MEHRDAD-NATEGH UTILIZATION OF END-OF-LIFE PV PANELS TO IMPROVE THE GEOTECHNICAL PROPERTIES OF THE CLAY SOIL Ph.D. THESIS YEAR 2024

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Declaration of Ethical Principles

I hereby declare that all information, documents, analysis and results in this thesis have been collected and presented according to the academic rules and ethical guidelines of Institute of Graduate Studies, Near East University. I also declare that as required by these rules and conduct, I have fully cited and referenced information and data that are not original to this study.

Mehrdad Nategh

Mehrdad Nategh

29/12/2024

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Abstract

Utilization of End-of-Life PV Panels to Improve the Geotechnıcal Properties of the Clay Soil

Nategh, Mehrdad
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12/2024, 128 pages

The problem of EoL photovoltaic (PV) panels is becoming more and more critical for many countries because of the growing quantities of EoL PV panels as waste. The presented research investigates the effectiveness of using one of the by-products of this waste material which is glass powder in combination with gypsum in geotechnical applications to enhance the mechanical properties of clay soil. The objective is to combine these materials for an environmentally friendly approach aimed at the management of EoL PV panels, which are often not explored in geotechnical engineering. In this study, composite samples are prepared by varying the amount of gypsum (0%, 5%, 10%, 15%) and glass powder (0%, 4%, 8 %, 12%) with respect to a fixed mass of soil. The compaction was carried out at dry densities of 1500 and 1700 kg/m^3 with curing periods of 7, 28, and 56 days. Several tests which included UPV, UCS, wet and dry cycle stopping tests, SEM, and XRD analysis, were carried out. The results show that while these properties are improved by the addition of gypsum, which was found to be the enhancement case always, they deteriorate with the introduction of glass powder to the soil until a certain threshold value at 12% is reached.

Formulations have been devised for estimating the q_u, G_0, and E, and can only be carried out by a single test. A correlation has also been generated that enables the prediction of both unconfined compressive strength and any elastic modulus of a specimen without the use of invasive. Furthermore, microstructure studies show other phenomena such as the progress of pozzolanic reactions, the presence of silicon-bearing compounds from glass powder, and the activity of additives, which modify the structure of the soil. It was revealed that soil strength was significantly improved by the addition of sintered gypsum, especially in denser samples, due to a steady increase of UCS. The addition of glass powder on the other hand had a varying effect on the UCS. The trends in stiffness followed UCS trends but very high sintered gypsum and

12% glass powder in samples also gave the peak stiffness. The durability tests showed that in comparison to other specimens, specimens with high volume of glass powder suffered greater mass loss and sintered gypsum reduced that effect. The Life Cycle Assessment (LCA) results showed that normalizing the environmental impacts to the mechanical properties of the samples reduced the environmental impacts relatively to the denser samples which had higher additive percentages.

Key Words: glass powder, sustainable management, waste utilization, clay stabilization, LCA

Özet

Ömrünü Tamamlamış PV Panellerin Kullanımı ile Kil Toprağın Jeoteknik Özelliklerinin İyileştirilmesi

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Doktora, İnşaat Mühendisliği Bölümü

