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Research article

Laboratory investigation of the influence of aluminum hydroxide on the compressive strength of nickel slag-stabilized soft soils

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Abstract: Chemical stabilization is considered a more effective and efficient method for improving soft soil in road foundation construction. Nickel slag, a byproduct of the nickel industry, has the potential to be developed as an environmentally friendly pozzolanic material for soft soil improvement. Our previous research has shown that nickel slag enhances the mechanical properties of high-plasticity organic soil but fails to meet road foundation standards. As such, additional materials are needed to achieve the required specifications. This study aims to analyze the effect of adding aluminum hydroxide [$Al(OH)_3$] to soil stabilized with nickel slag. The addition of $Al(OH)_3$ is based on weight ratios of nickel slag at 1.5, 2.5, and 3.5. The effectiveness of adding nickel slag was assessed based on the unconfined compressive strength (q_u) of the mixture matrix. In addition, mineral characterization of the mixture matrix was tested using X-ray diffraction (XRD) to observe changes in mineral fractions. The results of this study indicate that the addition of $Al(OH)_3$ can improve the mechanical performance of soft clay soil better than soil stabilized with nickel slag alone, with the 1.5% weight ratio providing the highest compressive strength value of 237.39 kPa. This improvement may be due to the formation of pozzolanic reactions, including C–S–H, C–A–H, and C–S–A–H, as shown by the XRD test results.

Keywords: soil stabilization; soft soil; nickel slag; aluminum hydroxide

1. Introduction

Soil is a natural material that, in its natural state, possesses low bearing capacity and stability [1]. Therefore, soil properties need to be improved, either mechanically or chemically. Chemical stabilization, aimed at enhancing the properties of soft soil to meet specific technical requirements, has proven to be a more effective and economical solution compared to other methods [2], especially in large-scale road construction projects. From an economic standpoint, the use of chemical materials in the process of soft soil improvement in road construction can reduce project costs by 30% to 45% [3].

Cement and lime are common chemical materials used in soil stabilization. Scientifically, the use of these materials has shown significant effects on improving the physical characteristics and mechanical properties of various types of soft soil [4–6]. The growing reliance on cement and lime in civil construction poses significant environmental challenges, primarily due to their high energy requirements, carbon dioxide emissions, and contribution to environmental degradation [7]. The production of conventional cement and lime through combustion processes releases CO_2, a greenhouse gas that contributes to global warming [8]. In fact, the cement industry and lime calcination processes contribute to an increase in CO_2 emissions by 5% to 8% [9,10]. Therefore, it is crucial to focus on the efficient use of other, more environmentally friendly natural resources in place of those used in cement production, such as industrial byproducts or waste materials.

Supplementary cementitious materials (SCMs) are inorganic materials that impart specific properties to cement mixtures through hydraulic activity, pozzolanic activity, or both [11]. The cementation process utilizing industrial byproducts primarily depends on the pozzolanic reactions that occur between the stabilization material and the soil matrix. Pozzolanic materials themselves are defined as substances containing silica, or both silica and alumina, which have little or no cementitious value on their own. When soil particles are finely divided and come into contact with water, they undergo a chemical reaction with calcium hydroxide at room temperature, resulting in the formation of compounds that exhibit cementitious properties [12]. The pozzolanic reaction of materials used as stabilizers is influenced by several factors, including cation exchange capacity, specific surface area of the material, and the Si/Al molar ratio [13]. In other words, the presence of silica and alumina minerals plays a crucial role in the formation of calcium aluminate hydrate (C–A–H) or calcium silicate hydrate (C–S–H), known as cement gel, which in turn improves the mechanical properties of stabilized soft soil [14].

The nickel industry in Indonesia is currently experiencing rapid growth, particularly in the North Maluku Province. The extraction of nickel ore generates a significant amount of waste material, both solid and liquid, one of which is nickel slag. Nickel slag is a solid waste material produced from the extraction of nickel ore through the pyrometallurgical process. The mineralogical composition of nickel slag, as shown by X-ray diffraction (XRD) analysis, includes 44.89% SiO_2, 25.11% Fe_2O_3, 20.27% MgO, and 3.34% CaO, classifying it as a pozzolan type F [15]. This indicates that nickel slag has great potential not only as a construction material but also for development in advanced environmentally friendly material engineering for other industries, such as sensors and shielding materials [16].

