

MECHANICAL PROPERTIES OF CONCRETE WITH TYPE F FLY ASH ADDITION UNDER ACIDIC CONDITIONS

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ABSTRACT: Concrete is a fundamental construction material whose performance can be significantly improved through the incorporation of supplementary cementitious materials such as fly ash, a by-product of coal combustion. This study examines the effects of replacing 20% of cement with Type F fly ash on the mechanical properties of concrete exposed to acidic mine water over varying curing periods (28, 42, 56, and 86 days). A total of 33 cylindrical specimens (150 mm in diameter and 300 mm in height) were prepared and immersed in acidic mine water to simulate aggressive environmental conditions. The results showed that concrete with 20% fly ash reached a compressive strength of 24.67 MPa at 28 days, then increased to 26.37 MPa at 42 days, and subsequently declined at later ages. In contrast, the split tensile strength consistently increased, peaking at 2.89 MPa at 56 days. The incorporation of Type F fly ash was proven to improve the mechanical resistance of concrete under acidic exposure by reducing the detrimental effects of acid attack. These findings indicate that fly ash-modified concrete exhibits superior mechanical performance and acid resistance, with the optimal curing period observed at 42 days.

Keywords: Concrete, Fly Ash, Acid Water, Compressive Strength, Split Tensile Strength

1. INTRODUCTION

In the context of sustainable development and environmental conservation, the utilization of industrial by-products such as fly ash represents a promising strategy for enhancing concrete performance, especially under aggressive environmental conditions. Incorporating fly ash into concrete mixtures not only helps reduce cement consumption and CO₂ emissions but also improves the physical and mechanical properties of concrete, such as resistance to ion penetration, sulfate attack, and reduced porosity. This makes fly ash a highly valuable supplementary material, particularly in areas facing environmental challenges due to industrial or mining activities.

One common environmental issue found in mining regions is the formation of acidic mine lakes, characterized by low pH and high concentrations of heavy metals. The water in these lakes can accelerate concrete deterioration through calcium leaching and the breakdown of its microstructure. Therefore, it is essential to investigate the behavior of fly ash-modified concrete when immersed in acid mine water. This study aims to evaluate the extent to which fly ash contributes to improving the durability of concrete under such extreme conditions, while also supporting the development of more environmentally friendly and long-lasting construction materials.

Fly ash is one of the most widely used fine additives in modern concrete production. The utilization of fly ash, particularly as a partial replacement for cement in concrete mixtures, has

proven to be an effective approach for reducing production costs while simultaneously minimizing the environmental impact of the construction industry. The use of high volumes of fly ash—up to 50% of the total binder content—has been shown to produce compressive strengths ranging from 20 to 40 MPa, without significantly increasing costs compared to conventional concrete. Previous studies even classify concrete with fly ash content exceeding 50% as high fly ash content concrete, which is increasingly studied for its potential in promoting sustainable construction [1].

Concrete is a dominant material in building structures due to its high compressive strength, durability, and adaptability in shaping. A key component of concrete is aggregate, which is sourced either from natural materials like stone and sand or from artificial sources such as recycled concrete aggregates [2]. With increasing construction demand, the extensive use of natural aggregates exerts pressure on natural resource availability. Consequently, recycling construction waste as concrete material becomes essential. Recycled concrete aggregate production serves as a crucial strategy for environmental conservation, especially considering that approximately 40% of industrial waste originates from construction and demolition activities [3].

Fly ash itself is classified as a pozzolanic material that is chemically reactive in moist environments. It consists of finely divided amorphous aluminosilicates with varying amounts of calcium. When mixed with Portland cement and water, fly ash reacts with calcium hydroxide (Ca(OH)₂), which is released

during the cement hydration process, forming calcium silicate hydrate (C-S-H) and calcium aluminate hydrate compounds that strengthen the concrete matrix[4]. However, using high volumes of fly ash may slow the cement hydration process, which in turn can reduce the early-age mechanical properties of the concrete [5], [6].

Despite this drawback, the use of fly ash in the range of 40% to 60% has been shown to positively impact the physical and mechanical properties of concrete. Specifically, fly ash reduces water permeability, lowers water absorption, and inhibits chloride ion penetration. In addition, studies show that high fly ash content in self-compacting concrete (SCC) improves resistance to sulfuric acid attack [7]–[9]. The ultrafine fly ash particles fill voids between aggregates and act as a natural lubricant. This not only enhances the workability of fresh concrete but also improves mix uniformity, resulting in higher concrete density and compressive strength [10]–[12]. Continuous pozzolanic reactions between fly ash and $\text{Ca}(\text{OH})_2$ generate additional C-S-H, strengthening the microstructure and improving long-term durability.

High-calcium fly ash, particularly that derived from the combustion of lignite or sub-bituminous coal, offers specific advantages in enhancing concrete strength. This type of fly ash exhibits both pozzolanic and self-cementing properties, enabling it to improve the compressive strength of concrete, whether used as a partial or complete replacement for cement [13]–[19]. In addition to structural strength, Type F fly ash improves the workability of concrete mixtures, reduces permeability to water and ions, and increases sulfate resistance. There are two main types of fly ash: Type C and Type F, distinguished primarily by their lime content, and the type of fly ash used in this study is Type F. Type F fly ash typically contains more than 10% lime, which plays a significant role in binding reactions and the formation of a dense concrete structure [20]–[22]. The use of Type F fly ash as a partial cement replacement not only lowers cement consumption but also significantly reduces CO_2 emissions associated with cement manufacturing, while enhancing overall concrete performance [23]–[25].

In Indonesia, mining activities are commonly found, particularly on the island of Borneo. This island is rich in natural resources such as coal, making it the largest and most intensively mined region in the country. One of the environmental impacts of these activities is the formation of abandoned mining pits, which often become filled with water. Due to the high iron content present in the residual materials, the water becomes acidic, leading to the development of acid mine lakes.

The potential reuse of post-mining land for residential or industrial purposes requires a thorough understanding of how construction materials,

particularly concrete, perform under acidic exposure. Conventional concrete is known to deteriorate rapidly in such environments, prompting the need for modifications or supplementary materials to improve its resistance. In this context, Type F fly ash is considered a promising additive due to its pozzolanic properties, which may enhance concrete durability in aggressive chemical environments.

