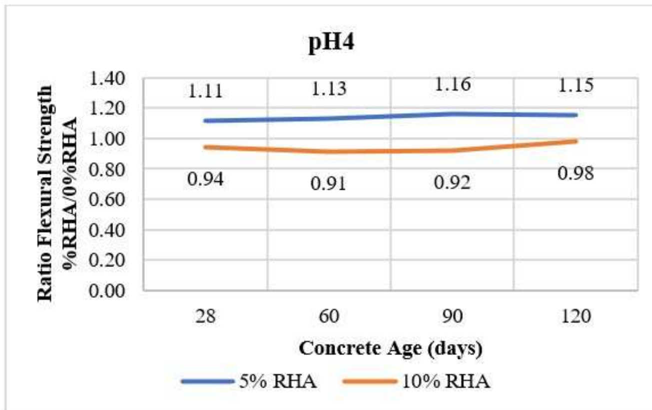

Fig. 28 Ratio flexural strength (pH4)

Figure 29 shows that in the pH3 environment, the ratio values for both 5% RHA and 10% RHA are almost the same as in the pH4 environment. This illustrates that for the mechanical properties of flexural strength, the role of RHA in maintaining flexural strength is not as significant as the compressive strength properties. Previous researchers also obtained this result: the flexural strength of concrete using 20% RHA was 5.9 MPa. Meanwhile, the flexural strength that does not use RHA is 4.9 MPa [67]. The flexural strength of concrete using 0% RHA and 10% RHA is 7.94 MPa and 8.15 MPa [68], and 4.61 MPa and 4.90 MPa [69]. This situation can be caused by the aggregation properties of concrete with RHA, which makes it less able to withstand high-tensile stress [70]. This observation points to a weak condition in the interfacial transition zone not being improved, reducing the flexural strength at concrete ages above 28 days. The use of RHA as a substitute material for PCC cement does not produce high amounts of calcium hydroxide [71]. The influence of sulfuric acid and nitric acid causes an increase in the percentage of gypsum compounds, weakening concrete strength [72].

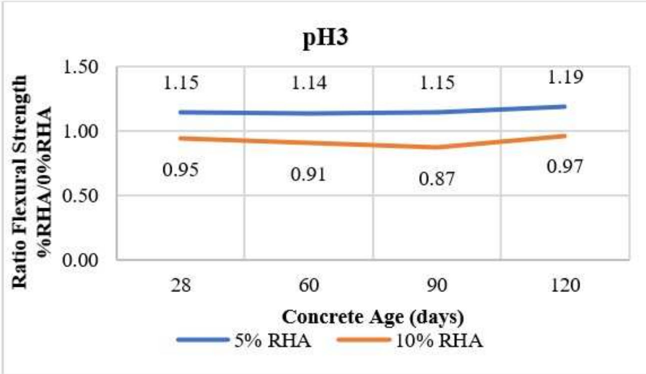

Fig. 29 Ratio flexural strength (pH3)

5) Compressive Strength and Flexural Strength Coefficients: ACI 318I-19 specifies that flexural strength, in this case, the rupture modulus, for normal concrete is calculated using the following equation:

$$f_r = 0.6\sqrt{fc'} \quad (1)$$

$$f_r = c\sqrt{fc'} \quad (2)$$

TABLE X
COMPRESSIVE STRENGTH AND FLEXURAL STRENGTH COEFFICIENTS

Immersion	% RHA	Compressive Strength MPa (fc')	Flexural Strength MPA (fr)	Coefficient
	0% RHA	32.33	3.422	0.602
Normal	5% RHA	34.22	3.453	0.590
	10% RHA	30.54	3.187	0.577
	0% RHA	27.51	2.956	0.564
pH4	5% RHA	33.20	3.289	0.571
	10% RHA	27.15	2.789	0.535
	0% RHA	27.01	2.822	0.543
pH3	5% RHA	32.00	3.233	0.572
	10% RHA	26.47	2.667	0.518

Table X shows that for normal environments, the coefficient c in equation (2) for % RHA, 5% RHA, and 10% RHA concrete is 0.602, 0.590, and 0.577, respectively. These three values are relatively the same as the ACI 318I-19 coefficient, namely 0.6. This coefficient decreases to less than 0.6 when the concrete is in a pH4 and pH3 environment, ranging from 0.518-0.572 for all RHA variations. This coefficient can help determine the properties of concrete mixtures containing RHA in an acidic environment at 28 days. Several researchers have created a model of the relationship between compressive strength and flexural strength, which has a linear relationship [71], [73]. Tran *et al.* [74] We also provided coefficient values for concrete ages 3, 7, 28, and 56, ranging from 0.8 to 0.86. The research results describe how the coefficient value of 0.6 must be modified to calculate the rupture modulus for green concrete in locations experiencing acid rain.