The use of nickel slag as a stabilization material has been shown to modify the physical and mechanical characteristics of soft soil [17–19]. However, this improvement in mechanical properties has not yet met the technical specifications required for application in civil construction, particularly for the stabilization of soft soils. While each chemical additive can bring significant improvements to soil performance when applied individually, combining several chemical materials can expand the potential for soil stabilization to a higher level [20]. Liangyou et al. [21] revealed that the activity of nickel-iron slag powder can be enhanced by adding activators, such as calcium oxide and sodium sulfate, to accelerate the pozzolanic reaction rate.

The XRD analysis of the nickel slag used in this study shows that the mineral does not contain aluminum (Al), which is essential in the cement gel formation process. The absence of aluminum could affect the effectiveness of nickel slag in enhancing the mechanical stability of the soil. Therefore, this study will focus on the addition of aluminum hydroxide [$Al(OH)_3$] to address this deficiency, with the aim of improving the mechanical properties of soil stabilized with nickel slag. The goal is to produce a more robust material suitable for civil engineering applications.

The use of local materials in construction offers significant cost savings compared to conventional materials like cement. Local materials, such as nickel slag, are generally more affordable due to their abundant availability and simple processing, which does not require complex technologies like those used in cement production. Additionally, the transportation costs of local materials are lower since they are sourced near the project site, unlike cement, which must be transported from large manufacturing plants. For non-structural applications or small-to-medium scale projects, local materials are more economical as they can often be used directly or with minor modifications. While cement excels in strength and durability for permanent structures, local materials are a more cost-effective option for simpler construction needs while also supporting local economic development.

2. Materials and methods

2.1. Materials

In this study, soft soil samples were taken from Subaim Village in East Halmahera Regency, North Maluku Province. Visually, soil samples are blackish in color and have a very fine grain size. The nickel slag material, on the other hand, is greenish in color with grains larger than sand and has a smooth surface. The slag was obtained from a nickel mining industry located in Kawasi Village, South Halmahera Regency, as shown in Figure 1. The aluminum hydroxide [$Al(OH)_3$] used in this study was sourced from the market, with a purity level of 99.5%, white in color, and a grain size of 45 µm.

Figure 1. Samples site location (Reproduced from Ref. [18] with permission).

2.2. Materials preparation and samples production

Physical and mechanical properties testing of the materials used in this study was conducted according to ASTM standards, including sieve analysis (ASTM C316), specific gravity (ASTM D-854-02), Atterberg limits (ASTM D4318-00), moisture content (ASTM D4442), standard Proctor test (ASTM D698), and unconfined compression strength (ASTM D2166). Additionally, the preparation of materials and test specimens was guided by findings and methodologies from previous research studies.

The soil preparation was carried out through drying under sunlight to avoid excessive heat that could be caused by using an oven. Excessive heating has the potential to affect the mineral characteristics of clay materials [22]. As for the slag material used in this study, it was finely ground, and the material used was passed through a sieve No. 400 (0.0375 mm), as shown in Figure 2. This aligns with the perspective of Lin et al. [23], who emphasized that particle fineness and the specific surface area of stabilizing agents are critical factors in enhancing the physical and mechanical properties of soft soil. These parameters play a significant role in explaining the observed increase in density and cohesion in soft soil.

Previous research on the use of nickel slag as a stabilizing material for soft soil has shown that the maximum unconfined compressive strength (UCS) is achieved with a 6% addition of nickel slag relative to the dry weight of the soil (γ_{dry}), with a value of 106,43 kPa. Based on these results, the addition of $Al(OH)_3$ is referenced according to the weight of nickel slag with weight ratios of nickel slag/$Al(OH)_3$ of 1.5, 2.5, and 3.5. For more details, the mixed design involving soil, nickel slag, and aluminum hydroxide is shown in Table 1.

Table 1. Mixed design of soil stabilized with nickel slag and $Al(OH)_3$.

Nickel slag	γ_{dry} (kg/m^3)	Sample weight (g)	Nickel slag weight (g)	Soil weight (g)	Ratio of nickel slag to $Al(OH)_3$	$Al(OH)_3$ weight (g)
6%	1090	191.3	11.5	179.8	1.5	7.7
					2.5	4.6
					3.5	3.3

Figure 2. Nickel slag (a) before grinding and (b) after grinding and passing through a No. 400 sieve.

The process of preparing test specimens for UCS testing includes the thorough mixing of soil, nickel slag, and aluminum hydroxide. The moisture content used in the preparation of UCS specimens was based on the optimum moisture content of the clay soil obtained from the soil compaction test. The test specimens are cylindrical, with a diameter of 48 mm and a height of 96 mm. A total of three specimens were prepared for each treatment, regardless of the addition of $Al(OH)_3$ or the curing time period applied. Test specimens are wrapped in plastic to maintain their moisture content and are cured for 3, 7, 14, 21, and 28 days before testing.

