International Journal of Scientific Research and Engineering Development-– Volume 7 Issue 3, May-June 2024

*Available at **www.ijsred.com***

RESEARCH ARTICLE OPEN ACCESS

Ash-tonishing Groundwork: A Geotechnical Exploration on the Impacts of Mixing Volcanic Ash on the Plasticity, Compaction, and Bearing Capacity of Silty Soil

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Abstract:

The study looks at the impacts of volcanic ash on soil plasticity, compaction, and bearing capacity in Bacolor, Pampanga, following Mount Pinatubo's eruption. Laboratory studies and analysis show that volcanic ash has little effect on soil plasticity index but considerably alters compaction properties and bearing capacity. Volcanic ash modifies the optimal moisture content and maximum dry density, offering considerable obstacles to soil stabilization and construction approaches. A combination containing 10% volcanic ash is found to have the best compaction qualities for practical uses. Furthermore, the study shows that the load-bearing capacity varies depending on the amount of volcanic ash present, with 10% volcanic ash offering the highest carrying capacity. These findings can help civil engineers, geotechnical experts, disaster management authorities, and environmental engineers make more informed decisions and promote sustainable development in volcanic zones like as Bacolor, Pampanga.

Keywords **—volcanic ash, soil stabilization, geotechnical engineering, sustainable construction, soil properties**

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I. THE PROBLEM AND A REVIEW OF RELATED LITERATURES AND STUDIES

A. *Introduction*

This document is a template. An electronic copy can be downloaded from the conference website. For questions on paper guidelines, please contact the conference publications committee as indicated on the conference website. Information about final paper submission is available from the conference website. Throughout history, several civilizations have recognized the value of ash, particularly in the fields of civil and geotechnical engineering. Going back to Rome, the Romans utilized ash as concrete to reinforce other concrete and build constructions such as bath houses, temples, aqueducts/bridges, and so on. Of all the simple yet ancient methods for building structures with ash, lime, and water, this technique has been identified as having several distinct advantages[1]. Professor AdmirMasic and his research team were instrumental in preserving the practice of mixing ingredients and describing the significance of lime and volcanic ash in the manufacture of ornamental self-healing concrete that reacts to cracks and releases calcium ions[2].

A group of experts from the Massachusetts Institute of Technology discovered that adding fine dust of volcanic ash to cement manufacture makes the process more environmentally friendly while also improving the mechanical qualities of the cement concrete. This skilled method targets the nature of cement manufacture, which is typically energy intensive, and delivers a 16% reduction in embodied energy. Furthermore, the coarser the ash particle size is, the less workable the concrete becomes, although the concrete strength may increase[3].

To highlight the study's distinctive aspects, the thesis draws clear references to previous methodologies and recent research endeavors. As previously said, the concentrations of volcanic ash in concrete and its nutrient content in soil have gotten a lot of attention, but the impacts of volcanic ash on geotechnical soil qualities have received less attention. The primary goal of this research is to answer numerous questions about the effects of volcanic ash on the geotechnical properties of soils.

The subsequent parts of this thesis will highlight the limitations of previous research and emphasize the need for a more complete elaboration of the soil's primary physical properties as well as a better knowledge of the geotechnical aspects of the processes. The highlighted deficiencies need a complete experimental research in a laboratory to close them and gain a better knowledge of changes in silt soil behavior when polluted by volcanic ash in terms of flexibility, compaction, and bearing capacity.

B. Review of Related Literature

1) Studies on Materials Mixed on Soils:

Iron Ore Tailings

An experiment blended iron ore tailing sands with calcareous red earth to assess soil physical properties at the Jinshandian tailings pond. Results showed significant effects: bulk density increased non-linearly by 4.0% to 26.8% for natural soil and 2.6% to 24.8% for compacted soil. Soil density linearly increased by 1.7% to 20.2%. Porosity increased with an optimal sand-to-soil ratio, while hygroscopic coefficient decreased by 10% to 87%, correlating negatively with the ratio. Maximum water-holding capacity exhibited distinct stages, with an optimal mixing ratio identified. This approach improves soil properties and water/gas regulation, with the most effective mixing rate falling within 30% to 40% of iron ore tailings to soil[4].

Another study investigated the effects of iron ore tailings (IOT) on the compaction and plasticity of black cotton soil (BCS) and lateritic soil (LTS). Following testing at various mix ratios, a statistical model was created to forecast the maximum dry density (MDD) and optimal moisture content (OMC). Higher IOT concentrations were associated with greater specific gravity, which improved soil flexibility. For LTS and BCS, plastic limitations varied while liquid limits declined. With IOT treatment, the plasticity index went down for LTS but somewhat up for BCS. For LTS, MDD varied, while for BCS, it grew steadily. OMC patterns changed with IOT treatment, rising for LTS and falling for BCS. The model predicted the outcomes with accuracy. However, LTS and BCS treated with 8% to 10% IOT had better qualities appropriate for pedestrian pathways, whereas BCS treated with IOT did not fulfil sub-base and base course material specifications[5].

Granular Materials

The focus of the study was to assess how adding granular materials will affect the characteristics of soft soil. Soft soil from a construction site in Karbala, Iraq, was tested in its natural state and blended with various granular material proportions. Tests included shear strength and static loading using a cylindrical model. Results showed improved soil reduced settlement by 0.61 on average and increased bearing capacity by 31%. The bearing capacity ratio ranged from 1.23 to 1.39 with 25% granular materials, showing significant improvement with a consistency index at unity. Notable variations were observed between consistency indices, with higher indices showing more pronounced enhancement from granular materials[6].

Steel Slag

A study evaluated the application of substantial amounts of steel slag (SL) for subgrade purposes. Experiments consisted of compaction, liquid-plastic limit assessments, and CBR (California Bearing Ratio) tests to find the best SL-to-original soil (S) ratio. Following tests on soil incorporating SL at the ideal ratio demonstrated notable enhancements in physical characteristics, specifically liquid-plastic limit and soil water stability. The best ratio was found to be 50% SL, resulting in SSL achieving the highest CBR value at 60%. The inclusion of SL increased both the shear strength and dynamic modulus. SSL met the volume stability requirements of Chinese standards, and incorporating 2% cement enhanced both strength and stability. Environmental impact tests revealed no contamination, with SSL's permeability coefficient staying within standard levels. In general, SSL improves soil characteristics both mechanically and environmentally, showing potential for sustainable road construction materials[7].

Soil and Organic Mixtures

In their study, Lancaster et al. (1996) performed numerous modified Proctor tests to assess how including organic content influences the optimal moisture content of soil maximum dry unit weight combined by various organic materials. The soils under examination comprised poorly graded sandy soil (SP – SM) blended with shredded redwood bark, rice hulls, or municipal sewage sludge[8].

Volcanic Ash on the Strength and Permeability of Mortar

The study entitled “The Influence of Volcanic Ash on Mortar Strength and Permeability” investigates the impact of volcanic ash on mortar strength and permeability, aiming to enhance environmental sustainability and concrete durability. Volcanic ash, often overlooked in engineering, is evaluated from Mount Dukono. Test specimens with varying ash proportions (0% to 25%) relative to cement weight were prepared. Results show improved compressive strength at 5% and 10% ash levels, with strengths of 21.73 MPa and 30.40 MPa, respectively. Higher proportions (15% to 25%) decrease strength. Optimal performance is observed at 10% ash, highlighting its potential as an environmentally friendly and performance-boosting mortar additive[9].

Powdered Golden Apple Snail Shells as a Stabilizing Agent to Sandy Clay Loam Soils

This study investigates the utilization of GAS (Golden Apple Snail) shells to stabilize sandy clay loam soils. Soil testing revealed elevated clay levels, designated as A–7–6 per AASHTO guidelines, posing potential pavement hazards because of its high plasticity. The research explores the impact of stabilizer type and quantity, type of soil, and curing conditions on these risks. In the Philippines, GAS shells, abundant and considered bothersome, have a significant calcium carbonate (CaCO3) content that yields around 90% calcium oxide (CaO) when heated. The study investigates the potential of stabilizing excavation soil (clay soil) using calcined GAS shells. In all cases, the Atterberg Limit, the California Bearing Ratio (CBR), and the Standard Proctor were used to calculate the amount of improvement achieved by the mixes at 5%, 10%, 15%, and 20% CaO relative to the prepared soil.

The Atterberg Limit test gave a Plasticity Index for the soil and results indicated that after adding calcined shells there was a decreased PI for the soil. To determine maximum dry density (MDD) and optimum moist content (OMC) of each soil with GAS assemblage, standard proctor test was performed. In this case, the concrete had a bulk density increased from 1515 kg/m3 to 1584 kg/m3 when 20% of calcined shells were added. A selected specified ratio of calcined GAS shells having been stabilised by a set of OMCs were also used for CBR testing to assess the change in swelling and CBR parameters with variation of shell ratio. The results show that increasing the specified stabilizer caused the soil swelling to increase from 2. 90% to 5.21%, discovered that the CBR 900RR enhanced high-speed stability by 21% and boosted CBR values by 4%[10].