The superior acid resistance of concrete with fly ash is primarily attributed to the reduction of free calcium hydroxide through pozzolanic reactions that produce more stable C-S-H and C-A-S-H compounds, thereby decreasing the portions most vulnerable to acid attack. In addition, the additional hydration products from the pozzolanic reaction fill the pores of the concrete, resulting in a denser microstructure and more restricted diffusion pathways for acid ions. With a lower Ca/Si ratio and a silica-rich structure, fly ash concrete exhibits higher chemical stability, leading to a slower rate of degradation in acidic environments compared to normal concrete [34].

A number of studies have investigated strategies to mitigate the deterioration of concrete in acidic or sulfate-rich mining environments. For example, research on sulfide mining conditions ($\text{pH} < 3$, high sulfate concentration) demonstrated that the use of polypropylene fibers and protective coatings such as polyurethane and asphalt improved performance to some extent. Mechanical and durability assessments—including compressive and tensile strength, permeability, and surface resistance—showed that acid mine water was extremely corrosive, with compressive strength decreasing by nearly 43% within six months. Nevertheless, such studies did not examine the influence of Type F fly ash nor compare the performance of ordinary and pozzolanic concrete [30]. Other research focused on concrete degradation mechanisms under exposure to synthetic acidic solutions, analyzing changes from the microstructural to structural scale. While this work contributed to understanding acid attack pathways, it did not employ real acid mine water and overlooked the potential role of Class F fly ash [31]. Further investigations into high-strength concrete exposed to actual acid mine drainage revealed adverse effects, including increased porosity, mass loss, and reduced compressive strength. Some approaches incorporated magnesium oxide (MgO) for self-healing purposes. However, these studies did not evaluate ordinary concrete, relied on wet-dry immersion cycles, and excluded Type F fly ash as a durability-enhancing material [32].

In light of these gaps, the present research emphasizes two main contributions. First, it utilizes real acid mine drainage as the exposure medium, rather than synthetic acidic solutions commonly employed in earlier laboratory-based studies. Second, it provides a direct comparison between ordinary concrete and fly

ash-blended concrete, thereby evaluating the effectiveness of Type F fly ash in enhancing the mechanical performance of concrete under severe acidic conditions.

This study aims to investigate the effect of immersion in acid mine water on the mechanical characteristics of normal concrete and concrete incorporating Type F fly ash as an additive. This study advances beyond existing research on fly ash concrete durability by specifically investigating the combined effects of acid exposure and fly ash incorporation on both mechanical properties and microstructural changes.

The remainder of this paper is structured as follows. Section 2 described the research significance. Section 3 describes the materials, specimen preparation, and testing methods employed in this study. Section 4 presents the experimental results, including compressive strength and splitting tensile strength of normal and fly ash-modified concrete under acidic exposure, accompanied by microstructural analyses. Finally, Section 5 concludes the study by summarizing the key outcomes and providing recommendations for future research on the use of Type F fly ash in aggressive environmental conditions.

2. RESEARCH SIGNIFICANCE

This research provides novel insights into the durability of fly ash-modified concrete under aggressive acidic mine water conditions, a critical but underexplored environmental challenge. Unlike conventional studies focused on neutral or alkaline environments, this work uniquely evaluates mechanical performance over extended curing periods, highlighting strength development and deterioration patterns. The originality lies in identifying the optimal curing period (42 days) for maximizing acid resistance and mechanical performance, thereby advancing practical guidelines for sustainable construction in mining-affected areas. By demonstrating the dual role of Type F fly ash as a strength enhancer and acid resistance improver, this study contributes new knowledge to green concrete technologies.

3. MATERIAL AND METHODS

3.1 Materials

This study utilized several primary materials in concrete production, including Type I Portland cement as the main binder, natural sand as fine aggregate, and crushed stone with a maximum size of 20 mm as coarse aggregate. Clean water was used both in the mixing process and during the curing stage to ensure optimal hydration of the cement. Additionally, Type F fly ash was incorporated at 20%

of the cement weight as a partial replacement, aimed at enhancing the concrete's durability in aggressive environments due to its high calcium oxide (CaO) content. To simulate corrosive environmental conditions, acid mine drainage with low pH characteristics was used as the immersion medium to assess the concrete's resistance to acidic exposure. The physical properties of the fine and coarse aggregates indicate that these materials comply with Indonesian National Standards, confirming their suitability as concrete constituents.

3.2 Test Object Manufacturing

The test specimens in this study were produced using a lightweight concrete mix design, with cylindrical molds measuring 15 cm in diameter and 30 cm in height. The fly ash content used was 20% of the cement mass, a percentage obtained from the authors' previous study, which showed that the highest compressive strength was achieved with the addition of 20% fly ash [33]. Concrete mixing and casting were conducted in accordance with the Indonesian standard SNI 7656:2012. Mix design parameters are shown in Table 1.

Table 1. Concrete mix design parameters for normal and fly ash-modified concrete

Parameter	Value
Water-cement ratio (w/c)	0.61
Cement content used	316.39 kg/m ³ concrete
Fly ash content	20% of cement mass
Specific gravity of fine aggregate (Samboja)	2.62 g/cm ³
Specific gravity of coarse aggregate (Palu)	2.70 g/cm ³
Slump value (normal concrete)	10 cm
Slump value (fly ash concrete)	8 cm
Target compressive strength (f' _c)	25 MPa

Specimens were categorized into four series based on fly ash content and curing environment: BNS 01 and BN 02 (without fly ash) and BS 01 and BS 02 (with 20% fly ash). Mechanical tests conducted included compressive strength and split tensile strength, evaluated at curing ages of 28, 42, 56, and 86 days. Curing environments consisted of fresh water and acid mine water, depending on the test series. The quantity of specimens for each test and curing duration is summarized in Table 2. The concrete mix utilized coarse aggregate from Palu with a No. 56 gradation and a maximum particle size of 25

mm, and fine aggregate from Samboja whose gradation falls into Zone 4 (fine). Type F fly ash as a supplementary cementitious material, and Portland cement—all selected for their conformity to Indonesian National Standards and proven suitability in concrete applications.