The mineral characterization analysis of the test specimens is conducted using XRD with a SHIMADZU XRD-7000, employing a Cu-Kβ line (40 kV, 30 mA, 2θ = 20–70°) as the radiation source. This method is a non-destructive technique that provides information about crystal phases, crystal structure, average crystal size, micro and macro strains, crystal defects, and more [24,25]. The XRD spectrum data will be analyzed using the Match! software.

3. Results and discussions

3.1. Physical characteristics of clay soil

The physical and mechanical characteristics of the soft soil are based on our previous research [18], as shown in Table 2. Test results indicate that this soil is dominated by a clay fraction of 77.3%, with silt and sand fractions of 14.3% and 8.4%, respectively. The soil exhibits medium to high plasticity based on its liquid limit (LL) of 64.92%, plastic limit (PL) of 41.34%, and plasticity index (PI) of 23.58%. The natural water content of 33.08% suggests that the soil is relatively saturated, while the specific gravity (Gs) of 2.11 indicates a potential presence of organic material or low-density minerals. Mechanically, the soil has a dry density (γ_{dry}) of 1090 kg/m^3 and an UCS of 38.32 kPa, which classifies it as very soft soil with low bearing capacity.

Tabel 2. Soft soil properties.

Soft soil properties		Value
Physical characteristics	Specific gravity (Gs)	2.11
	Water content (wt%)	33.08
	Sieve analysis	
	Sand (%)	8.4
	Silt (%)	14.3
	Clay (%)	77.3
	Atterberg limit	
	Liquid limit (%)	64.92
	Plastic limit (%)	41.34
	Plasticity index (%)	23.58
Mechanical characteristics	Dry density (kg/m^3)	1090
	UCS (kPa)	38.32

According to the Unified Soil Classification System (USCS), this soil is classified as CH (clay of high plasticity), characterized by LL > 50% and PI > 7%. Based on the American Association of State Highway and Transportation Officials (AASHTO) classification, the soil falls into category A-7-6, indicating high-plasticity clay with significant expansive potential. Soils with these characteristics tend to be unstable for direct use in construction without improvement, as they possess low bearing capacity and high susceptibility to volumetric changes. Therefore, stabilization or soil improvement techniques are necessary to enhance its performance for civil engineering applications.

3.2. Unconfined compression strength characteristics

The mechanical behavior of the test specimens, as shown by the unconfined compressive strength tests, is illustrated in Figure 3. From the stress-strain curve, it can be observed that the maximum unconfined compressive strength for specimens cured for 28 days with nickel slag to aluminum hydroxide ratios of 1.5, 2.5, and 3.5 are 243.88, 218.06, and 197.97 kPa, respectively. The strain values for the specimens are relatively consistent across variations, ranging between 2% and 2.5%. Based on this mechanical behavior, it can be seen that adding $Al(OH)_3$ to the mixture of soil and nickel slag at a 6% rate significantly increases the unconfined compressive strength compared to soil without stabilization or soil stabilized only with nickel slag. Regarding strain values, the addition of $Al(OH)_3$ enhances the soil's stiffness compared to untreated soil, although this value is still lower than that of soil stabilized only with nickel slag.