2) *Studies on Soil-Cement Mixture:*

Failure Behavior of Cement-Treated Soil Under Triaxial Tension Conditions

The present results of tension tests on the cement treated soil were found to exhibit definite such as stress strain paths which were governed by effective confining pressures. Except for one sample that exclusively showed tensile failure, axial strain at peak stress increased with pressure, demonstrating a variety of failure modes: shear at high pressures and tensile at low pressures. A proposed failure criterion effectively described stress states at the boundary between these modes. The study suggests a uniform stress-strain relationship for shear behavior, independent of loading conditions, impacting constitutive models[11].

Strength of Soil-Cement Mixture

William Herbert Wilson, Jr. discusses various testing techniques and their impact on soil-cement strength in his thesis titled "Strength Assessment of Soil Cement." There was little variation among bag-cured specimens and moist-cured ones, but fan-cured and air-cured samples displayed greater strengths. The specimens that were cured in a bag and those that were cured in a damp environment did not significantly differ in terms of compressive strength. Neoprene pads were deemed inappropriate for covering soil-cement cylinders. The specimen mold setup complied with ASTM C 1633 standards, indicating that testing can be done without capping if perpendicularity and planeness tolerances are an issue, in which case gypsum capping compound is advised. The research found that ASTM C 39 L/D correction factors are not suitable for soil-cement cylinders made and tested with ASTM D 1632 and ASTM D 1633. It suggests avoiding strength correction factors for length-to-diameter ratios of 1.0 to 2.0[12].

Permeability of Soil-Cement Mixture

The research on soil-cement mixtures' permeability evaluated 16 samples with varying mix proportions, using laboratory-made N2 and K2, along with field-collected R1-R9. The coefficient generally fell within 10^{-5} cm/s, with minimal impact from changes in confining and seepage pressures. Soil-cement mixtures showed resilience against high seepage gradients without physical failure. Hollow cylinder seepage tests (SOV tests) explored shear stress impact on permeability. Results showed permeability increased with axial strain under low confining pressure (SOV00403), while under high confining pressure (SOV00803), it remained stable or slightly decreased due to stress state and volumetric strain transitions[13].

Mechanical Properties of Cement-Treated Soil Mixed with Cellulose Nanofiber

The study investigated the utilization of cellulose nanofibers (CNF) in soft ground cement treatment, with particular attention on mixing techniques, differences in strength, and alterations in permeability. Dry state mixing, either of soil or additives (cement, CNF), aimed to reduce water content in treated soil, with dry powder or concentrated gel mixing considered practical for on-site applications. CNF's properties, including water absorption and thickening, facilitated even cement distribution despite reducing flowability during mixing. CNF increased initial strength but reduced long-term development, potentially advantageous for cement treatment. Shortening mixing times with CNF improved strength uniformity and reduced variations. CNF addition also increased flexural strength, addressing shortcomings in cement-treated soil. While CNF caused slight changes in permeability, the impact was minimal. The study highlights CNF's potential benefits but acknowledges challenges such as limited production and high costs, emphasizing the need for further testing and understanding of chemical mechanisms for reliable incorporation in practical applications[14].

3) *Studies on Volcanic Ash-Cement Mixture:*

Engineering Properties of Volcanic Ash-Cement Soil Mixtures and Zeolite-Cement Soil Mixtures

This research explores the soil mixtures' engineering characteristics with volcanic ash and cement, along with zeolite and cement. Tests are performed such as freezing-thawing, unconfined compression, and SEM and XRD analysis. To make the preparation, samples with porous zeolite or volcanic ash from Mount Baekdusan are combined with various cement ratios, either with or without metakaolin. Findings indicate that the compressive strength reduces with higher levels of zeolite or volcanic ash, but increases with the addition of metakaolin. The blends show adequate durability against freezing and thawing cycles. SEM and XRD examinations demonstrate the existence of ettringite, a byproduct of cement hydration that is believed to enhance the strength of the mixture[15].

Volcanic Ash as a Substitute for Cement to Flexure Strength of Geopolymer Concrete

Concrete is a popular construction material for a variety of infrastructures, and its demand is predicted to rise in response to the growing demand for basic amenities. However, typical cement production contributes significantly to CO2 emissions, causing environmental challenges such as global warming. In order to address this, different cements that act as substitutions for ordinary cement are being studied, and one such solution identified is the geopolymer concrete. Geopolymer concrete, which lacks conventional cement, employs elements such as sinabung ash as a binding agent. Flexural strength is determined by testing samples that have been cured at 60°C for 4, 8, 12, and 24 hours. Flexural strength increases steadily with cure time, peaking at 24 hours. This work assesses an endeavour to show that geopolymer concrete could be the answer in producing environmentally friendly concrete compared to standard approaches[16].

Volcanic Ash and Portland Cement Blend for Property Enhancement of Concrete

The purpose of this study is to determine the extent to which Lege-Dadi Volcanic Ash can substitute for cement problems in concrete production in order to eliminate sustainability difficulties. Initial tests revealed that the ash meets ASTM C618-00 specifications. Different concrete samples were created with varying percentages of ash (0%, 5%, 10%, 15%, and 20% by weight) in a specific mix ratio. Tests examined compression strength, wear resistance, water absorption, and acid resistance. Compressive tests showed lower initial strength but strength increased with longer curing times. The ideal substitution threshold was determined at 15% ash content, exhibiting a 21.3 MPa of compressive strength, just 4% lower than the standard level. The higher the ash percentage, the lower the permeability, but there was no significant impact on abrasion resistance. The acid attack affected both control and ash-containing concrete, but ash samples showed reduced mass loss after 28 days. These findings highlight Lege-Dadi Volcanic Ash's potential as a sustainable and effective replacement material in concrete production[17].

4) Studies on the Use of Volcanic Ash in Concrete:

Strength Performance of Concrete Produced with Volcanic Ash

The research examines the use of volcanic ash instead of cement in making concrete to address environmental issues. Experiments were conducted with various proportions of volcanic ash in concrete mixtures to evaluate compressive strength, split tensile strength, flexural strength, and workability. Results indicate volcanic ash acts as a good pozzolan with a combination of SiO_2, Al_2O_3, and Fe_2O_3 content of 74.8%. Concrete with 10% volcanic ash replacement demonstrated the highest compressive strength, surpassing plain concrete, while 5% replacement yielded comparable results. Similar trends were observed in split tensile and flexural strength tests, suggesting volcanic ash's efficacy in enhancing concrete strength. The study recommends a partial replacement for cement into volcanic ash, particularly in aggressive environments, with an optimal replacement level of 10%. It also suggests considering up to 15% replacement due to promising results[18].

Durability and Microstructure Analysis of Concrete Made with Volcanic Ash

Concrete is widely used in construction, but its durability faces challenges due to factors like chloride penetration and sulfate exposure. Studies on volcanic ash (VA) concrete show promise in addressing these issues. However, scattered information makes it hard to assess its benefits. This article (Part III) reviews VA concrete's physical and chemical aspects, emphasizing its impact on durability and microstructure. Results show VA enhances durability through pozzolanic reactions and micro-filling of voids. A cost–benefit analysis suggests a 30% cost reduction with 10% VA utilization. Yet, research gaps need addressing before widespread VA concrete application[19].

Effect of Volcanic Ash on the Properties of Concrete

The study examined volcanic ash's impact on concrete properties by conducting initial tests on various materials. Concrete samples were made using different quantities (0%, 5%, 10%, and 15%) of volcanic ash substitutes in a 1:2:4 mix with a water-to-cement ratio of 0.5. Workability tests were conducted, followed by casting 405 samples using cube and cylinder molds. Compressive strength tests were performed on 162 cubes, while tensile strength was determined using the split tensile method on 162 cylinders. Samples were cured and tested at intervals of 7, 14, 21, 28, 56, and 90 days. Results showed that Miango volcanic ash met setting time and soundness requirements. After 28 days, concrete samples with 10% volcanic ash replacement showed an improvement of about 7.99% in compressive strength and 6.14% in split tensile strength. The study concluded that Miango volcanic ash delays concrete setting time while enhancing its properties, recommending its use as an admixture for robust and dense concrete[20].