Table 2. Test Object Requirements

Test Object Code	Fly Ash	Number of Samples				Water
		28	42	56	86	
		(Days)				
BNS 01 (Compressive Strength)	0%	6	-	-	-	Fresh and Acid
BN 02 (Split Tensile Strength)	0%	6	-	-	-	Fresh and Acid
BS 01 (Compressive Strength)	20%	3	3	3	3	Acid
BS 02 (Split Tensile Strength)	20%	3	3	3	-	Acid



Fig. 1 Material preparation

Figure 1 illustrates the preparation of raw materials used in the concrete mix, including the weighing, drying, and mixing processes. Each material—coarse aggregate, fine aggregate, fly ash, and cement—was carefully measured and conditioned to ensure consistency and compliance with mix design requirements. This stage is essential to achieving the desired quality and performance of the resulting concrete specimens.

3.3 Slump Test Experiment

The concrete was poured into the mold in three equal layers, each approximately one-third of the mold's total volume. Each layer was compacted

uniformly by tamping it 25 times using a standard tamping rod. Care was taken to ensure that the rod penetrated through to the bottom of each preceding layer to achieve proper consolidation. For the first layer, the tamping rod was inserted at an angle to match the inclination of the mold walls.

After the final layer was compacted, the top surface was struck off with a straight edge to level it flush with the top of the mold. Any excess concrete around the base was immediately removed. The mold was left undisturbed for approximately 30 seconds before being lifted vertically in a steady motion without any lateral or torsional movement. Immediately after removing the mold, the slump was measured as the difference between the height of the mold and the average height of the concrete specimen. This measurement indicates the concrete's consistency and workability. Water–cement ratio (w/c) = 0,61. A single water–cement ratio (w/c = 0.61) was applied, as the target concrete strength was set at $f'c$ = 25 Mpa. The slump test value is shown in Table 3.

Table 3. Slump Test Value

No	Fly Ash Variance (%)	Slump Value (cm)
1	0%	10 cm
2	20%	8 cm

3.4 Concrete Curing

Following the casting process and initial setting, the molds were removed, and the concrete specimens were properly labeled. Curing was subsequently performed by immersing the specimens in designated containers containing either freshwater or acid mine drainage water, in accordance with the test parameters. The immersion durations were determined based on the curing schedule established for each test series.

This curing procedure was implemented to ensure optimal hydration of the cementitious materials, which is essential for the development of mechanical strength. Furthermore, it serves to prevent cracking caused by rapid moisture loss and to maintain favorable curing conditions. Proper curing enhances key performance characteristics of the concrete, including durability, impermeability, resistance to abrasion, and dimensional stability, all of which are critical for the long-term structural integrity of concrete exposed to aggressive environments.

The curing regime was established to assess the mechanical performance of concrete at different ages, namely 28, 42, 56, and 86 days. Two curing conditions were applied: conventional water curing for ordinary concrete and acid mine drainage (AMD) curing for fly ash–modified concrete. For the

reference specimens (ordinary concrete), curing was carried out by immersion in clean water at ambient laboratory temperature, following the procedures outlined in ASTM C511 and ASTM C192 for standard moist curing. This condition served as the control benchmark.

In contrast, the fly ash concrete specimens were immersed directly in acid mine drainage obtained from abandoned mine sites. The curing medium was maintained at ambient temperature (25–27 °C) and kept static for the entire 86-day duration without replacement or agitation. This method was intended to simulate real field conditions, where concrete in post-mining environments is typically exposed to stagnant acidic water. The pH of the acid mine drainage was measured only at the start of the curing process to characterize the initial chemical environment. No subsequent regulation or adjustment of acidity was performed, allowing the specimens to experience the natural evolution of the aggressive medium throughout the curing period. Table 4 shows the chemical analysis of acid mine drainage.

Table 4. Chemical Analysis of Curing Water

Parameter	Unit	Value
pH	-	4
[H ⁺]	mol/L	0,000158
SO ₄ ²⁻	mg/L	1200
Fe ²⁺	mg/L	60
Fe ³⁺	mg/L	40
Cl ⁻	mg/L	50
Ca ²⁺	mg/L	205
Alkalinitas	mg/L as CaCO ₃	12
Al	mg/L	20
Mn	mg/L	7,5
Zn	mg/L	1,2
Cd	mg/L	0,004

3.5. Compressive and Split Tensile Strength Test

The compressive strength test is a fundamental procedure in concrete research, aimed at evaluating the mechanical performance, stability, and overall quality of concrete mixtures. By determining the maximum compressive load a concrete specimen can withstand before failure, researchers can assess whether the mix design meets structural requirements and adheres to relevant performance standards. This test is essential in ensuring that concrete possesses adequate strength to sustain service loads under various field conditions.

In parallel, the split tensile strength test is conducted to investigate the concrete's ability to resist tensile stresses, which are critical to

understanding its cracking potential and overall durability. In this test, cylindrical specimens are positioned horizontally and subjected to a diametrical compressive load, generating tensile stress perpendicular to the applied load. The resulting data provides insights into the tensile behavior of the concrete, complementing the compressive strength results. Together, these mechanical tests enable engineers to verify that the concrete possesses the requisite strength properties for safe and long-lasting structural performance.

The mechanical tests that were carried out were as follows: compressive strength in accordance with ASTM C39/C39M-12a, and split tensile strength in accordance with ASTM C496/C496M-17. The value of compressive strength can be calculated using Equation (1), while the split tensile strength can be determined using Equation (2).

$$f'_c = \frac{P}{A} \quad (1)$$

$$f_t = \frac{2P}{\pi LD} \quad (2)$$

Where:

f'_c - compressive strength, f_t - splitting tensile strength [MPa], f_f - flexural strength [MPa], P - maximum applied load [N], A - cross-sectional area of the specimen [mm²], D - diameter of the cylindrical specimen [mm], L - length of the specimen [mm].

4. RESULTS AND DISCUSSIONS

4.1 Atomic Absorption Spectroscopy (AAS) Testing

Atomic Absorption Spectroscopy (AAS) is a spectrophotometric method used to determine the chemical composition of materials, particularly for analyzing fly ash. In this study, the AAS test was conducted by researchers at the PT. SUCOFINDO Laboratory in Samarinda, and the results are presented in Table 2.

The chemical composition of the fly ash utilized in this study was analyzed using Atomic Absorption Spectroscopy (AAS) testing, with the results presented in Table 5. The primary oxides present include SiO₂ (40.55%), Al₂O₃ (20.94%), and Fe₂O₃ (23.38%), which cumulatively account for 84.87% of the total composition. This is a critical value in classifying fly ash according to ASTM C618, which specifies that fly ash can be categorized as either Type F or Type C based on its chemical makeup. Class F fly ash, typically derived from anthracite or bituminous coal, is characterized by a total SiO₂ + Al₂O₃ + Fe₂O₃ content of at least 70%, CaO content below 10%, and a Loss on Ignition (LOI) not exceeding 6%. In this study, the fly ash exhibited a

CaO concentration of 6.22% and an LOI of 1.90%, both of which fall within the acceptable range for Type F classification.