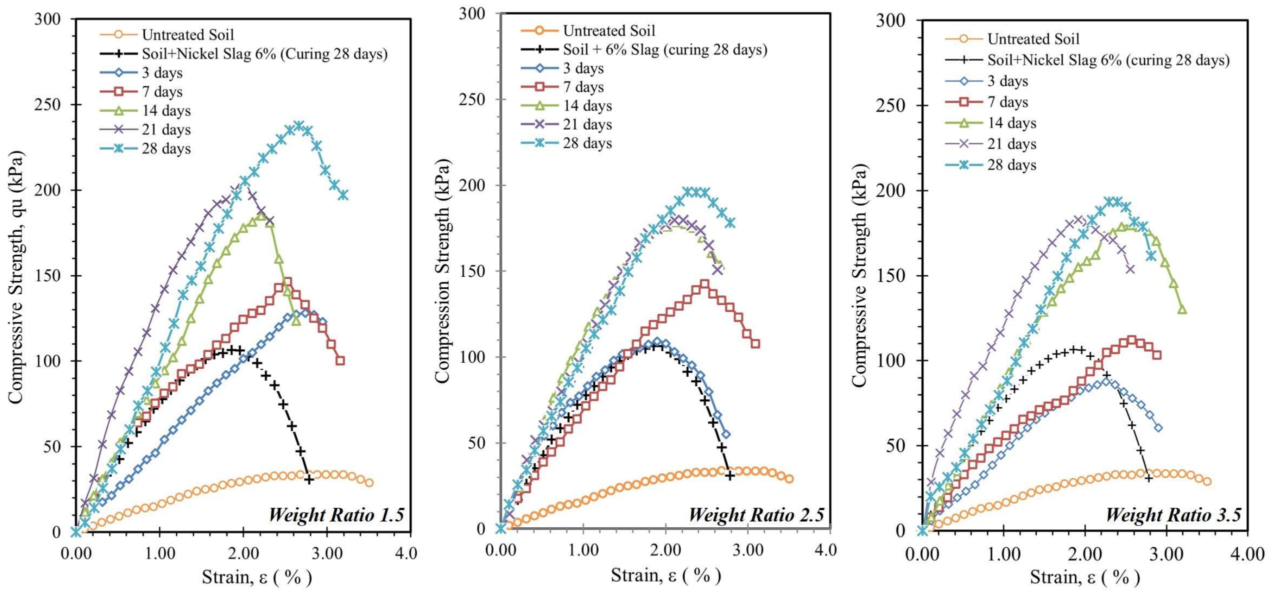

Figure 3. Stress-strain behavior of specimens.

The stress-strain behaviors indicate that adding aluminum hydroxide to soil stabilized with nickel slag provides significant benefits in terms of increased compression strength and ductility [26] compared to untreated soil and soil stabilized only with nickel slag. This suggests that the presence of aluminum hydroxide and curing in soil stabilized with nickel slag enhances the pozzolanic reaction process between soil, silica (nickel slag), and alumina (aluminum hydroxide), forming C–S–H, C–A–H, and C–S–A–H compounds with cementitious properties [27,28]. The formation of these hydration products helps to improve the physical and mechanical properties of the soil by strengthening the bonds between soil particles, reducing porosity, and increasing resistance to deformation and load [29,30].

From the stress-strain relationship results, it is evident that curing time and the variation in the addition of aluminum hydroxide significantly enhance the material's stiffness, as represented by Young's modulus (E). This value has important implications when applied as a road foundation structure. The material with a nickel slag/$Al(OH)_3$ ratio of 1.5 demonstrates excellent stability and the highest stiffness value, with E reaching 960.38 MPa after 28 days of curing. This indicates that the material is more resistant to long-term elastic deformation under repeated vehicle loads, making it ideal for road foundation structures requiring stability and resistance to elastic settlement under continuous pressure. Meanwhile, the nickel slag/$Al(OH)_3$ ratios of 2.5 and 3.5 yielded lower stiffness values after 28 days of curing. The lower stiffness indicates that the material is more susceptible to deformation, which may lead to settlement under applied loads.

The effect of aluminum hydroxide and the impact of curing on the test specimens in a soil mixture stabilized with nickel slag are shown in Figure 4. The unconfined compressive strength of the soil material stabilized with both nickel slag and aluminum hydroxide presents a very significant increase compared to the soil material stabilized only with nickel slag. The unconfined compressive strength of the test specimen stabilized with nickel slag and $Al(OH)_3$ after 28 days of curing increased by 705% compared to untreated clay. Furthermore, when compared to soil stabilized solely with nickel slag, this value shows an improvement of 225%. In addition to the enhancement in unconfined compressive strength, Figure 4 highlights that the addition of $Al(OH)_3$ can accelerate the progression of strength improvement. This is reflected in the UCS value of soil stabilized with only nickel slag after 28 days of curing, which is comparable to the unconfined compressive strength of soil stabilized with both nickel slag and $Al(OH)_3$ after just 3 days of curing.