Micro-Structural Study of Concrete with Indigenous Volcanic Ash

In Pakistan, promoting green concrete production using waste materials is crucial. Incorporating concrete and Volcanic Ash (VA) can lead to sustainable structures with reduced CO2 emissions, benefiting the environment. Strength tests were performed on VA concrete at different levels (0%, 10%, and 20%) with a consistent water-to-cement (W/C) ratio. The findings show that adding 10% VA significantly enhances the overall strength of the matrix, as proven by scanning electron microscopy. This demonstrates VA's capabilities as a sustainable and environmentally benign component in concrete construction, promoting eco-conscious building practices in Pakistan[21].

Strength Characteristics of Laterized Concrete using Lime-Volcanic Ash Cement

The study employed various combinations of volcanic ash (VA) and calcium oxide (CaO) at ratios of 90%:10% and 80%:20% to increase the volcanic ash concrete and investigate the impact of the calcium oxide.

Sixty 150 mm cubes were made with varying quantities of laterite (ranging from 0% to 20%) replacing sand in the specimens. The control group aimed to achieve a 28-day strength of 25 N/mm² by using ordinary Portland cement (OPC) in the concrete mixture. The cubes were tested for compressive strength and water curing at 7, 14, 21, and 28 days. The strength of the volcanic ash-lateralized concrete was found to rise with extended hydration durations, and the strength qualities were further enhanced by calcium oxide. Particularly, the 20%lat/20%CaO: 80%VA sample had a higher compressive strength at various hydration days compared to the 10%lat/10%CaO: 90%V.A sample; at 28 days, reached 22.07N/mm² (81.74%) as opposed to 21.53N/mm² (79.74%). After 28 days, the control mix's strength was 27.0N/mm² (100%). According to the study, lateralized concrete containing volcanic ash-lime cement shows promising pozzolanic activity, making it appropriate for a variety of construction projects, such as the construction of buildings and rural infrastructure[22].

Compressive Strength of Volcanic Ash or Ordinary Portland Cement Laterized Concrete

This review examined howlaterized compressive strength of concrete altered when volcanic ash (VA) was used in partially replacing cement. With 0% to 30% laterite replacement for sand and VA replacement for cement, 192 cubes, each measuring 150 mm, were cast and water-cured for 7, 14, 21, and 28 days. A control mixture with a goal of 25 N/mm² for 28 days was used. The findings indicate that concrete's density and compressive strength decrease with increasing VA concentration. During the 0-30% VA variation without laterite, the density decreased from 2390 kg/m³ to 2285 kg/m³ (loss of 4.4%) and the compressive strength dropped from 25.08 N/mm² to 17.98 N/mm² (loss of 28%) after. While laterized concrete strength increased with curing age, compressive strength decreased as laterite content increased[23].

5) *Studies on Volcanic Ash and Soils:*

Volcanic Ash on Improving Hydro-Physical Properties of Vertisol

The goal of the investigation is to enhance particular hydro-physical and physical characteristics of vertisols in the southern region of Sweda Governorate, Syria. Soil samples from Al-Thahallah village underwent experiments with varying quantities of volcanic ash (1.25%, 2.5%, and 5%) alongside a control treatment, cultivating Sham variety wheat as a cover crop in plastic pots during the 2018 or 2019 agricultural season. Results showed significant improvements in infiltration rate (328.60%) with 5% volcanic ash, increasing from 0.42 cm/hr to 1.80 cm/hr. Additionally, air porosity and volume of infiltrated water rose by 89% and 40%, respectively, compared to the control. In comparison to the control, ash addition also decreased dry bulk density, total soil porosity, and volumetric swelling coefficient by 18.60%, 5.80%, and 314%, respectively. Furthermore, it lowered the weighted moisture content at saturation and field capacity significantly. The study recommends incorporating 5% volcanic ash into the soil and further exploring enhancements using volcanic ash and organic waste at different levels[24].

Compressive Strength of Sandy Soils Stabilized with Alkali-Activated Volcanic Ash and Slag

Alkali activator solutions were utilized at various absorptions (4, 8, and 12 M) and alkali-to-binder ratios (1, 1.5, 2, and 3). The specimens were cured for 1, 7, and 28 days at room temperature and in an oven before being assessed for unconfined compressive strength (UCS). Predictive approaches, such as artificial neural network (ANN) and evolutionary polynomial regression (EPR) modeling, were used to simulate the unconfined compressive strength of geopolymerized sand samples. The ANN model with architecture 8-5-10-1 performed well, with a 97% coefficient of determination, an RMS error of 0.0439, and an MAE of 0.0336. Three-dimensional parametric experiments were carried out to evaluate how changes in the alkali solution, binder, and curing conditions affect UCS values simultaneously. Sensitivity analysis found that VA concentration had the least effect on compressive strength, but the Si/Al ratio had the highest impact[25].

Clayey Soil Stabilization Using Alkali-Activated Volcanic Ash and Slag

This study investigates the feasibility of employing alkali-activated GGBS (Ground Granulated Blast Furnace Slag) and VA as eco-friendly soil stabilizing binders to reduce carbon emissions associated with conventional cement use. The main findings show that different Liquid-to-Solid (L/S) ratios had varying effects on sample strengths depending on curing conditions, with higher ratios reducing strength under Organic Carbon (OC) conditions but increasing strength under Ambient Conditions (AC), particularly with longer curing times. An appropriate blend of VA and GGBS was employed to form N-A-S-H and C-(A)-S-H gels, which strengthened the sample by filling holes in the material structure. GGBS increased sample resistance to Wet-Dry (W-D) and Freeze-Thaw (F-T) cycles, meeting the strength requirements for cement-stabilized base and subbase[26].

Volcanic Ash and Natural Lime Based Stabilized Clayey Soils

This study investigates how finely ground natural lime (NL), cement, and volcanic ash (VA) effect the stability of clayey soils, leading to the following findings:

1. Stabilized soils often have higher mechanical properties, such as tensile and compressive strength, California bearing ratio (CBR), and modulus of elasticity, as well as greater resistance to water and shrinkage.
2. The effectiveness of stabilization is influenced by elements like the soil type,

different stabilizer combinations, the age of the stabilized soils and the amount of stabilizer applied. Combinations with up to 20% VA are proven to be more efficient than mixtures containing VA together with cement or NL. Still, blends such as cement or NL with VA continue to exhibit satisfactory mechanical and durability properties.

3. Considering the widespread availability of VA, lime deposits, and clayey soils in various regions, VA- or NL-stabilized soils could offer economical alternatives to cement-stabilized soil, potentially reducing costs and environmental impact[27].

Volcanic Ash-Soil Mixtures Under One Dimensional Compression Testing

Research was conducted to explore the effectiveness of using Volcanic Ash (VA) in stabilizing clayey soils by conducting tests under different curing periods and moisture conditions. Key findings include:

1. Adding VA leads to an increase in void ratio and Optimum Moisture Content (OMC), due to the creation of space and bonds following the pozzolanic reaction, leading to greater water absorption. The best VA percentages for OMC conditions are 5% and 15% for uniaxial and one-dimensional compression tests, respectively. In saturated curing conditions, there is no specific percentage of VA that is considered optimal, suggesting that the existence of water helps in the formation of bonds.
2. The addition of VA greatly enhances soil stiffness parameters, especially when curing conditions are saturated. Longer curing times result in more significant enhancements, allowing for more bond fabrication through the pozzolanic reaction.
3. The effectiveness of VA is more pronounced for low-service loads, as higher stress levels lead to bond fragmentation, diminishing stiffness and resilience. VA stabilization is found suitable for pavement design but less effective for foundation-based improvement.
4. VA addition has a greater impact on decreasing the Recompression Index (Cr) compared to the Compression Index (Cc), with minimal effects on the Swelling Index (Cs). The impact of additional VA on consolidation parameters is negligible in the short term but becomes considerable over long-term periods[28].

Effective Utilization of Volcanic Ash for Soil Improvement

Ahmad Rifa'i, Noriyuki Yasufuku, and Kiyoshi Omine investigate the capacity of volcanic ash as a material for stabilizing soil in engineering projects, highlighting its good impact on the environment. They investigate its characterization, classification, and utilization, analyzing its impact on engineering properties, soil mixture characteristics, and mineral composition. Their research shows that incorporating volcanic ash into soft soil after 14 days of curing enhances different engineering properties, including decreasing liquid limit, adjusting the distribution of grain size, increasing bearing capacity, and reducing potential swelling. They suggest an ideal combination plan including 35% volcanic ash and 5% lime. Nevertheless, additional research is required to confirm these initial findings[29].