IV. CONCLUSION

In normal and acidic environments, concrete with 10% RHA has the highest standard deviation, indicating non-uniformity of the resulting compressive strength. This is caused by PCC-type cement, which, if added with RHA above 5%, can slow the hydration process. The age coefficient of 5% RHA shows a lower value than concrete without RHA at ages below 28 days but higher at ages above 28 days in normal and acidic environments. However, for 10%RHA in an acidic environment, the lifetime coefficient decreases to 20%. This shows that 10%RHA cannot increase compressive strength in an acidic environment compared to 5%RHA. This is also caused by the RHA pozzolanic process, which requires longer to reach maximum strength.

The compressive strength ratio compares the compressive strength of concrete without and with RHA in normal and acidic environments. A ratio above 1 indicates that the residual compressive strength of concrete with RHA is greater than the compressive strength without RHA. This condition occurs in 5%RHA concrete in both normal and acidic environments. Meanwhile, 10% RHA concrete produces a ratio of less than 1. This shows that the percentage of RHA used together with PCC-type cement must be considered. This linear ratio equation can be used as a reference to determine the design compressive strength in areas with high acidity levels (acid rain).

The flexural strength ratio compares the flexural strength of concrete without and with RHA in normal and acidic environments. In a normal environment, the flexural strength ratio of concrete with 5% RHA increases to 1.07 on the 120th day. In a pH 4 environment, the flexural strength ratio reached 1.15 on the 120th day. Concrete with 10% RHA shows a lower and fluctuating flexural strength ratio, especially in acidic environments, indicating that using RHA does not significantly increase concrete flexural strength. If applied in construction, it is necessary to use the precast method, so the hydration process is complete when green concrete is exposed to high acidity levels of acid rain.

The coefficients for compressive strength and flexural strength in normal environments show results consistent with the ACI 318I-19 values. However, this coefficient decreases in acidic environments (pH 4 and pH 3), indicating that using RHA affects the mechanical properties of concrete under acidic conditions. This coefficient is helpful in determining the rupture modulus value when planning the service strength of green concrete structures.

NOMENCLATURE

Y absorbance concentration based on linear regression

REFERENCES

[1] C. Winter, B. Schröter, and S. Fidaschek, "The German Cement Industry as a CO2 Source for Other Industries," *Fuels*, vol. 3, no. 2, pp. 342–352, Jun. 2022, doi: 10.3390/fuels3020021.

[2] Y. Shan, Q. Huang, D. Guan, and K. Hubacek, "China CO2 emission accounts 2016–2017," *Scientific Data*, vol. 7, no. 1, Feb. 2020, doi:10.1038/s41597-020-0393-y.

[3] I. Vázquez-Rowe, K. Ziegler-Rodriguez, J. Laso, I. Quispe, R. Aldaco, and R. Kahhat, "Production of cement in Peru: Understanding carbon-related environmental impacts and their policy implications," *Resources, Conservation and Recycling*, vol. 142, pp. 283–292, Mar. 2019, doi: 10.1016/j.resconrec.2018.12.017.

[4] X. Ma, C. Li, and B. Li, "Carbon Emissions of China's Cement Packaging: Life Cycle Assessment," *Sustainability*, vol. 11, no. 20, p. 5554, Oct. 2019, doi: 10.3390/su11205554.

[5] M. Soomro, V. W. Y. Tam, and A. C. Jorge Evangelista, "Production of cement and its environmental impact," *Recycled Concrete*, pp. 11–46, 2023, doi: 10.1016/b978-0-323-85210-4.00010-2.

[6] J. Liu, S. Zhang, and F. Wagner, "Exploring the driving forces of energy consumption and environmental pollution in China's cement industry at the provincial level," *Journal of Cleaner Production*, vol. 184, pp. 274–285, May 2018, doi: 10.1016/j.jclepro.2018.02.277.