Table 5. Chemical Composition of Fly Ash Based on AAS Analysis

No	Parameter (Abbreviation)	Unit (%Wt)	Result
1	Silicon Dioxide (SiO ₂)	%Wt	40.55
2	Aluminum Oxide (Al ₂ O ₃)	%Wt	20.94
3	Ferric Oxide (Fe ₂ O ₃)	%Wt	23.38
4	Calcium Oxide (CaO)	%Wt	6.22
5	Magnesium Oxide (MgO)	%Wt	3.62
6	Sodium Oxide (Na ₂ O)	%Wt	0.24
7	Potassium Oxide (K ₂ O)	%Wt	1.11
8	Titanium Dioxide (TiO ₂)	%Wt	0.81
9	Manganese Dioxide (MnO ₂)	%Wt	0.44
10	Chromium Oxide (Cr ₂ O ₃)	%Wt	0.01
11	Phosphorus Pentoxide (P ₂ O ₅)	%Wt	0.45
12	Sulfur Trioxide (SO ₃)	%Wt	2.00
13	Loss on Ignition (LOI)	%Wt	1.90
14	Carbon, Dry Base	%Wt	1.79

The chemical composition of the fly ash utilized in this study was analyzed using Atomic Absorption Spectroscopy (AAS), revealing a composition of 40.55% SiO₂, 20.94% Al₂O₃, and 23.38% Fe₂O₃, totaling 84.87%. According to ASTM C618, fly ash is classified as Class F when the combined content of these oxides exceeds 70%, the CaO content is typically below 10%, and the Loss on Ignition (LOI) does not exceed 6%. In this case, the CaO content is 6.22%, and the LOI is 1.90%, confirming the classification as Type F fly ash.

Based on these parameters, the fly ash used in this research clearly satisfies the requirements for Type F fly ash, indicating its pozzolanic nature rather than self-cementing. This classification is highly relevant in the context of structural concrete applications, particularly in aggressive or acidic environments, as Type F fly ash enhances long-term durability, reduces permeability, and mitigates the risk of alkali-silica reaction. Moreover, the relatively low calcium content supports the use of this material in acid resistance studies, such as the one conducted in this paper. These findings are consistent with previous studies, which have shown that high-pozzolan Type F fly ash significantly enhances sulfate and acid resistance in concrete composites [26].

Type F fly ash is predominantly pozzolanic and is known for enhancing the durability and strength of concrete over time. Studies have shown that

incorporating Type F fly ash as a partial replacement for cement can improve concrete's resistance to sulfate attack, reduce permeability, and decrease drying shrinkage. For instance, research on concrete with Type F fly ash exhibited lower water sorptivity and chloride permeability, contributing to enhanced durability [27], [28].

Incorporating Type F fly ash into concrete mixes improves mechanical properties and offers environmental benefits by reducing CO₂ emissions associated with cement production. The pozzolanic reaction of fly ash contributes to the formation of additional calcium silicate hydrate (C-S-H), which densifies the concrete matrix and enhances long-term strength. Therefore, the use of Type F fly ash in concrete is a sustainable approach that aligns with the goals of green construction and environmental conservation [29].

4.2 The Compressive Strength of Concrete

Compressive strength is a fundamental property that reflects the performance and durability of concrete, particularly its ability to withstand mechanical loads and pressure. This property is influenced by various factors such as material quality, mix proportions, water-to-cement ratio, and curing methods [4]. Proper curing is essential for the hydration process, which significantly contributes to the development of concrete strength over time [1]. In general, concrete reaches approximately 70% of its design strength at 28 days and can continue to gain strength depending on the materials used and environmental conditions [6]. The use of standardized testing procedures, such as cylindrical specimens subjected to axial loads, is crucial to obtaining accurate compressive strength results [28]. Moreover, advancements in concrete technology have enabled the optimization of mix designs to enhance compressive strength without compromising workability or durability [3]. One widely adopted innovation is the incorporation of fly ash as a partial replacement for cement, which has been shown to improve the overall performance of concrete, including its compressive strength, due to its pozzolanic properties and ability to enhance durability[5].

Compressive strength tests were conducted at different curing ages: 28 days for normal concrete, and 42, 56, and 86 days for concrete containing fly ash. The tests were carried out using cylindrical specimens measuring 15 cm in diameter and 30 cm in height. After completing the designated curing periods, the samples were subjected to compressive strength testing at the Civil Engineering Laboratory of Mulawarman University. A concrete compression testing machine was used to measure the strength of each specimen. The detailed results of the compressive strength tests are presented in Table 6.

Table 6. Compressive Strength Test Results

No.	Fly Ash Content	Curing Medium	Concrete Age	f_c (MPa)	f_{cr} (MPa)	Standard Deviation	f_{cr} (MPa)
1	0%	Fresh Water	28 Days	24,14	24,09	0,06	24,07
2				24,11			
3				24,03			
4	0%	Acid Water	28 Days	22,09	21,53	0,50	21,33
5				21,12			
6				21,38			
7	20%	Acid Water	28 Days	24,34	24,87	0,53	24,67
8				24,88			
9				25,39			
10	20%	Acid Water	42 Days	26,87	26,50	0,33	26,37
11				26,37			
12				26,26			
13	20%	Acid Water	56 Days	26,18	25,73	0,91	25,37
14				24,68			
15				26,33			
16	20%	Acid Water	86 Days	24,27	24,09	0,16	24,03
17				24,02			
18				23,98			

One limitation of this study was the lack of a freshwater-soaked concrete sample containing 20% fly ash for comparison. However, this data was obtained from a previous study with a 28-day soaking period. The compressive strength of 20% fly ash concrete cured in normal water was 30.88 MPa [33].