6) Engineering Applications and Challenges:

The construction industry, which is dealing with the challenges of urban population growth, is looking for sustainable alternatives to the environmentally damaging increase in cement production. Due to its unique chemical composition and amorphous structure, volcanic ash (VA) presents an accessible and cost-effective alternative to standard Portland cement clinker in cement manufacture. Newly-fabricated alkali-activated VA materials have high mechanical strength, low porosity and hardening, and can be applied in most building sectors[30]. An opportunity to save money on civil-engineering projects came in the form of a huge deposit of volcanic ash following the 1991 eruption of Mount Pinatubo in the Philippines. Previous research showed that the use of volcanic ash in the form of hot-rolled and asphalt concrete has given a good road surface performance. Addition of volcanic ash improves resistance to load associated deformations and has compatibility with the existing vegetation besides saving huge cost, more economical and better way of using wasteland for road construction of lower volume, particularly under difficult terrain conditions[31].

A 2015 Ethiopian research titled "Use of natural pozzolans (volcanic ash) to stabilize cinder gravel in road foundations" yielded some notable results. Natural pozzolans, such as volcanic ash and pumice, were successfully used with cinder gravel to make road foundations. Importantly, adding 20% volcanic ash or pumice to the cinder gravel increased its characteristics and resulted in the highest stabilization rate. Covering the volcanic ash or pumice with water caused the development of pozzolanic characteristics and a considerable rise in unconfined compressive strength over time. Although soaking lowered California Bearing Ratio (CBR) values, the lowest wet CBR was 98% after 4 days and the highest soaked CBR was 245% after 28 days for the optimal combination of 80% cinder gravel and 20% volcanic ash or pumice, respectively. These results emphasize the potential and efficacy of using volcanic ash or pumice for stabilizing cinder gravel in road base construction in Ethiopia, highlighting new prospects for infrastructure development[32].

A different research study looked into how volcanic ash (VA) influences concrete when used instead of cement in high-temperature conditions (25°C to 400°C). Concrete mixes containing 20% to 40% VA showed enhanced strength between 25°C to 200°C, attributed to tobermorite formation from the interaction of anhydrate VA particles and lime at higher temperatures. In contrast, control concrete with ordinary Portland cement experienced a 14% strength reduction without observable damage. Between 200-400°C, VA-incorporated concrete displayed a decline in strength (19% to 33%) but remained structurally intact with minor cracks. These findings highlight the potential benefits of VA at lower temperatures and underscore the need for further research to optimize its use in high-temperature applications[33]. Volcanic ash initially lowers concrete compression loads but enhances compressive strength after 28 days, surpassing standard concrete with 2% and 4% ash. At 6% and 8% ash, strength nearly matches standard concrete, suggesting ash can partially replace cement, boosting strength at specific ratios. Hence, volcanic ash shows promise as a viable cement substitute in concrete mixtures[34].

In the study focusing on the impact of volcanic ash deposition on paved surfaces' skid resistance—a crucial safety aspect, researchers evaluated road asphalt and airfield concrete surfaces in New Zealand. They examined various ash characteristics and pavement types, using the British pendulum test method. Thin ash deposits (~1 mm) reduced skid resistance on SMA surfaces. The study concludes with recommendations for maintaining road safety and effective cleaning measures in areas affected by volcanic ash[35].

This detailed study examines at the inherent pozzolanic properties of Mt. Mazama volcanic ash, specifically its possible use in construction materials. The study investigates the ash's compatibility with different conditions using a variety of testing methods, such as standard ASTM procedures, modified strength activity index testing, cylinder slurry tests, and dynamic chemical analysis. The findings show that, while volcanic ash is chemically similar to fly ash, it must be crushed and processed before being used as a natural pozzolan constituent in Portland cement concrete. Notably, the study shows that when Mt. Mazama volcanic ash is combined with Portland cement or lime, compressive strength in mortar cubes can increase, providing insight into alternative construction techniques. Additionally, the study evaluates the environmental sustainability of using Mount Mazama volcanic ash, which reduces carbon emissions and energy storage when replacing Portland cement in construction applications, highlighting its potential as a green solution[36].

Mount Merapi, a highly active volcano, erupts every two to five years, emitting volcanic ash that poses environmental challenges when not managed properly. In Indonesia, where extensive road networks are built on soft soil, volcanic ash emerges as a promising option for soil enhancement. Research examines volcanic ash's effects as a substitute material for soil stabilization, with a focus on environmental implications. Various engineering properties are analyzed, highlighting the importance of volcanic ash fineness. Optimal soil improvement is achieved with a mixture containing 35% volcanic ash and 9% lime, offering engineering benefits and environmental advantages for soft soil enhancement[37].

The main obstacle in utilizing volcanic ashes for engineering applications lies in their variability in mineralogy and chemical composition across different deposits, requiring comprehensive assessments for suitability. Interestingly, this variability also presents a range of potential applications. Volcanic ashes, alongside pyroclastic materials such as pumice and scoria, have demonstrated suitability for use in cement, concrete, civil engineering, and various other fields. Despite their potential, several deposits of volcanic ashes remain underutilized. Common pyroclastic materials like pumice and scoria find applications in civil engineering, geopolymer synthesis, insulation, ceramics, refractory materials, as well as absorbents and filters. These materials offer environmentally friendly and cost-effective solutions, showcasing the enduring importance and potential of volcanic ashes as a valuable resource for diverse developmental opportunities[38].

C. Background of the Study

In 1991, the massive eruption of Mount Pinatubo stood as one of the most impactful volcanic events in recent history. Following the eruption, extensive layers of volcanic material blanketed Central Luzon, notably impacting Pampanga, Tarlac, and Zambales. These deposits extended up to 30 kilometers from the volcano and measured depths of 40 centimeters.

The eruption had significant effects on agriculture in these areas, leading to the collection and analysis of volcanic ash samples to assess its impact. Within a 30 km radius, such as in Pampanga, the ash primarily comprised medium to coarse sand, making up 90% to 95% of the composition, along with pumice fragments ranging from 0.5 cm to 3 cm.

Furthermore, the study examined the chemical characteristics of soil combined with volcanic ash. The soil's pH levels ranged from almost neutral to slightly alkaline. The volcanic ash was found to contain components such as hornblende, quartz, and mica. While these components are normally associated with low soil fertility, they showed improved fertility after weathering. Additionally, the ash's high salt level contributed to soil slaking.

While the findings are significant, further research is needed to completely understand the effects of volcanic ash on soil mechanics, including plasticity, compaction, and bearing capacity. As a result, the purpose of this study is to investigate how volcanic ash affects various soil qualities through AASHTO Standards laboratory testing. As a result, this study promises to provide useful data and insights, pushing the boundaries of knowledgein geotechnical engineering and providing practical advice on construction methods in volcanic zones.

D. Statement of the Problem

The Philippines has a unique natural environment that fosters volcanic eruptions and seismic activity. This is evident in the Municipality of Bacolor, where the eruption of Mount Pinatubo caused substantial changes in soil composition and topography due to the deposition of volcanic ash and lahar. While previous research focuses on changes in soil chemical properties following an eruption, there is still a lack of information about the impact of volcanic ash on soil bearing capacity, compaction, and plasticity, all of which are important elements in building and development. Given the Philippines' volcanic history, studying these effects is critical for understanding how volcanic ash affects fundamental soil engineering properties. The objective of this study is to answer the following questions:

1. Does the addition of volcanic ash affect the soil plasticity index?
2. How does adding volcanic ash affect soil's bearing capacity, and which ratios result in the greatest load-bearing capacity?
3. How does the addition of volcanic ash affect soil compaction properties, such as ideal moisture content and maximum dry density?

E. Objectives of the Study

General Objectives

To investigate and analyze the effect of incorporating volcanic ash on the plasticity, bearing capacity, and compaction of soil. This research also seeks to investigate in depth the effect of volcanic ash on soil stability and behavior, with the goal of assessing its suitability for use in construction and foundation design.

Specific Objectives

1. To procure soil samples, specifically from Bacolor, Pampanga, with the primary objective of examining the inherent plasticity, compaction, and bearing capacity characteristics of the soil in its natural state.
2. To undertake laboratory investigations, notably the Atterberg Limit Test, California Bearing Ratio (CBR), and Standard Proctor Test utilizing soil specimens admixed with varying proportions of volcanic ash (10%, 15%, 20%, and 25%). The proportioning will be determined by the maximum weight that the sample size is capable of carrying.
3. To conduct a statistical analysis on the soil properties and emphasize a positive trend in the changes through descriptive analysis.

II. METHODOLOGY

The research study was conducted in three phases: Phase 1 - Development of Ideas and Preliminary Preparations, Phase 2 – Data Collection, and Phase 3 – Data Analysis and Interpretation.

A. Phase 1: Development of Ideas and Preliminary Preparations

1) Stage 1: Literature Review

During Stage 1, the focus was on gathering existing research and information from various sources related to the materials under study. This included examining how soil interacts with different materials (Soil-Material Mixtures), the effects of volcanic ash combined with various materials (Volcanic Ash-Material Mixtures), and understanding the behavior of concrete when infused with volcanic ash (Volcanic Ash-Infused Concrete). Additionally, studies specifically exploring mixtures of volcanic ash and soil (Volcanic Ash-Soil Mixtures) were crucial. This comprehensive literature review provided a solid foundation of knowledge to guide following stages of the study.