[7] L. Tang et al., "Plant-level real-time monitoring data reveal substantial abatement potential of air pollution and CO2 in China's cement sector," *One Earth*, vol. 5, no. 8, pp. 892–906, Aug. 2022, doi:10.1016/j.oneear.2022.07.003.

[8] C. Durastanti and L. Moretti, "Environmental Impacts of Cement Production: A Statistical Analysis," *Applied Sciences*, vol. 10, no. 22, p. 8212, Nov. 2020, doi: 10.3390/app10228212.

[9] S. H. Teh, T. Wiedmann, A. Castel, and J. de Burgh, "Hybrid life cycle assessment of greenhouse gas emissions from cement, concrete and geopolymer concrete in Australia," *Journal of Cleaner Production*, vol. 152, pp. 312–320, May 2017, doi:10.1016/j.jclepro.2017.03.122.

[10] J. Xu, Y. Guan, J. Oldfield, D. Guan, and Y. Shan, "China carbon emission accounts 2020-2021," *Applied Energy*, vol. 360, p. 122837, Apr. 2024, doi: 10.1016/j.apenergy.2024.122837.

[11] C. Cai, R. P. Devassy, M. M. El-Sherbiny, and S. Agusti, "Cement and oil refining industries as the predominant sources of trace metal pollution in the Red Sea: A systematic study of element concentrations in the Red Sea zooplankton," *Marine Pollution Bulletin*, vol. 174, p. 113221, Jan. 2022, doi:10.1016/j.marpolbul.2021.113221.

[12] O. Elawa, T. M. Galal, N. M. Abdelatif, and E. A. Farahat, "Evaluating the Potential Use of Four Tree Species in the Greenbelts to Mitigate the Cement Air Pollution in Egypt," *Egyptian Journal of Botany*, vol. 0, no. 0, pp. 0–0, Nov. 2021, doi:10.21608/ejbo.2021.94944.1780.

[13] M. T. Rahman, "A Research on Green Concrete," *International Research Journal of Modernization in Engineering Technology and Science*, Jul. 2023, doi: 10.56726/irjmets43284.

[14] M. T. De Grazia, L. F. M. Sanchez, and A. Yahia, "Towards the design of eco-efficient concrete mixtures: An overview," *Journal of Cleaner Production*, vol. 389, p. 135752, Feb. 2023, doi:10.1016/j.jclepro.2022.135752.

[15] S. M.P., S. K. B, and R. J, "Green Concrete – A Review," *International Research Journal of Multidisciplinary Technovation*, pp. 458–464, Nov. 2019, doi: 10.34256/irjmtcon64.

[16] F. Findik, "Green concrete for structural buildings," *Heritage and Sustainable Development*, vol. 4, no. 1, pp. 67–76, May 2022, doi:10.37868/hsd.v4i1.84.

[17] S. Karthik, P. R. M. Rao, P. O. Awoyera, R. Gobinath, and R. R. Karri, "Alkalinity and strength properties of concrete containing macro silica and ground granulated blast furnace slag," *7th Brunei International Conference on Engineering and Technology 2018 (BICET 2018)*, 2018, doi: 10.1049/cp.2018.1603.

[18] S. Zhuang, Q. Wang, and T. Luo, "A quantitative method to assess and predict the exothermic behavior of steel slag blended cement," *Cement and Concrete Research*, vol. 175, p. 107373, Jan. 2024, doi:10.1016/j.cemconres.2023.107373.

[19] M. Bouasria et al., "Insight into the partial replacement of cement by ferronickel slags from New Caledonia," *European Journal of Environmental and Civil Engineering*, vol. 26, no. 8, pp. 3662–3680, Sep. 2020, doi: 10.1080/19648189.2020.1814421.

[20] M. J. Ahmed, S. Durand, M. Antoun, F. Gauvin, S. Amziane, and H. J. H. Brouwers, "Utilization of air granulated basic oxygen furnace slag as a binder in belite calcium sulfoaluminate cement: A sustainable alternative," *Journal of Cleaner Production*, vol. 436, p. 140539, Jan. 2024, doi: 10.1016/j.jclepro.2023.140539.