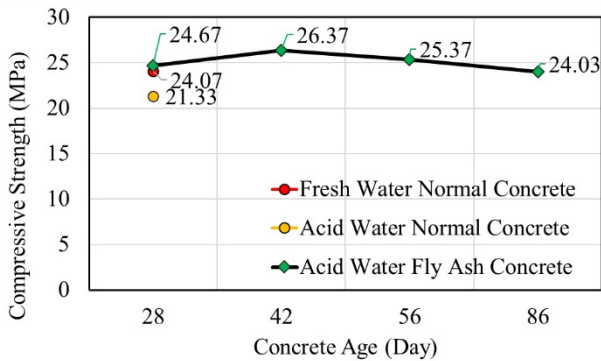


Fig. 2 Compressive strength result graph

The data in Table 6, visualized as a line graph in Figure 2, illustrates a fluctuating trend in compressive strength, particularly for concrete containing 20% fly ash cured in acidic water. The compressive strength increases from 24.67 MPa at 28 days to 26.37 MPa at 42 days, reflecting a positive strength development during the curing process. However, a slight decrease is observed at 56 days (25.37 MPa), followed by a more significant drop at 86 days (24.03 MPa). This pattern suggests that while fly ash contributes to early strength gain through pozzolanic reactions, prolonged exposure to an acidic environment may begin to deteriorate the concrete matrix or slow down the rate of strength development.

Concrete specimens without fly ash exhibited varying performance depending on the curing medium. At 28 days, the compressive strength reached 24.07 MPa when cured in fresh water, but decreased to 21.33 MPa under acid water exposure. This reduction suggests that acidic environments

adversely affect cement hydration, resulting in weaker bonding and microstructural deterioration. Similar observations have been reported, showing that aggressive ions present in seawater or acidic conditions can compromise the strength and durability of concrete [20]. Another observation from this study is that the weight of the specimen after immersion can be seen in Table 7.

Table 7. Weight of Specimen After Immersion

No	Fly Ash	Concrete Age (day)	Weight (kg)
1	0% Fresh water	28	12160
2	0% Acid water	28	12230
3	20% Acid water	28	12580
4	20% Acid water	42	12440
5	20% Acid water	56	12460
6	20% Acid water	86	13080

The variation in specimen weight following immersion exhibited considerable fluctuations, indicating that weight change alone is not a dependable parameter for assessing the severity of acid attack.

The incorporation of 20% fly ash significantly improved the compressive strength of concrete exposed to acidic environments. Whereas acid curing reduced the strength of control concrete, fly ash concrete exhibited higher early strength (24.67 MPa at 28 days) and continued to gain strength, peaking at 26.37 MPa at 42 days. This performance is attributed to sustained pozzolanic activity and pore refinement, which densify the matrix and promote secondary C-S-H formation [1], [3]. Beyond 42 days, however, strength declined gradually (24.03 MPa at 86 days), indicating progressive degradation under prolonged acid exposure [13], [22], [26]. Moreover, the X-Ray Diffraction (XRD) test on 20% fly ash concrete can be seen in Figure 3.

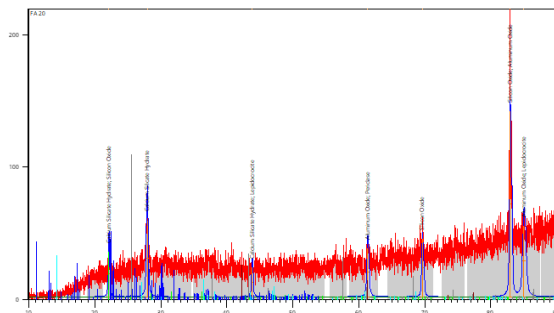


Fig. 3 XRD graphic of the 20% fly ash concrete

XRD results confirmed that amorphous C-S-H gel is the dominant phase in 20% fly ash concrete, while quartz was present as an inert filler. Portlandite (CH) was nearly absent, reflecting extensive pozzolanic

reactions and additional CH consumption in acidic conditions. Minor phases such as MgO and FeOOH were also detected, suggesting increased microstructural complexity. These transformations reduce CH availability and shift matrix dependence toward C-S-H gel, thereby enhancing chemical stability.

The scanning electron microscopy (SEM) analysis of 20% fly ash concrete provided additional insight into microstructural behavior under acidic exposure, as shown in Figure 4. At lower magnifications, the matrix appeared denser with fewer large voids compared to the control concrete, confirming the role of fly ash in refining the pore system.

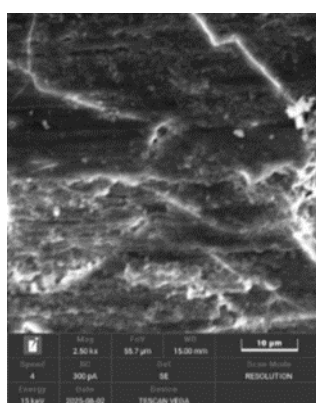


Fig. 4 SEM image at 2500 x magnification

SEM observations corroborated the XRD findings. The fly ash concrete displayed a denser morphology than the control mix; however, at 2500 $\times$ magnification, fine fissures, leached hydration gels, and localized porosity were evident. Occasional bright relics, likely unreacted fly ash particles or secondary precipitates, further indicated acid–cement interactions. While fly ash improved microstructural compactness, long-term acid exposure still promoted progressive damage, consistent with the strength decline after 42 days.

The EDS analysis results of normal concrete immersed in acidic water are presented in Figure 5, while those of concrete with 20% fly ash are shown in Figure 6.

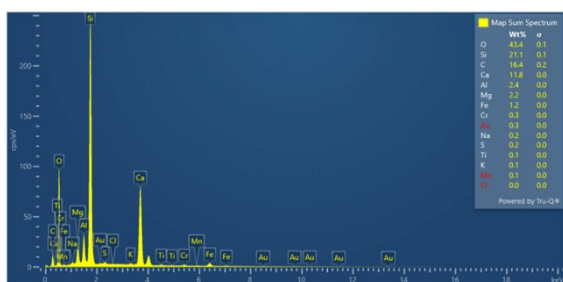


Fig.5 EDS test results for normal concrete immersed in acidic water

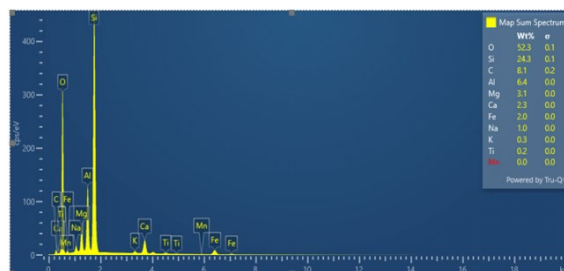


Fig.6 EDS test results for concrete with 20% fly ash immersed in acidic water

The EDS results revealed a decrease in calcium (Ca) and carbon (C) contents in both normal concrete and concrete with 20% fly ash after 28 days of immersion in acidic water. The reduction in Ca indicates the dissolution of $\text{Ca}(\text{OH})_2$ due to hydrogen ion (H^+) attack, which lowers the pH and weakens the binding matrix. In contrast, the reduction in C reflects the degradation of carbonate phases (CaCO_3) and calcium silicate hydrate (C-S-H), leading to structural deterioration of the concrete. This suggests that although the incorporation of 20% fly ash reduces free $\text{Ca}(\text{OH})_2$ and enhances resistance to acidic environments, the concrete matrix remains susceptible to progressive damage under highly aggressive conditions.