2) Stage 2: Identification of properties to be analyzed and experiments to be conducted

This stage focuses on identifying and analyzing three key properties of the soil-volcanic ash mixtures: plasticity, compaction, and soil bearing capacity. Plasticity, which indicates the mixture's ability to deform without breaking, will be measured using the Atterberg Limit Test. Compaction, reflecting the mixture's density and stability, will be assessed through the Standard Proctor Test. Finally, soil bearing capacity, which determines the mixture's ability to support loads, will be evaluated using the California Bearing Ratio (CBR) Test. These experiments will provide essential data on the performance and suitability of different soil-volcanic ash mixtures for construction and engineering applications.

3) Stage 3: Search the location of the material to be used and the laboratories that accommodates the experiments

The goal is to identify where to obtain the necessary volcanic ash and soil, as well as finding suitable laboratories that can conduct the required tests (Atterberg Limit, Standard Proctor, and California Bearing Ratio). This involves researching regions known for volcanic activity to source volcanic ash and identifying local or nearby areas with suitable soil. At the same time, it's crucial to seek out laboratories that have the appropriate facilities and expertise to conduct these particular geotechnical tests. The volcanic ash was intended to come from Mt. Pinatubo because of its importance to Bacolor, as suggested by a geologist from PHILVOLCS. The soil was to be sourced from Bacolor, and the experiments were to be conducted at the Department of Public Works and Highways Regional Office III.

4) Stage 4: Acquisition of the volcanic ash and soil

The volcanic ash was originally intended to be sourced from Mt. Pinatubo with assistance from the Local Government Unit of Botolan, Zambales. However, due to slow progress and the uncertainty of obtaining a sufficient quantity of volcanic ash, the researchers decided to consider alternatives. Fortunately, they established contact with a geologist from the Mines and Geosciences Bureau Regional Office III. With the geologist's help, they acquired an initial sample of volcanic ash from an outcrop in a quarry in Porac, Pampanga. This material was submitted to the Mines and Geosciences Bureau Central Office in Quezon City for verification. While awaiting the results of the sedimentological analysis, they sieved the remaining material through a 0.075mm (No. 200) sieve to obtain fine particles identified as volcanic ash by both the researchers and the geologist. However, after sieving 90kg of material, only 2kg of volcanic ash was obtained. Thankfully, the geologist recalled tuff, a rock composed of 90-95% volcanic ash. With her assistance, tuff was sourced from the base of Mt. Arayat. This tuff underwent megascopic analysis for verification. While waiting for results, the researchers ground the tuff using a mortar and pestle. The sedimentological analysis indicated that the ash-sized sediments were unidentifiable, but the megascopic analysis confirmed that the rocks were composed of volcanic ash.

Initially, soil was acquired from an extension lot of Don Honorio Ventura State University and stored beside the CE Lab. However, due to the 2024 Southeast Asia heat wave, the university shifted to online classes, prohibiting students from entering the campus. This prevented the researchers from accessing the soil for experiments. Consequently, they collected soil from a nearby location just outside the campus.

5) Stage 5: Preparation of the samples with varying proportions of volcanic ash

The researchers created a range of soil samples by blending volcanic ash with soil in different ratios. This process required precise measurement and mixing of volcanic ash with soil at specific percentages—10%, 15%, 20%, and 25%—according to the weight specifications for the tests. Each blend was meticulously mixed to guarantee consistent dispersion of volcanic ash within the soil. These prepared samples will be used in following experiments to examine how different levels of volcanic ash affect soil properties such as plasticity, compaction, and bearing capacity.

B. Phase 2: Data Collection

6) Stage 6: Gathering of data by conducting Atterberg Limit Test, Standard Proctor Test, and California Bearing Ratio Test

The researchers collected data on the properties of the volcanic ash-soil mixtures through three primary tests. The Atterberg Limit Test was used to evaluate the plasticity of the mixtures, assessing their flexibility and consistency limits. The Standard Proctor Test measured the compaction characteristics, determining the maximum density and optimal moisture content for the mixtures. Lastly, the California Bearing Ratio (CBR) Test assessed the load-bearing capacity, indicating the mixtures' ability to support weight effectively. These tests provided significant insights into how varying proportions of volcanic ash affect the overall performance and suitability of the soil mixtures for different applications.

C. Phase 3: Data Analysis and Interpretation

7) Stage 7: Analysis of the soil property data

In this stage, the researchers focused on analyzing the data collected from the Atterberg Limit Test, Standard Proctor Test, and California Bearing Ratio (CBR) Test. They carefully examined and interpreted the results to understand the specific properties demonstrated by each soil-volcanic ash mixture. This included identifying patterns, relationships, and differences in plasticity, compaction, and bearing capacity across different mixture ratios. With the assistance of professionals, they interpreted the results and considered how these findings would translate into the performance of the volcanic ash-soil mixture in real-life applications. These insights informed decisions regarding the selection and optimization of the most effective mixture ratio for practical use in the next stages of the research.

8) Stage 8: Evaluation and comparison of results

In Stage 8, Evaluation and Comparison of Results, the data gathered from the Atterberg Limit Test, Standard Proctor Test, and California Bearing Ratio (CBR) Test was comprehensively analyzed to evaluate the performance of each volcanic ash-soil mixture. This process involved comparing the plasticity, compaction, and bearing capacity of each sample to identify the mixture that demonstrated the most desirable properties for practical applications. Each mixture's performance was evaluated against established standards to enable a clear comparison and to identify the ratio that achieved the best balance of plasticity, stability, and load-bearing capacity.

9) Stage 9: Selection of the ratio that yield the optimum performance in accordance to the standards set by each experiment

Following tests assessing plasticity, compaction, and soil bearing capacity, attention turns to selecting the mixture ratio that demonstrates superior performance according to standards set by each experiment. This process involves analyzing data from the tests and comparing outcomes with established standards or industry norms. By pinpointing the ratio that meets or surpasses these standards across all critical properties, researchers can confidently choose the optimal composition. This ensures that the integration of volcanic ash maximizes benefits, guaranteeing the material meets desired performance criteria for potential applications like construction or soil stabilization projects.

III. RESULTS AND DISCUSSION

A. Presentation and Interpretation of the Atterberg Limit Test

TABLE 1:
LIQUID AND PLASTIC LIMIT OF THE NATURAL SOIL

	LIQUID LIMIT				**PLASTIC LIMIT**	
Determination number	**1**	**2**	**3**	**4**	**1**	**2**
Container number	Cannot be determined				Non-Plastic	
Container + wet soil						
Container + dry soil						
Moisture						
Container						
Dry soil						
Moisture content						
Number of blows						

SIEVE SIZE	**% PASSING**
4.75	94
2.00	88
0.425	51
0.075	13
Liquid Limit	-
Plastic Limit	-
Plasticity Index	Non-Plastic
Group Index	0
Soil Classification	A-2-4 (0)
Soil Designation	Silty Gravel and Sand

Based on the results, the soil sample was classified as non-plastic since it could not be molded or rolled when moistened. The Liquid Limit (LL) and Plastic Limit (PL) were indeterminable; hence the Plasticity Index was classified as non-plastic. As a result, the sample's Group Index was found to be 0, as LL and PL could not be calculated. Based on the AASHTO Classification System, this soil was classed as A-2-4, specifically as Silty Gravel and Sand.

TABLE 2
Liquid and Plastic Limit of the Natural Soil with 10% of Volcanic Ash

	LIQUID LIMIT				**PLASTIC LIMIT**	
Determination number	**1**	**2**	**3**	**4**	**1**	**2**
Container number	Cannot be determined				Non-Plastic	
Container + wet soil						
Container + dry soil						
Moisture						
Container						
Dry soil						
Moisture content						
Number of blows						

SIEVE SIZE	% PASSING
4.75	96
2.00	90
0.425	54
0.075	14
Liquid Limit	-
Plastic Limit	-
Plasticity Index	Non-Plastic
Group Index	0
Soil Classification	A-2-4 (0)
Soil Designation	Silty Gravel and Sand

Testing showed that the soil sample was non-plastic, which means it could not be shaped or molded while wet. The Plasticity Index was classified as non-plastic due to an inability to determine the Liquid Limit (LL) and Plastic Limit (PL). As a result, because LL and PL could not be calculated, the sample's Group Index was set to 0. The AASHTO Classification System classified this soil as A-2-4, with a focus on Silty Gravel and Sand.