[21] H. Ashad, "Minimizing the impact of microorganism intrusion on the concrete physical and mechanical properties with nickel waste as a partial substitution for cement," *Heliyon*, vol. 9, no. 2, p. e13303, Feb. 2023, doi: 10.1016/j.heliyon.2023.e13303.

[22] L. S. Ho and T.-P. Huynh, "Long-term mechanical properties and durability of high-strength concrete containing high-volume local fly ash as a partial cement substitution," *Results in Engineering*, vol. 18, p. 101113, Jun. 2023, doi: 10.1016/j.rineng.2023.101113.

[23] E. Khankhaje, T. Kim, H. Jang, C.-S. Kim, J. Kim, and M. Rafieizonooz, "Properties of pervious concrete incorporating fly ash as partial replacement of cement: A review," *Developments in the Built Environment*, vol. 14, p. 100130, Apr. 2023, doi:10.1016/j.dibe.2023.100130.

[24] S. Džidić and A. Popрženović, "One experimental research with cement substitution by fly ash," *IOP Conference Series: Materials Science and Engineering*, vol. 1298, no. 1, p. 012032, Dec. 2023, doi:10.1088/1757-899x/1298/1/012032.

[25] A. Harmaji and A. Fadillah, "Morphological and Properties of Portland-Composite Cements with Class C Fly Ash," *International Journal of Innovation in Mechanical Engineering and Advanced Materials*, vol. 4, no. 2, p. 46, Feb. 2023, doi:10.22441/ijimeam.v4i2.17036.

[26] M. H. Andika, Suherman, and J. Endawati, "Mechanical properties of pervious concrete with slag and silica fume as cement substitution for highway shoulder," *IOP Conference Series: Materials Science and Engineering*, vol. 508, p. 012062, May 2019, doi: 10.1088/1757-899x/508/1/012062.

[27] M. Fattouh and E. Elsayed, "Influence of Utilizing Glass Powder with Silica Fume on Mechanical Properties and Microstructure of Concrete," *Delta University Scientific Journal*, vol. 6, no. 1, pp. 111–122, Apr. 2023, doi: 10.21608/dusj.2023.291027.

[28] A. Ali Abed, I. Kamal, and A. Mojtahedi, "Enhancing Concrete Properties Using Silica Fume: Optimized Mix Design," *Journal of Smart Buildings and Construction Technology*, vol. 5, no. 1, pp. 84–91, Jun. 2023, doi: 10.30564/jsbct.v5i1.5678.

[29] A. Nafees et al., "Modeling of Mechanical Properties of Silica Fume-Based Green Concrete Using Machine Learning Techniques," *Polymers*, vol. 14, no. 1, p. 30, Dec. 2021, doi:10.3390/polym14010030.

[30] H. Alhazmi, S. A. R. Shah, and M. A. Basheer, "Performance Evaluation of Road Pavement Green Concrete: An Application of Advance Decision-Making Approach before Life Cycle Assessment," *Coatings*, vol. 11, no. 1, p. 74, Jan. 2021, doi:10.3390/coatings11010074.

[31] A. A. Jhatial, W. I. Goh, K. H. Mo, S. Sohu, and I. A. Bhatti, "Green and Sustainable Concrete – The Potential Utilization of Rice Husk Ash and Egg Shells," *Civil Engineering Journal*, vol. 5, no. 1, p. 74, Jan. 2019, doi: 10.28991/cej-2019-03091226.

[32] S. A. Endale, W. Z. Taffese, D.-H. Vo, and M. D. Yehualaw, "Rice Husk Ash in Concrete," *Sustainability*, vol. 15, no. 1, p. 137, Dec. 2022, doi: 10.3390/su15010137.

[33] I. A. Ahmad, N. Pertiwi, and N. A. S. Taufieq, "Reliability of rice husk ash as substitution of Portland composite cement producing green concrete," *Ecol. Environ. Conserv*, vol. 24, pp. S56–S63, 2018.

[34] B. N. Morato et al., "Influence of Coconut Fiber Waste and Rice Husk Ash on Green Concrete," *Revista de Gestão Social e Ambiental*, vol. 18, no. 3, p. e04588, Dec. 2023, doi: 10.24857/rgsa.v18n3-033.