The strength peaked at 42 days (26.37 MPa), indicating that the pozzolanic reaction remained active beyond 28 days and continued to enhance the binding matrix in acidic conditions. However, at 56 days, the strength slightly declined to 25.37 MPa, followed by a further reduction to 24.03 MPa at 80 days. This trend may suggest microstructural degradation due to prolonged acid exposure, consistent with findings that extended sulfate or acid attack can weaken concrete, even when supplementary cementitious materials such as fly ash are used [13], [26], [35]. The practical implication of this study is that incorporating 20% Type F fly ash cannot serve as a standalone strategy to ensure long-term durability of concrete exposed to acid mine drainage environments. Structures that are in direct contact with acidic mine water, such as drainage channels, sedimentation ponds, and foundations, are at risk of accelerated service-life reduction compared with their design expectations. A key limitation of this research lies in its relatively short testing period of 86 days and its focus on a single fly ash dosage, which may not fully capture the severity of field conditions or long-term deterioration mechanisms. To enhance the resilience of concrete in such aggressive environments, supplementary measures should be considered, including the use of blended pozzolanic materials, optimization of mix design with a lower water-to-binder ratio, or the application of acid-resistant surface coatings. These strategies, if integrated with fly ash modification, could provide a

more robust framework for extending the durability of concrete in mining-affected regions.

4.3 Splitting Tensile Strength of Concrete

Concrete was tested for splitting tensile strength at the ages of 28, 42, and 56 days, particularly for mixtures incorporating additional fly ash. Cylindrical specimens measuring 15 cm in diameter and 30 cm in height were used for the tests. After the curing period was completed, the specimens proceeded to the testing phase, which was conducted in the Civil Engineering Laboratory at Mulawarman University. A standard compression testing machine was utilized for the splitting tensile strength test. The results of the splitting tensile strength test of the concrete are presented in Table 8 and illustrated in the graph in Figure 7.

Table 8. Split Tensile Strength Results

No	Fly Ash Content	Curing Medium	Concrete Age	f_t	f_{tr} (MPa)	Standard Deviation	f_{tr} (MPa)
1	0%	Fresh Water	28 Days	1,86	1,86	0,03	1,85
2				1,88			
3				1,83			
4	0%	Acid Water	28 Days	1,43	1,45	0,02	1,45
5				1,46			
6				1,47			
7	20%	Acid Water	28 Days	2,31	2,16	0,16	2,10
8				2,18			
9				1,99			
10	20%	Acid Water	42 Days	3,02	2,71	0,27	2,60
11				2,56			
12				2,54			
13	20%	Acid Water	56 Days	2,91	2,93	0,09	2,89
14				3,02			
15				2,85			

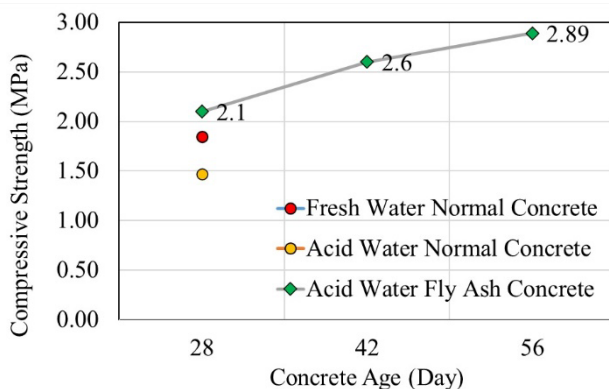


Fig. 7 Split Tensile Strength Result (Line Graph)

The graphical data in Figure 7 illustrate the variation in splitting tensile strength across different curing conditions and ages. After 28 days, concrete cured in acid water without fly ash exhibits a reduction in tensile strength compared to concrete cured in fresh water (1.47 MPa vs. 1.85 MPa).

However, when 20% fly ash is added, and the concrete is cured in acid water, the splitting tensile strength shows a consistent increase over time, reaching 2.10 MPa at 28 days, 2.60 MPa at 42 days, and peaking at 2.89 MPa at 56 days.

This trend suggests that the presence of fly ash significantly enhances the tensile performance of concrete, even under acidic curing conditions. The dissolution of $\text{Ca}(\text{OH})_2$ in acidic water appears to primarily impact compressive strength due to its influence on load-bearing capacity. In contrast, the tensile performance—governed by the concrete's resistance to pulling forces—remains unaffected or even improves due to the pozzolanic reaction and filler effect contributed by fly ash. Overall, these results indicate that fly ash plays a crucial role in improving the splitting tensile strength of concrete, while acid curing does not substantially hinder tensile strength development.

The split tensile strength test results revealed that concrete incorporating 20% fly ash exhibited a significant increase in tensile strength over time, reaching 2.89 MPa at 56 days compared to 2.10 MPa at 28 days. This trend indicates that fly ash contributes positively to tensile strength development, particularly in acidic curing environments. Previous studies have shown similar behavior, where the inclusion of fly ash enhanced the mechanical performance of concrete due to ongoing pozzolanic reactions and refined microstructures [1], [4]. The pozzolanic reaction between fly ash and calcium hydroxide produces additional calcium silicate hydrate (C-S-H), which densifies the matrix and improves tensile strength [5], [6]. Moreover, the increase in tensile strength over time aligns with findings that fly ash concrete continues to develop strength at later ages due to its slower but more sustained hydration process [11], [23]. These results confirm that fly ash not only mitigates the degradation effects of acidic environments but also enhances the tensile resistance of concrete as it matures.