TABLE 3
Liquid and Plastic Limit of the Natural Soil with 15% of Volcanic Ash

	LIQUID LIMIT				PLASTIC LIMIT	
Determination number	**1**	**2**	**3**	**4**	**1**	**2**
Container number	Cannot be determined				Non-Plastic	
Container + wet soil						
Container + dry soil						
Moisture						
Container						
Dry soil						
Moisture content						
Number of blows						

SIEVE SIZE	% PASSING
4.75	94
2.00	88
0.425	55
0.075	18
Liquid Limit	-
Plastic Limit	-
Plasticity Index	Non-Plastic
Group Index	0
Soil Classification	A-2-4 (0)
Soil Designation	Silty Gravel and Sand

According to the findings, the soil sample is non-plastic since it cannot be molded or formed while moist. The Plasticity Index was designated as non-plastic due to the inability to determine the Liquid Limit (LL) and Plastic Limit (PL). As a result, the sample's Group Index was set to a value of 0, as LL and PL could not be computed. This soil was classed as A-2-4 in the AASHTO Classification System, which is more specifically defined as Silty Gravel and Sand.

TABLE 4
Liquid and Plastic Limit of the Natural Soil with 20% of Volcanic Ash

	LIQUID LIMIT				PLASTIC LIMIT	
Determination number	**1**	**2**	**3**	**4**	**1**	**2**
Container number	Cannot be determined				Non-Plastic	
Container + wet soil						
Container + dry soil						
Moisture						
Container						
Dry soil						
Moisture content						
Number of blows						

SIEVE SIZE	% PASSING
4.75	95
2.00	90
0.425	56
0.075	17
Liquid Limit	-
Plastic Limit	-
Plasticity Index	Non-Plastic
Group Index	0
Soil Classification	A-2-4 (0)
Soil Designation	Silty Gravel and Sand

The soil sample had been identified as non-plastic since it could not be molded or rolled after becoming moist. The Plasticity Index was classified as non-plastic due to an inability to identify the Liquid Limit (LL) and Plastic Limit (PL). As a result, the sample's Group Index was set to 0 since LL and PL could not be calculated. This soil was classified as A-2-4 in the AASHTO Classification System and defined as silty gravel and sand.

TABLE 5
Liquid and Plastic Limit of the Natural Soil with 25% of Volcanic Ash

	LIQUID LIMIT				PLASTIC LIMIT	
Determination number	**1**	**2**	**3**	**4**	**1**	**2**
Container number	Cannot be determined				Non-Plastic	
Container + wet soil						
Container + dry soil						
Moisture						
Container						
Dry soil						
Moisture content						
Number of blows						

SIEVE SIZE	% PASSING
4.75	94
2.00	88
0.425	50
0.075	14
Liquid Limit	-
Plastic Limit	-
Plasticity Index	Non-Plastic
Group Index	0
Soil Classification	A-1-b (0)
Soil Designation	Stone Fragment Gravel and Sand

According to the results, the soil sample is non-plastic since it cannot be molded or formed while moist. The Plasticity Index was designated as non-plastic due to the inability to determine the Liquid Limit (LL) and Plastic Limit (PL). Given the uncertainty regarding LL and PL, the sample's Group Index was set to 0. According to the AASHTO Classification System, this soil was classified as A-1-b, namely Stone Fragment Gravel and Sand.

B. *Presentation and Interpretation of the Standard Proctor Test*

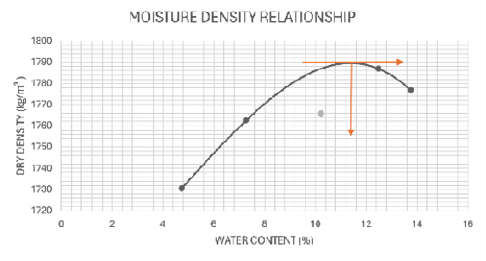

Fig. 1 The Moisture-Density Relationship of the Natural Soil

Fig. 1 begins with an initial increase in density, starting at a water content of around 4.74% and a corresponding dry density of approximately 1730.62 kg/m³. As the water content increases, so does the dry density. The highest point on the curve is reached at a water content of 11.50%, where the dry density peaks at 1790 kg/m³. At this point, the balance between water as a lubricant and water filling void spaces is optimal, achieving the greatest density. However, as the water content continues to increase beyond 11.50% to values like 12.48% and 13.75%, the dry density begins to decline, as evidenced by the points at 1786.94 kg/m³ and 1776.77 kg/m³, respectively. This decline suggests that additional water begins to affect soil compaction adversely. The excessive water fills up the voids between soil particles, increasing the volume but reducing the particle-to-particle contact necessary for high density, resulting in a less compact and potentially less stable soil structure.

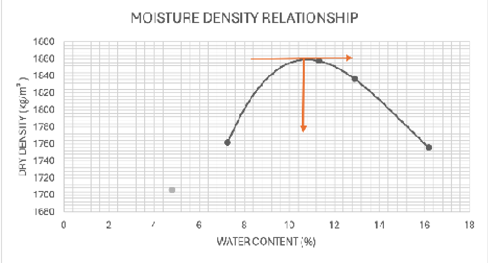

Fig. 2 The Moisture-Density Relationship of the Natural Soil with 10% of Volcanic Ash

The initial point on the graph in Fig. 2 starts at a water content of 2.73%, where the dry density is relatively low at 1711.44 kg/m³, suggesting limited moisture availability for effective compaction. As the water content increases to 4.8% and further to 7.27%, the dry density correspondingly rises to 1705.9 kg/m³ and 1761.66 kg/m³. Then, the graph reaches its peak at a water content of 10.25%, where the dry density hits a maximum of 1865 kg/m³. At this point, the moisture content is ideally balanced to maximize particle packing while minimizing pore spaces, facilitating optimal soil compaction. The density remains high at 1857.71 kg/m³, even slightly past the OMC, at a water content of 11.32%, showing that the soil maintains near-optimal compaction. However, as the moisture content continues to rise to 12.9% and 16.19%, there is a noticeable decrease in dry density to 1836.5 kg/m³ and 1755.84 kg/m³, respectively.

Overall, the initial slope leading up to the OMC is steep, indicating that the soil responds well to increases in moisture, enhancing its compaction efficiency. Beyond the OMC, the slope declines gradually, reflecting a steady decrease in density as excess moisture impedes compaction.

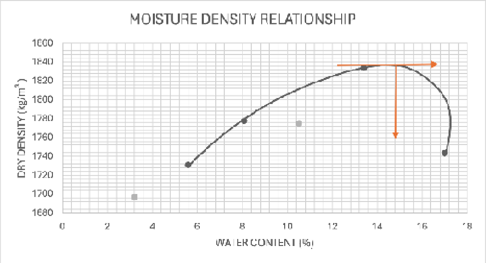

Fig. 3 The Moisture-Density Relationship of the Natural Soil with 15% of Volcanic Ash

At the starting point of the graph, the water content is 3.22%, with a corresponding dry density of 1696.93 kg/m³, suggesting that the soil has limited moisture available to facilitate effective compaction. As the moisture content increases to 14.50%, identified as the OMC, the soil achieves its highest compaction effectiveness, indicated by a peak dry density of 1840 kg/m³. Beyond this point, any additional moisture results in decreased density.

The curve analysis reveals an initial slope that is progressive from the start point to the OMC. This portion of the curve shows a steady increase in dry density as moisture content increases, highlighting that the addition of moisture significantly enhances the soil's ability to compact. The climb is fairly consistent, suggesting better compaction efficiency with higher moisture levels. Once reaching the OMC, the curve starts to descend as the moisture content rises to 17%. The decline after the OMC is gentle, displaying a consistent decrease in density rather than a sudden plunge, suggesting that the soil's composition gradually becomes less compact as moisture surpasses the ideal amount.

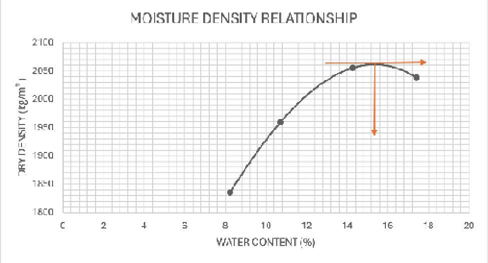

Fig. 4 The Moisture-Density Relationship of the Natural Soil with 20% of Volcanic Ash

Fig. 4 shows that when the water content is 8.22%, the dry density is 1834.97 kg/m³ in the moisture-density relationship, suggesting that there is not enough moisture for proper soil compaction. This starting situation implies that a lack of moisture may hinder soil particles from coming closer together when compacting. When the water content reaches 15.50% at the optimum moisture content (OMC), the soil attains its maximum level of compaction efficiency, resulting in a peak dry density of 2075 kg/m³.