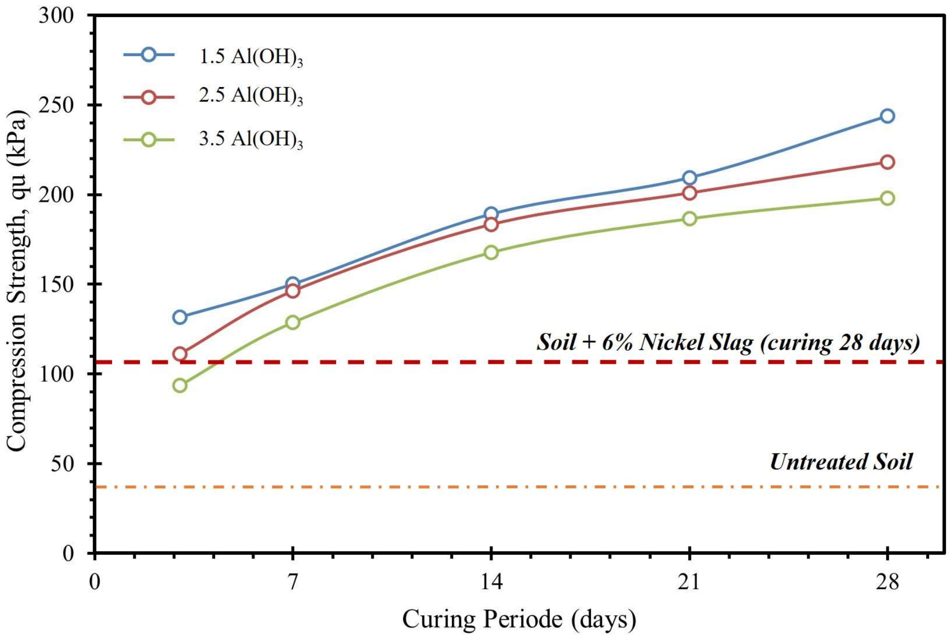

Figure 4. Strength increase by curing periods.

3.3. XRD analysis of specimens

XRD is an instrumental test method that gives an initial idea about materials as potential pozzolans by determining silica and aluminum oxide composition and the amorphous phase. The process begins by importing raw XRD data, including 2θ angles and corresponding intensities, into Match! software. Background subtraction and smoothing are applied to enhance the quality of the diffraction pattern. The software identifies peaks in the pattern based on intensity data, with these peaks corresponding to diffraction from specific planes in the crystal structure. The positions (2θ values) of these peaks are critical for phase identification, and Match! compares them against reference patterns in a database using a search-match algorithm. This algorithm matches the detected peak positions with those in a database of known phases, often using the ICDD PDF-2 database as a reference. The software suggests possible phases based on the match, with the accuracy of phase identification depending on the quality of the reference database. This process is essential for identifying the phases present in a crystalline sample.

The interpretation of XRD results indicating the formation of pozzolanic reactions is based on several pieces of literature, as follows: the formation of calcium silicate hydrate (C–S–H) generally occurs at peaks around 29–32° [31,32]. Calcium aluminate hydrate (C–A–H) can be observed at peaks with a 2θ angle of 18.0, 28.0, and 34.0° [33]. Calcium silicate aluminate hydrate (C–S–A–H) forms at peaks with 2θ angles of 10.6, 20.8, 30.6, and 40.7° [34–36].

The characterization test results of the mixed matrix of soil, nickel slag, and varying amounts of aluminum hydroxide in this study are shown in Figure 5. The diffraction patterns obtained from the XRD analysis demonstrate a significant difference between the material with added $Al(OH)_3$ and the soil without $Al(OH)_3$. In the soil stabilized only with nickel slag, the identified pozzolanic reactions are limited to C–S–H and C–A–H, while the addition of $Al(OH)_3$ results in diffraction patterns that show the formation of C–S–A–H compounds with higher intensity. At a ratio of nickel slag to $Al(OH)_3$ of 1.5, peak 8 exhibits the highest intensity (2θ = 28.0483°, d = 3.17871 Å, intensity = 29), which likely corresponds to the most abundant mineral present in the sample, possibly originating from quartz (d = 3.34 Å) or Feldspar (d = 3.171 Å) [37]. Additionally, peak 16 (2θ = 35.3400°, d = 2.53777 Å, intensity = 17) also shows a considerable intensity, which may be linked to minerals such as gypsum (d = 2.531 Å) or barite (d = 2.512 Å) [38]. Meanwhile, peak 7 (2θ = 26.8600°, d = 3.31658 Å, intensity = 17) displays the same intensity as peak 16.

The formation process of C–S–H, C–A–H, and C–S–A–H compounds at nickel slag/$Al(OH)_3$ ratios of 2.5 and 3.5 in the samples shows similar results to the sample with a 1.5 weight ratio but with lower spectrum intensity. The interpretation of the XRD results for the weight ratios of 2.5 and 3.5 suggests that the possible C–S–H phase is indicated by characteristic peaks for C–S–H found around 2θ values of approximately 29.4, 32.5, and 49.3°, with interplanar spacings of 3.04, 2.76, and 1.85 Å, respectively. The C–A–H phase, such as Hydrogarnet, may exhibit peaks around 2θ values of approximately 11.7, 23.4, and 33.6°, with corresponding interplanar spacings of 7.56, 3.81, and 2.66 Å. The C–S–A–H phase, such as Ettringite, may have peaks around 2θ values of approximately 9.1, 15.9, and 22.9°, with corresponding interplanar spacings of 9.72, 5.57, and 3.88 Å.