5. CONCLUSIONS

The research results showed the mechanical characteristics of concrete, including compressive strength and split tensile strength. The compressive strength of normal concrete cured in fresh water at 28 days was 24.07 MPa, while that of normal concrete cured in acid water was reduced to 21.33 MPa. Meanwhile, concrete with a fly ash mixture and cured in acid water achieved compressive strength values of 24.67 MPa, 26.37 MPa, 25.37 MPa, and 24.03 MPa at 28, 42, 56, and 86 days, respectively. The split tensile strengths at 28, 42, and 56 days were 2.10 MPa, 2.60 MPa, and 2.89 MPa, respectively.

Based on these results, it can be concluded that curing in acid water significantly decreased the

compressive strength of concrete at 28 days. However, the incorporation of fly ash mitigated this effect due to its high silica content, which improved resistance to acidic environments. The highest compressive strength was achieved at 42 days, indicating enhanced long-term performance due to the pozzolanic reaction of fly ash.

The splitting tensile test results revealed that the comparison between 0% and 20% fly ash at a given age did not show a significant reduction under acid exposure. This suggests that concrete degradation in acidic environments has a more pronounced impact on compressive strength than on splitting tensile strength. The likely reason is that splitting tensile strength is governed more by the internal cohesion of the concrete and its resistance to tensile stresses. In contrast, compressive strength is more susceptible to the leaching and degradation of calcium hydroxide ($\text{Ca}(\text{OH})_2$) in acidic conditions.

Overall, the incorporation of fly ash contributes to the enhancement of long-term mechanical performance. Acting as a pozzolanic material, fly ash refines the microstructure, reduces porosity, and facilitates the development of additional strength over time, making it an effective partial replacement for cement under aggressive conditions. Nevertheless, the indication of strength reduction after prolonged immersion requires further microstructural and chemical investigation. Such advanced characterization is essential to understand better the degradation mechanisms of the C–S–H phase and the consumption of calcium hydroxide, thereby ensuring more reliable predictions of long-term durability.

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7. REFERENCES

- [1] Cuong N.H., Study on Compressive Strength and Chloride Ion Permeability of High Fly Ash Content Self-Compacting Concrete. *International Journal of GEOMATE*, 26(113) 2024, pp.34-40. <https://doi.org/10.21660/2024.113.4164>
- [2] Fauzan, Nur O.F., Albarqi K., Melinda A.P., Jauhari Z.A., The Effect of Waste Tyre Rubber on Mechanical Properties of Normal Concrete and Fly Ash Concrete. *International Journal of GEOMATE*, 20(77) 2021. pp. 55-61. <https://doi.org/10.21660/2020.77.5737>.
- [3] Arifi E., Zacoeb A., and Shigeishi M., Effect of Fly Ash on the Strength of Concrete Made from Recycled Aggregate by Pulsed Power.

- International Journal of GEOMATE*, 7(1) 2014. pp.1009-1016. <https://doi.org/10.21660/2014.13.87890>.
- [4] Andrabi S.B.Q., Optimizing the use of fly ash in concrete. *International Journal of Scientific Research*, 8(1), 2019, pp.1744–1763. <https://doi.org/10.21275/ART20194647>
- [5] Zhao H., Sun W., Wu X., and Gao, B., Sustainable self-compacting concrete containing high-amount industrial by-product fly ash as supplementary cementitious materials. *Environmental Science and Pollution Research*, 29(3), 2022, pp.3616–3628. <https://doi.org/10.1007/s11356-021-15883-2>
- [6] Şahmaran, M., Yaman, İ.Ö., and Tokyay, M., Transport and mechanical properties of self-consolidating concrete with high volume fly ash. *Cement and Concrete Composites*, 31(2), 2009, pp.99–106. <https://doi.org/10.1016/j.cemconcomp.2008.12.003>
- [7] Vishwakarma V., Uthaman S., Dasnamoorthy R., and Kanagasabai V., Investigation on surface sulfate attack of nanoparticle-modified fly ash concrete. *Environmental Science and Pollution Research*, 27(33), 2020, pp.41372–41380. <https://doi.org/10.1007/s11356-020-10134-2>
- [8] Jalal M., Teimortashlu E., and Grasley Z., Performance-based design and optimization of rheological and strength properties of self-compacting cement composite incorporating micro/nano admixtures. *Composites Part B Engineering*, 163, 2019, pp.497–510. <https://doi.org/10.1016/j.compositesb.2019.01.028>
- [9] Hawileh R.A., Shaw S.K., Assad M., Dey A., Abdalla J.A, and Kim J.H., Influence of Fly Ash on the Compressive Strength of Ultrahigh-Performance Concrete: A State-of-the-art Review Towards Sustainability. 2025,19:25. <https://doi.org/10.1186/s40069-024-00757-x>
- [10] Nanda B., and Rout S., Properties of concrete containing fly ash and bottom ash mixture as fine aggregate. *International Journal of Sustainable Engineering*, 14(4), 2021, pp.809–819. <https://doi.org/10.1080/19397038.2021.1920641>
- [11] Kumar S., and Rai B., Synergetic effect of fly ash and silica fume on the performance of high volume fly ash self-compacting concrete. *Journal of Structural Integrity and Maintenance*, 7(1), 2022, pp.61–74. <https://doi.org/10.1080/24705314.2021.1892571>
- [12] Kapoor K., Singh S.P., and Singh B., Permeability of self-compacting concrete made with recycled concrete aggregates and Portland