[35] I. A. Ahmad, H. Parung, M. W. Tjaronge, and R. Djamaluddin, "Corrosion of Concrete Using Portland Composite Cement and Rice Husk Ash under Simulated Acid Rain Environment," *Advanced Materials Research*, vol. 0, pp. 511–514, Sep. 2013, doi:10.4028/www.scientific.net/amr.0.511.

[36] M. Amin and B. A. Abdelsalam, "Efficiency of rice husk ash and fly ash as reactivity materials in sustainable concrete," *Sustainable Environment Research*, vol. 29, no. 1, Nov. 2019, doi:10.1186/s42834-019-0035-2.

[37] K. Abd Elghani, F. Ali, and O. Hussien, "Effect of Agricultural Wastes on Mechanical Properties of Green Concrete," *Egyptian Journal of Chemistry*, vol. 0, no. 0, pp. 0–0, Aug. 2023, doi:10.21608/ejchem.2023.228035.8397.

[38] H. T. T. Pham, A. T. Nguyen, T. T. H. Nguyen, and L. Hens, "Stakeholder Delphi-perception analysis on impacts and responses of acid rain on agricultural ecosystems in the Vietnamese upland," *Environment, Development and Sustainability*, vol. 22, no. 5, pp. 4467–4493, Jun. 2019, doi: 10.1007/s10668-019-00393-6.

[39] Z. Liu et al., "Increasing acid rain frequency promotes the microbial community dissimilarities of forest soil rather than agricultural soil in southern China," *Ecotoxicology and Environmental Safety*, vol. 230, p. 113123, Jan. 2022, doi: 10.1016/j.ecoenv.2021.113123.

[40] Z. Liu et al., "Idiosyncratic responses of microbial communities and carbon utilization to acid rain frequency in the agricultural and forest soils," *Global Ecology and Conservation*, vol. 26, p. e01429, Apr. 2021, doi: 10.1016/j.gecco.2020.e01429.

[41] R. Balaraman and N. S. Elangovan, "Behaviour of cupola slag and TiO2 nanoparticles in concrete as partial replacement for coarse aggregates and cement," *Applied Nanoscience*, vol. 13, no. 5, pp. 3415–3420, Feb. 2022, doi: 10.1007/s13204-021-02216-5.

[42] J. Guo, X. Li, Y. Xu, P. Zhang, and K. Wang, "Neutralization evolution of concrete under acid rain and carbonation erosion: a review," *Journal of Materials Research and Technology*, vol. 25, pp. 1376–1405, Jul. 2023, doi: 10.1016/j.jmrt.2023.06.040.

[43] L. Zhang, Y. Pan, K. Xu, L. Bi, M. Chen, and B. Han, "Corrosion behavior of concrete fabricated with lithium slag as corrosion inhibitor under simulated acid rain corrosion action," Journal of Cleaner Production, vol. 377, p. 134300, Dec. 2022, doi:10.1016/j.jclepro.2022.134300.

[44] M. Hosseini, A. R. Dolatshahi, and E. Ramezani, "Effect of Acid Rain on Physical and Mechanical Properties of Concrete Containing Micro-Silica and Limestone Powder," *J. Min. Environ.*, vol. 13, no. 1, pp. 185–200, 2022.

[45] M.-C. Chen, K. Wang, and L. Xie, "Deterioration mechanism of cementitious materials under acid rain attack," *Engineering Failure Analysis*, vol. 27, pp. 272–285, Jan. 2013, doi:10.1016/j.engfailanal.2012.08.007.

[46] S. Xie, L. Qi, and D. Zhou, "Investigation of the effects of acid rain on the deterioration of cement concrete using accelerated tests established in laboratory," *Atmospheric Environment*, vol. 38, no. 27, pp. 4457–4466, Sep. 2004, doi: 10.1016/j.atmosenv.2004.05.017.

[47] I. A. Ahmad, N. Pertiwi, and N. A. S. Taufieq, "Constitutive Relations for Concrete Properties Under Acid Environment," *Lecture Notes in Civil Engineering*, pp. 473–483, May 2018, doi:10.1007/978-981-10-8016-6_39.