Analyzing the curve, the initial slope progresses from the starting low moisture content up to the OMC. During this phase, the dry density steadily increases, highlighting that the addition of moisture significantly improves the soil's ability to compact. Despite that, after reaching the OMC, the curve slopes downwards as the moisture content increases from 15.50% to 17.41%. The corresponding density reduces from the peak of 2075 kg/m³ down to 2037.93 kg/m³.

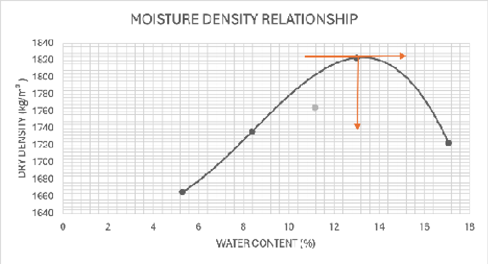

Fig. 5 The Moisture-Density Relationship of the Natural Soil with 25% of Volcanic Ash

For Fig. 5, the starting water content is 5.29%, and the dry density is 1665.41 kg/m³. As the moisture content increases to the OMC of 12.50%, the soil reaches its best compaction effectiveness, allowing a maximum density of 1830 kg/m³. Anyhow, as it reached the moisture content of 17.07%, there was a decrease in dry densities from the peak of 1830 kg/m³ down to 1722.78 kg/m³.

In conclusion, the curve analysis reveals that from the starting point to the OMC, there is a continuous increase in dry density. Meanwhile, post-OMC, the curve begins to slope downward as the moisture content continues to increase beyond the optimum.

C. Presentation and Interpretation of the California Bearing Ratio Test

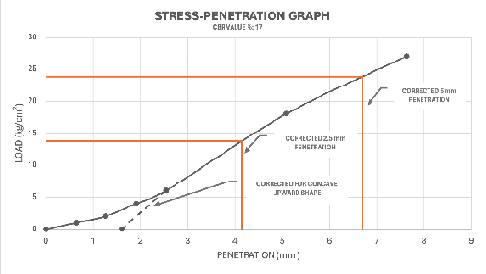

Fig. 6 The Stress-Penetration of the Natural Soil

Fog. 6 depicting the California Bearing Ratio (CBR) test begins at zero load and penetration, progressing swiftly to a corrected origin at 1.6 mm penetration. This initial correction accounts for surface irregularities or the seating of the piston, suggesting preliminary adjustments in the data. From this adjusted starting point, the load experienced by the soil increases nearly linearly with deeper penetration up to approximately 2.5 mm. This early behavior of the graph reflects the soil's initial resistance to penetration, indicative of its density and level of compaction.

Although the yield point in a CBR test is not as sharply defined as in other types of stress-strain tests, an inferred yield point can be observed around the 2.5 mm penetration mark, where the first correction occurs. This point marks a transition in soil behavior from primarily elastic to more plastic deformation, indicating a restructuring of soil particles under increasing pressure.

Post-peak, the graph illustrates a continued increase in load beyond the 5 mm penetration correction. However, this increase in load may occur at a decreasing rate relative to further penetration, suggesting that while the soil continues to exhibit resistance, the rate of compaction and density increase diminishes, possibly reaching the practical limits of compaction under the standard test load.

With the resultant CBR value of 17%, the soil demonstrates adequate performance under typical loading conditions and suggests that, when properly compacted, it can meet the demands of infrastructure projects requiring standard stability and durability. Within embankment construction, this performance level means the soil is likely to function well under normal conditions, although more demanding situations may necessitate additional reinforcement or stabilization techniques.

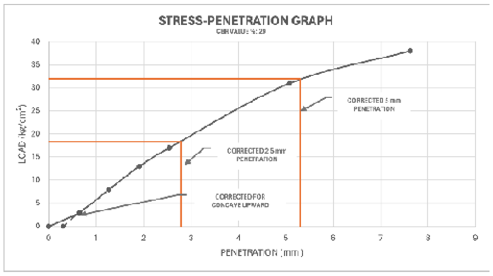

Fig. 7 The Stress-Penetration of the Natural Soil with 10% of Volcanic Ash

Starting from a corrected origin at 0.3 mm penetration, the curve from Fig. 7demonstrates a gradual yet consistent increase in unit load from 0 to 38 kg/cm² as the penetration deepens from 0 to 7.62 mm. This steady climb in load across increasing depths highlights the soil's commendable initial strength and compactness, suggesting a well-compacted material resistant to initial penetration.

Moreover, the graph does not exhibit a clear yield point; instead, it shows a continuous ascent without any significant change in slope. This absence of a distinct yield behavior within the tested load range implies that the soil structure does not exhibit typical elastic to plastic deformation under the given conditions. The peak load occurs at 38 kg/cm² with a penetration depth of 7.62 mm, marking the highest load the soil can tolerate before undergoing substantial deformation or structural failure.

Following this peak, the stress-penetration curve slightly dips, indicating a decrease in stress despite further penetration. This post-peak behavior suggests potential deformation or the beginning of failure within the soil structure under the maximal stress applied, revealing limits to its capacity for compaction and resistance.

A CBR Value of 29% underscores the soil's capability to support substantial loads, making it apt for various construction applications that demand high structural integrity without additional stabilization or enhancement.

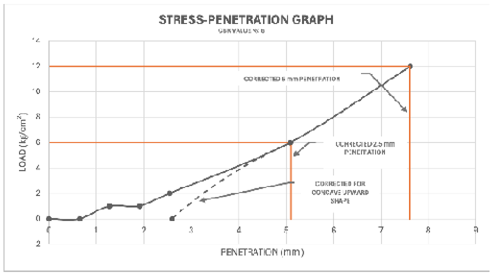

Fig. 8 The Stress-Penetration of the Natural Soil with 15% of Volcanic Ash

The CBR value recorded in Fig. 8 is 6%, with corrections made starting from a penetration depth of 2.6 mm.

The initial part of the graph, up to approximately 2.54 mm penetration, shows a relatively steady increase in unit load from 0 to 2 kg/cm². This segment is nearly linear, indicating consistent resistance from the compacted soil against the penetrating piston, suggesting uniform compaction and resistance.

The yield point, where the soil begins to transition from elastic to plastic deformation, appears to be around 2.54 mm penetration, corresponding to a load of 2 kg/cm². Behind this point, the soil structure begins to deform under the increasing load.

Although the graph does not distinctly show a traditional peak load as in a stress-strain curve, the highest load reached is 12 kg/cm² at a penetration of 7.62 mm. This continuous increase suggests the soil's ability to further compact under increasing pressure, typical in coarser or less cohesive soils.

After 7.62 mm penetration, the curve abruptly rises, indicating a significant increase in resistance, associated with the soil reaching a state of maximum densification where further penetration does not correspond to the typical load increase seen earlier.

With a CBR value of 6%, the soil has a lower bearing capacity, typical for non-cohesive materials like sandy or gravel soils. While it can support some loads, it may not be suitable for high-load applications without stabilization or improvement measures.

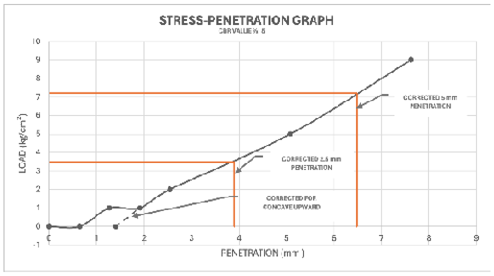

Fig. 9 The Stress-Penetration of the Natural Soil with 20% of Volcanic Ash

During the test's initial phase, Fig. 9shows a progressive increase in unit load from 0 kg/cm² at zero penetration to 2 kg/cm² at 2.54 mm penetration. This gradual rise demonstrates the soil's stable resistance to penetration, indicative of its compactness and structural integrity from the outset. Interestingly, the yield point, typically marked by a significant alteration in the curve's trajectory due to soil yielding under stress, is not distinctly apparent here. Instead, the continuous and steady increase in load without notable slope change suggests that the soil retains its structural cohesion, avoiding a clear shift from elastic to plastic deformation within the assessed range.

Reaching a peak load of 9 kg/cm² at 7.62 mm penetration, the graph delineates the maximum pressure the soil can withstand prior to significant deformation, marking a potential onset of decline in soil integrity under such load. Subsequent to this peak, the graph transitions into a linear progression, hinting at a potential failure or compression of the soil under sustained or increased loading conditions, a behavior typical of softer soil types.

Analyzing these results, the CBR value of 5% categorizes this soil at the lower spectrum of load-bearing capacity, indicating that while the soil is capable of bearing certain loads, it would likely necessitate stabilization or reinforcement for applications requiring greater structural demands, such as major roadway constructions or foundation setups for substantial structures.