- cement-fly ash-silica fume binder. *Journal of Sustainable Cement-Based Materials*, 10(4), 2021, pp.213–239. <https://doi.org/10.1080/21650373.2020.1809029>
- [13] Sathe S., and Patil S., Corrosion effects on bond strength in reinforced concrete with fly ash. *Journal of Adhesion Science and Technology*, 38(24), 2024, pp.4467–4495. <https://doi.org/10.1080/01694243.2024.2373152>
- [14] Jaelani A.A.P.B., Experimental Study of 30%, 35% and 40% Fly Ash Substitution in SCC Concrete on Bonding Time, Flowability, Porosity and Concrete Compressive Strength in Sulfuric Acid Resistance. *Infrastructure Engineering Journal*, 10(2), 2024, pp.75–88. <https://doi.org/10.31943/jri.v10i2.278>
- [15] Bachtiar E., Setiawan A.M., Rachim F., Marzuki I., The development of compressive strength on geopolymer mortar using fly ash as based material in South Sulawesi. *International Journal of Civil Engineering and Technology*, 2018. Available: <http://www.scopus.com/inward/record.url?eid=2-s2.085056135860&partnerID=MN8TOARS>
- [16] Bachtiar E., The Connection Between Oven Curing Duration and Compressive Strength on C-Type Fly Ash-Based Geopolymer Mortar. *ARPN Journal of Engineering and Applied Sciences*, 15(5), 2020. Available: www.arpnjournals.com
- [17] Bachtiar E., Marzuki I., Setiawan A.M., Nurpadli A., and Hernald Y.I., Correlation of NaOH Composition and Alkali Modulus to Compressive Strength on Geopolymers Mortar. *ARPN Journal of Engineering and Applied Sciences*, 15(5), 2020. Available: www.arpnjournals.com
- [18] Putri H.R., Paledung F., Bachtiar E., and Indrayani P., The Effect of Seawater on The Compressive Strength and Split Tensile Strength in Self-Compacting Geopolymer Concrete. *Civilla*, 6(2), 2021, pp.197. <https://doi.org/10.30736/cvl.v6i2.722>
- [19] Aris R.H., and Bachtiar E., Workability and Mechanical Properties Self-Compacting Geopolymer Concrete. *Civilla*, 6(2), 2021, pp.267–277. <https://doi.org/10.30736/cvl.v2i2>
- [20] Goyal A., and Karade S.R., Effect of fly ash and red mud on strength and electrochemical properties of seawater mixed concrete. *European Journal of Environmental and Civil Engineering*, 27(16), 2023, pp.4646–4663. <https://doi.org/10.1080/19648189.2023.2194956>
- [21] Kannur B., and Chore H.S., Strength and durability study of low-fines self-consolidating concrete as a pavement material using fly ash and bagasse ash. *European Journal of Environmental and Civil Engineering*, 27(11), 2023, pp.3507–3524. <https://doi.org/10.1080/19648189.2022.2140207>
- [22] Zahlim, A., Bachtiar, E., and Makbul, R., The effect of seawater curing on the compressive strength of high-strength concrete using fly ash as a sand substitute. *Borneo Engineering Journal Teknik Sipil*, 1(1), 2022, pp.1–10. <https://doi.org/10.35334/be.v1i1.2161>
- [23] Sultan, M.A., Hakim R., Effect of Fly Ash Addition on Compressive Strength of Cement Mortar. *Clapeyron Journal of Civil Engineering*, 2(1), 2020, pp.19–26. <https://ejournal.unkhair.ac.id/index.php/CLAP EYRON/article/view/3499>
- [24] Sofia D.A., and Kamal N., The Effect of Fly Ash Mixture on Concrete Compressive Strength, *Civil Engineering Journal*, 8(1) 2023 , pp. 19–24. <https://doi.org/10.31544/jtera.v8.i1.2023.19-24>
- [25] Hamri, A.M., Bachtiar, E., Indrayani, P., and Tata, A., Pengaruh Hujan Asam Terhadap Kuat Tekan Dan Pola Retak Beton Mutu Tinggi Yang Menggunakan Fly Ash Sebagai Substitusi Pasir. *Jurnal Sipilsains*, 10(2), 2020, pp.151–156. Available: <http://ithh.journal.ipb.ac.id/index.php/p2wd/article/view/22930>
- [26] Zhang Y., Wu D., Wang Y., Zhou Y., Wang S., and Zhao Y., Influence of Fly Ash Content on the Durability of Mortar Specimens under Dry/Wet Sulfate Attack. *Materials*, 17(1), 2023, pp.113. <https://doi.org/10.3390/ma17010113>
- [27] Saha A.K., Effect of class F fly ash on the durability properties of concrete. *Sustainable Environment Research*, 28(1), 2018, pp.25–31. <https://doi.org/10.1016/j.serj.2017.09.001>
- [28] Case R.J., Duan K., and Suntharavadivel T.G., On Effects of Fly Ash as a Partial Replacement of Cement on Concrete Strength. *Applied Mechanics and Materials*, 204–208, 2012, pp.3970–3973. <https://doi.org/10.4028/www.scientific.net/AM M.204-208.3970>
- [29] Akbulut Z.F., Yavuz D., Tawfik T.A., Smarzewski P., and Guler S., Enhancing Concrete Performance through Sustainable Utilization of Class-C and Class-F Fly Ash: A Comprehensive Review. *Sustainability*, 16(12),2024,4905. <https://doi.org/10.3390/su16124905>
- [30] Davila J.M., Rodriguez-Gomez C., and Sarmiento A.M., Use of fibres and surface treatment to improve the durability of concrete affected by sulphide mining. *Scientific Reports*, 15,2025,pp.25090. <https://doi.org/10.1038/s41598-025-10855-9>

- [31] Azimi N., Schollbach K., Oliveira D.V., and Lourenço P.B., Effect of acidic environment exposure on mechanical properties of TRM composites. SSRN, 2024. Available: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4712795
- [32] Wu H.-L., Du Y.-J., Yu J., Yang Y.-L., and Li V., Hydraulic conductivity and self-healing performance of Engineered Cementitious Composites exposed to Acid Mine Drainage. *Science of the Total Environment*, 716, 2020, pp.137095.
<https://doi.org/10.1016/j.scitotenv.2020.137095>
- [33] Jamal M., Tamrin, Sutanto H., Dicky T., and Gusty S., Analisis Fly Ash Tipe C sebagai Aditif terhadap Kuat Tekan Beton menggunakan Agregat Halus Samboja. *Jurnal Dinamika Rekayasa*, 20(1), 2024, pp.29–37.
<https://doi.org/10.20884/1.dinarek.2024.20.1.2>
- [34] Pradhan S. S., Mishra U., Biswal S. K., & Jangra P. (2025). Experimental Investigation on Strength and Durability Properties of Slag-Based Alkali Activated Concrete Incorporating Fly Ash. *Journal of Polymer and Composites*, 13(2), pp.393–400.
<https://doi.org/10.1007/s40974-024-00319-7>
- [35] Chavali R. V. P., Vindula S. K., Vydehi K. V., & Reddy P. H. P, Effect of Acid and Alkali Contamination on Swelling Behavior of Kaolin Clay. In *Geo-Congress 2020*. Retrieved from <https://doi.org/10.1061/9780784482827.024>

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