[48] A. N. Givi, S. A. Rashid, F. N. A. Aziz, and M. A. M. Salleh, "Assessment of the effects of rice husk ash particle size on strength, water permeability and workability of binary blended concrete," *Construction and Building Materials*, vol. 24, no. 11, pp. 2145–2150, Nov. 2010, doi: 10.1016/j.conbuildmat.2010.04.045.

[49] W. Zhang and Z. Song, "Theoretical Model and Experimental Research on Mortar Corrosion by Sulfuric Acid in Laminar Flow," *Tehnicki vjesnik - Technical Gazette*, vol. 30, no. 6, Dec. 2023, doi:10.17559/tv-20230713000800.

[50] L. Gao, Y. Lai, M. R. Islam Pramanic, and W. Zhang, "Deterioration of Portland Cement Pervious Concrete in Sponge Cities Subjected to Acid Rain," *Materials*, vol. 14, no. 10, p. 2670, May 2021, doi:10.3390/ma14102670.

[51] Y. Zhang, L. Gu, W. Li, and Q. Zhang, "Effect of acid rain on economic loss of concrete structures in Hangzhou, China," *International Journal of Low-Carbon Technologies*, vol. 14, no. 2, pp. 89–94, Jan. 2019, doi: 10.1093/ijlct/cty056.

[52] I. P. Kurniawati, H. Pratiwi, and S. Sugiyanto, "Indonesian Territory Clustering Based On Harvested Area and Rice Productivity Using Clustering Algorithm," *Journal of Social Science*, vol. 4, no. 1, pp. 100–110, Jan. 2023, doi: 10.46799/jss.v4i1.510.

[53] D. A. Usdianto and R. Setiyowati, "Mathematical Model of Rice Commodity Supply Chain in Indonesia," *Barekeng: Jurnal Ilmu Matematika dan Terapan*, vol. 17, no. 2, pp. 1139–1148, Jun. 2023, doi: 10.30598/barekengvol17iss2pp1139-1148.

[54] R. Khan, A. Jabbar, I. Ahmad, W. Khan, A. N. Khan, and J. Mirza, "Reduction in environmental problems using rice-husk ash in concrete," *Construction and Building Materials*, vol. 30, pp. 360–365, May 2012, doi: 10.1016/j.conbuildmat.2011.11.028.

[55] P. Qiu, "Erosion Resistance of Pre-Treated Rice Husk Ash Concrete Under Simulated Acid Rain," *Ceramics - Silikaty*, pp. 360–370, Aug. 2023, doi: 10.13168/cs.2023.0036.

[56] R. Sefrin and C. Glock, "Characteristic concrete compressive strength of existing structures—Evaluation of EN 13791:2019 for small sample sizes," *Structural Concrete*, vol. 23, no. 2, pp. 822–835, Jan. 2022, doi: 10.1002/suco.202100207.

[57] V. Revilla-Cuesta, M. Skaf, A. B. Espinosa, A. Santamaría, and V. Ortega-López, "Statistical Approach for the Design of Structural Self-Compacting Concrete with Fine Recycled Concrete Aggregate," *Mathematics*, vol. 8, no. 12, p. 2190, Dec. 2020, doi:10.3390/math8122190.

[58] C.-C. Vu, O. Plé, J. Weiss, and D. Amitrano, "Revisiting the concept of characteristic compressive strength of concrete," *Construction and Building Materials*, vol. 263, p. 120126, Dec. 2020, doi:10.1016/j.conbuildmat.2020.120126.

[59] I. H. Wagan, A. H. Memon, N. A. Memon, F. T. Memon, and M. H. Lashari, "Rice Husk Ash (RHA) Based Concrete: Workability and Compressive Strength with Different Dosages and Curing Ages," *Journal of Applied Engineering Sciences*, vol. 12, no. 1, pp. 113–120, May 2022, doi: 10.2478/jaes-2022-0016.

[60] Md. Safiuddin, J. S. West, and K. A. Soudki, "Hardened properties of self-consolidating high performance concrete including rice husk ash," *Cement and Concrete Composites*, vol. 32, no. 9, pp. 708–717, Oct. 2010, doi: 10.1016/j.cemconcomp.2010.07.006.

[61] M. A. Kareem, B. O. Orogbade, E. O. Ibiwoye, and N. O. Olasupo, "The Use of Palm Oil Mill Effluent as Mixing and Curing Water in Cement-Based Composite," *Silicon*, vol. 14, no. 3, pp. 1285–1296, Jan. 2021, doi: 10.1007/s12633-020-00864-w.