This XRD analysis has shown that the formation of hydro-silicate and hydro-aluminate minerals such as C–S–H, C–A–H, and C–S–A–H contributed to the increase in strength. Characteristic peaks in the XRD diffractograms showed the formation of C–S–H phase at 29–32°, CAH at 18, 28, and 34°, and C–S–A–H at 10.6, 20.8, 30.6, and 40.7°. The formation of these minerals indicates a chemical reaction between soil, nickel slag, and aluminum hydroxide that produces a cementitious matrix that binds soil particles, increasing soil strength and stiffness [39]. Thus, this reduction in intensity will affect the binding and strengthening effects provided by the soil mixture with its pozzolanic material, ultimately leading to a decrease in the soil's unconfined compressive strength [40,41].

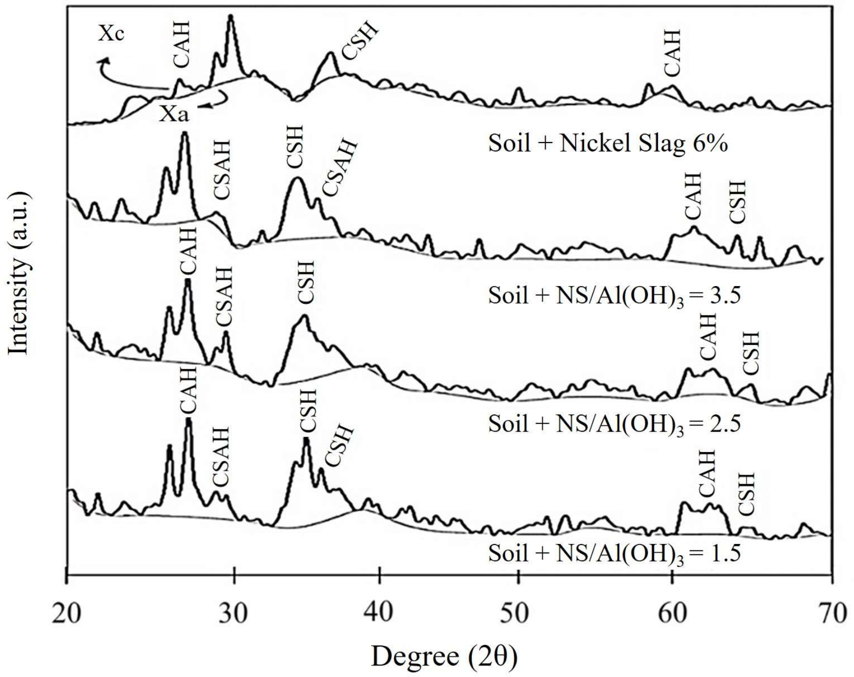

Figure 5. XRD spectrums of specimens.

4. Conclusions

The study results indicate that incorporating aluminum hydroxide into stabilized soil significantly boosts the reaction rate and unconfined compressive strength of clay soil. This is reflected in the unconfined compressive strength tests of specimens cured for 28 days, where the matrix mix strength increased by 225% compared to soil mixed with nickel slag and by 705% compared to untreated soil. Adding aluminum to nickel slag–stabilized soil accelerates and enhances pozzolanic reactions, as confirmed by XRD mineral characterization, which identifies C–S–H, C–A–H, and C–S–A–H reactions in each test variation. Therefore, modifying the stabilization material with $Al(OH)_3$ improves the soil's load-bearing capacity and deformation resistance, thereby reducing the risk of premature failure.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Author contributions

Ichsan Rauf conceptualized the research idea and methodology. Heryanto Heryanto carried out the experiments, including sample preparation and data collection. M. Taufiq Yuda Saputra was responsible for data analysis and interpretation. The XRD testing was performed by the M. Fatahilla Marsaoly in the Laboratory of Physics Department at Hasanuddin University. Ichsan Rauf wrote the initial draft of the manuscript, while all authors contributed to the review and editing process. All authors read and approved the final manuscript.

Conflict of interest

The authors declare that they have no conflicts of interest.

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