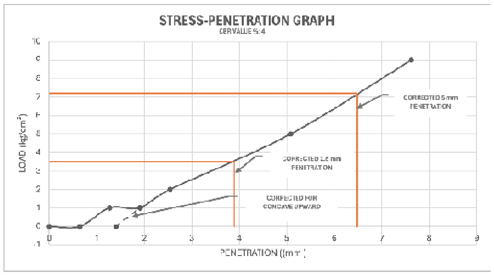

Fig. 10 The Stress-Penetration of the Natural Soil with 25% of Volcanic Ash

Fig. 10demonstrates a gradual increase in unit load with penetration depth, indicating the soil's initial resistance to penetration and suggesting some degree of initial strength and compactness. Meanwhile, no distinct yield point is observed in the graph, with the curve continuing to increase without a significant change in slope.

The peak load recorded during the test is 9 kg/cm² at a penetration of 7.62 mm, indicating the maximum load the soil can withstand before significant deformation or failure occurs. Following the peak load, the stress-penetration curve shows a slight decrease in stress with further penetration, possibly indicating some deformation or failure of the soil structure under the maximum applied load.

Additionally, the soil's CBR value of 4% suggests a limited bearing capacity, making it potentially unsuitable for high load-bearing applications without further stabilization or improvement efforts.

IV. CONCLUSIONAND RECOMMENDATIONS

Conclusion

The research examined at how volcanic ash affects the flexibility, density, and load-bearing capacity of soil in Bacolor, Pampanga, which had been extensively affected by the Mount Pinatubo eruption. By conducting comprehensive laboratory tests and detailed analyses, the researchers accomplished key findings that expanded the understanding of civil engineering and geotechnical sciences.

Although volcanic ash had little effect on the soil's plasticity index, it had a significant impact on compaction and carrying capacity. Engineers and geotechnical engineers had to review soil stabilization and construction methods due to the change in moisture content and dry density produced by volcanic ash.

All soil samples were non-plastic and therefore showed minimal plasticity, indicating that volcanic ash has no effect on the plasticity index. However, the addition of volcanic ash significantly altered the compaction properties, resulting in differences in the optimum moisture content and maximum dry density when compared to samples prepared from natural soil alone. In actual field applications, mixtures containing 10% volcanic ash provided the best compaction balance. Regarding soil bearing capacity, the soil bearing capacity changed depending on the amount of volcanic ash deposited, increasing at low percentages and decreasing at high percentages. The optimum ratio to achieve the highest load-bearing capacity was determined to be 10% volcanic ash.

The implications of the research extend beyond the laboratory, resonating with a diverse array of stakeholders, including civil engineers, geotechnical specialists, communities inhabiting volcanic regions, construction industry practitioners, disaster management authorities, environmental engineers, governmental entities, soil scientists, and prospective researchers. By elucidating the impact of volcanic ash on soil properties, this work serves as a cornerstone for informed decision-making, pioneering construction methodologies, disaster preparedness strategies, and sustainable development practices within volcanic zones. Furthermore, this thesis underscores the imperative for sustained exploration into the interactions between volcanic ash and soil, particularly in regions prone to volcanic activity, such as the Philippines. As the nation grapples with a history of significant volcanic events, comprehending the implications of volcanic ash on soil stability and behavior becomes increasingly crucial. By addressing this knowledge gap, our research contributes to enhancing resilience, safety, and sustainability in volcanic regions, thereby benefiting present and future generations.

In essence, this thesis serves as a catalyst for progress in civil engineering, geotechnical sciences, and disaster resilience. The researcher fervently hopes that the findings presented herein will inspire further research, inform policy decisions, and empower communities to navigate the challenges posed by volcanic activity with resilience and foresight.

Recommendations

1. **Further Research on Soil Variability:**Expand the study to encompass a wider range of soil profiles and sites throughout Pampanga in order to observe the diverse soil characteristics that exist in the area. Studying different types of soil will allow us to better understand how volcanic ash affects soil properties in different environments.
2. **On-Site Testing and Field Validation:**CBR field testing is carried out at construction sites to validate laboratory results and understand soil behavior under real-world conditions.
3. **Exploration of Additional Effects:**Expand research investigating the effects of volcanic ash on soil microbes, water uptake, soil composition, and interactions with plant species to gain a comprehensive understanding of those effects.
4. **Investment in Equipment and Resources:**To enable complete experiments and data collection, we fund the equipment and resources required to overcome financial constraints.
5. **Collaboration with Geological Agencies:**To facilitate the procurement of volcanic ash samples and gain access to essential resources and expertise, we will partner with geological agencies such as Mines and Geosciences Bureau (MGB).
6. **Optimization of Sampling Techniques:**Improve sampling techniques to ensure high quality volcanic ash samples for laboratory testing. Use efficient sieving and sample preparation techniques to improve the reliability and consistency of results.
7. **Long-Term Monitoring and Assessment:**To promote sustainable land management and infrastructure development, long-term monitoring programs should be established to measure the stability, compaction, and bearing capacity of volcanic ash-treated soils under a range of conditions.
8. **Community Engagement and Education:** Our educational initiatives for volcanic communities aim to raise awareness about the negative effects of volcanic ash on soils and ecosystems, while also advocating for proactive land management measures and disaster preparedness.
9. **Policy Advocacy and Guidelines Development:**Research findings will be integrated into policies and recommendations on land management, disaster risk reduction and infrastructure development in volcanic areas to support informed decision-making and resilience-building methodologies.
10. **Capacity Building and Training:**To enhance their understanding of soil science, geotechnical engineering, and disaster risk management, we provide workshops and trainings for engineers.

ACKNOWLEDGMENT

The researchers express their sincere gratitude to those who have made significant contributions to this research. The assistance provided has been crucial in completing this study.

First and foremost, the researchers extend heartfelt thanks to their thesis coordinator, Francis Cayanan, RCE, RMP, for sharing his extensive knowledge and experiences in writing thesis papers. His guidance ensured that the manuscript was formatted to the highest standard.

The researchers express their deepest gratitude to their thesis adviser, Carl Jason A. Coronel, RCE, MEnM. His constant guidance, help, and support throughout the duration of the thesis have been invaluable. His insights during the initial stages of the paper provided a clearer vision of the goals, and his willingness to assist was instrumental in the completion of this paper. A better thesis adviser could not have been chosen.

Special acknowledgement is due to Sir Ericson B. Bariso, the Science Research Specialist of the Geology & Geophysics Research and Development Division (GGRDD) of the Philippine Institute of Volcanology and Seismology (PHILVOLCS). His expertise in volcanology and geology provided essential answers to questions regarding volcanic ash. His knowledge about the distinction of volcanic ash compared to other pyroclastic materials, as well as the necessary contacts for acquiring volcanic ash, was immensely helpful.

The researchers extend their gratitude to the Local Government Unit of Botolan, Zambales, and the National Commission on Indigenous People (NCIP) Regional Office III for their willingness to assist during the initial stages of acquiring volcanic ash.

Appreciation is also extended to the CE Faculty Members who expressed their interest in the chosen topic. Their encouragement and belief in the significance of the topic to the community served as a source of motivation. The researchers believed in their thesis because of the support from these faculty members.

The researchers are grateful to the panelists who ensured that the content of the paper was accurate and polished: Engr. Mike Diether B. Galvez, Engr. Mildred M. Fabian, Engr. Raul O. Duya, and Engr. Joshua Renz Rosendo. Their questions allowed the researchers to defend the significance of the study, and their insights provided opportunities to enhance the paper. The time taken to evaluate the hard work is greatly appreciated.

Acknowledgment is extended to Ma’am Jocelyn C. Villanueva, the supervising geologist at the Mines and Geosciences Bureau Central Office in Quezon City. Her assistance in verifying the initial sample ensured that the correct material was used, thereby adding to the credibility of the thesis.

Gratitude is also expressed to the Department of Public Works and Highways Regional Office 3 for allowing the borrowing of tools and equipment to conduct experiments. Their support not only helped minimize the financial cost of the thesis but also provided valuable insights and assistance throughout the experiments, enhancing the ability to interpret the results and address the study's questions.

Lastly, the researchers express their deepest gratitude to Ma’am Ma. Lourdes Cruz, the supervising geologist of the Mines and Geosciences Bureau Regional Office III. Her full assistance in acquiring the volcanic ash was the most memorable part of this study. This thesis would not be complete without the volcanic ash, and her expertise in geology ensured that the material used was verified and appropriate for the study.

The researchers thank God for keeping everyone involved in this thesis safe throughout the study. The people who helped accomplish this study are blessings that will be treasured forever.

The researchers extend their thanks to their family and friends for unwavering support. Their continuous belief provided the strength needed throughout this journey.

To everyone who contributed to this effort, this achievement is dedicated to you.

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