[62] G. Zhang, C. Wu, D. Hou, J. Yang, D. Sun, and X. Zhang, "Effect of environmental pH values on phase composition and microstructure of Portland cement paste under sulfate attack," *Composites Part B: Engineering*, vol. 216, p. 108862, Jul. 2021, doi:10.1016/j.compositesb.2021.108862.

[63] C. Yoshida, I. Higashiyama, and N. Ito, "Influence of acid rain on deterioration of concrete. Sanseiu no concrete eno eikyo to rekka shiken," *Nogyo Doboku Gakkai-Shi (Journal Japanese Soc. Irrig. Drain. Reclam. Eng.*, vol. 60, no. 12, 1992.

[64] Y. Fan and H. Luan, "Pore structure in concrete exposed to acid deposit," *Construction and Building Materials*, vol. 49, pp. 407–416, Dec. 2013, doi: 10.1016/j.conbuildmat.2013.08.075.

[65] C. Lu, W. Wang, Q. Zhou, S. Wei, and C. Wang, "Mechanical behavior degradation of recycled aggregate concrete after simulated acid rain spraying," *Journal of Cleaner Production*, vol. 262, p. 121237, Jul. 2020, doi: 10.1016/j.jclepro.2020.121237.

[66] W. Hu, Y. Li, and H. Peng, "Experimental Study on Acid-Rain Corrosion Mechanism of Concrete Based on Periodic Immersion Method," *Science of Advanced Materials*, vol. 12, no. 8, pp. 1149–1156, Aug. 2020, doi: 10.1166/sam.2020.3785.

[67] S. Varadharajan, A. Jaiswal, and S. Verma, "Assessment of mechanical properties and environmental benefits of using rice husk ash and marble dust in concrete," *Structures*, vol. 28, pp. 389–406, Dec. 2020, doi: 10.1016/j.istruc.2020.09.005.

[68] N. Md. S. Hasan et al., "Integration of Rice Husk Ash as Supplementary Cementitious Material in the Production of Sustainable High-Strength Concrete," *Materials*, vol. 15, no. 22, p. 8171, Nov. 2022, doi: 10.3390/ma15228171.

[69] S. Abdul Kudus et al., "Effect of Rice-Husk as Replacement Cement on Mechanical Properties Concrete," *Journal of Mechanical Engineering*, vol. 20, no. 2, pp. 91–104, Apr. 2023, doi:10.24191/jmeche.v20i2.22056.

[70] A. A. K. Al-Alwan et al., "The impact of using rice husk ash as a replacement material in concrete: An experimental study," *Journal of*

King Saud University - Engineering Sciences, vol. 36, no. 4, pp. 249–255, May 2024, doi: 10.1016/j.jksues.2022.03.002.

[71] N. Bheel, P. Awoyera, I. A. Shar, S. Sohu, S. A. Abbasi, and A. Krishna Prakash, “Mechanical Properties of Concrete Incorporating Rice Husk Ash and Wheat Straw Ash as Ternary Cementitious Material,” Advances in Civil Engineering, vol. 2021, no. 1, Jan. 2021, doi: 10.1155/2021/2977428.

[72] I. A. Ahmad, N. Pertiwi, and N. A. S. Taufieq, “Mechanical and Microstructural Properties of Green Roof Slab Under Acid Rain Attack,” IOP Conference Series: Earth and Environmental Science, vol. 1209, no. 1, p. 012001, Jul. 2023, doi: 10.1088/1755-1315/1209/1/012001.

[73] M. A. Hosen et al., “Investigation of structural characteristics of palm oil clinker based high-strength lightweight concrete comprising steel fibers,” Journal of Materials Research and Technology, vol. 15, pp. 6736–6746, Nov. 2021, doi: 10.1016/j.jmrt.2021.11.105.

[74] H.-B. Tran, V.-B. Le, and V. T.-A. Phan, “Mechanical Properties of High Strength Concrete Containing Nano SiO2 Made from Rice Husk Ash in Southern Vietnam,” Crystals, vol. 11, no. 8, p. 932, Aug. 2021, doi: 10.3390/cryst11080932.