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Artan ömrünü tamamlamış (EoL) fotovoltaik (PV) panellerin atık malzemeler olarak çoğalması, birçok ülkeyi bu sorunun üstesinden gelmeye zorluyor. Sunulan araştırma, bu atık malzemenin bir yan ürünü olan cam tozunun, jeoteknik mühendisliğinde kil toprağın mekanik özelliklerini iyileştirmek için alçı ile birlikte kullanımını araştırmaktadır. Bu yaklaşım, EoL PV panellerinin sürdürülebilir yönetimi sorununa çözüm bulmak için bu malzemeleri entegre etmeyi amaçlamaktadır; bu, jeoteknik uygulamalarda yeterince kullanılmayan bir kaynaktır. Bu çalışmada, kil-toprak kütlesine göre alçı (%0, %5, %10 ve %15) ve cam tozu (%0, %4, %8 ve %12) oranları ayarlanarak kompozit numuneler oluşturulmuştur. 1500 ve 1700 kg/m³ kuru yoğunluklarda sıkıştırma işlemleri gerçekleştirilmiş ve 7, 28 ve 56 günlük kürleme süreleri uygulanmıştır. Ultrasonik darbe hızı (UPV), basit basınç dayanımı (UCS), ıslak ve kuru çevrim dayanıklılığı değerlendirmeleri, taramalı elektron mikroskobu (SEM) analizleri ve X-ışını difraksiyonu (XRD) analizleri dahil çeşitli testler gerçekleştirilmiştir. Sonuçlar, alçının sürekli olarak toprağın dayanım ve sertlik özelliklerini iyileştirdiğini, başlangıçta cam tozu eklenmesinin bu özellikleri azalttığını ancak %12 içeriğe ulaştığında iyileşme gösterdiğini ortaya koymuştur. Yalnızca tek bir test kullanılarak elde edilecek basit basınç dayanımı (q_u), başlangıç kayma modülü (G_0) ve elastik modül (E) değerlerini belirlemek için korelasyonlar önerilmiştir. Ayrıca, tahribatsız testler yoluyla herhangi bir numunenin basit basınç dayanımı ve elastik modülünü tahmin etmek için bir korelasyon geliştirilmiştir. Mikro yapısal analizler, puzolanik reaksiyonların ilerlemesini, cam tozundan gelen silikon açısından zengin bileşikleri tanımlayarak ve katkı maddelerinin toprak yapısını nasıl dönüştürdüğünü açıklayarak karmaşık etkileşimleri ortaya koymuştur. Sonuçlar, sinterlenmiş alçının, özellikle daha yoğun numunelerde, basit basınç dayanımını sürekli olarak artırarak toprak dayanımını önemli ölçüde iyileştirdiğini göstermiştir. Cam tozunun basit basınç dayanımına etkisi değişkenlik göstermiştir. Sertlik, yüksek sinterlenmiş alçı ve %12 cam tozu içeren numunelerde zirve yaparak, basit basınç dayanımı trendlerini takip etmiştir. Dayanıklılık testleri, daha yüksek cam tozu içeriğinin kütle kaybını artırdığını, sinterlenmiş alçının ise bu etkiyi azalttığını göstermiştir. Life Cycle Assessment (LCA) sonuçları, mekanik özelliklerle normalize edilen çevresel etkilerin, katkı maddelerinin daha yüksek yüzdeleriyle daha yoğun numunelerde daha düşük etkiler gösterdiğini ortaya koymuştur.

***Anahtar kelimeler**:* Cam tozu, Sürdürülebilir yönetim, Atıkların kullanımı, Kil stabilizasyonu, LCA

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List of Abbreviations

ALM:	Accumulative Loss of Mass
ASTM:	American Society for Testing and Materials
BCS:	Black Cotton Soil
BOFS:	Basic Oxygen Furnace Slag
BSG:	Brewery Spent Grain
C-A-H:	Calcium Aluminate Hydrate
C-S-H:	Calcium Silicate Hydrate
CW:	Construction Waste
EoL:	End-of-Life
FU:	Functional Unit
GBFS:	Granulated Blast Furnace Slag
GGBFS:	Ground Granulated Blast Furnace Slag
GP:	Glass Powder
GYP:	Gypsum
ICDD:	International Center for Diffraction Data
IEA:	International Energy Agency
IRENA:	International Renewable Energy Agency
ISO:	International Standardization Organization
LCA:	Life Cycle Assessment
LCI:	Life Cycle Inventory
MICP:	Microbial-Induced Calcite Precipitation

MNE: Ministry of National Education

MP: Marble Powder

MSWI: Municipal Solid Waste Incinerator

P/B: Porosity/Binder

PPE: Personal Protective Equipment

PSD: Position-Sensitive Detector

PV: Photovoltaic

RG: Recycled Glass

RHA: Rice Husk Ash

SEM: Scanning Electron Microscopy

TRNC: Turkish Republic of North Cyprus

UCS: Unconfined Compressive StrengthI

UPV: Ultrasonic Pulse Velocity

USCS: Unified Soil Classification System

WSLGP: Waste Soda Lime Glass Powder

XRD: X-Ray Diffraction

CHAPTER I
Introduction

Background

There has been a notable increase in interest in using waste materials to improve soil quality. This is due to the urgent need to address environmental sustainability and geotechnical engineering issues (Liu & Hung, 2023; Kheimi et al., 2022; Palansooriya et al., 2020). This study investigates the utilization of glass powder obtained from the protective layer of decommissioned photovoltaic (PV) panels and sintered gypsum sourced from natural materials for improving clay soil. The scientific effort seeks to address a complex problem with significant and wide-ranging consequences.

The average lifespan of photovoltaic (PV) panels is typically around 20 to 25 years (Nagarajan et al., 2020). With the increasing use of PV panels in developed countries, it is now crucial to implement proactive strategies for effectively managing the disposal of solar panels at the end of their life cycle (Wang, 2016).

Environmental Challenge

The disposal of photovoltaic (PV) panels at the end of their effective life has emerged as a critical environmental issue, contributing significantly to the growing electronic waste crisis. As the global reliance on solar energy intensifies, the adoption of PV-scale solar plants is increasing, leading to more PV panels reaching the end of their operational life. This rise in disposal rates is particularly alarming as it exacerbates the growing superfluous electronic waste problem, posing severe threats to waste management processes and environmental protection.

PV panels are constructed from a variety of materials, with glass shields being a crucial component that protects the photovoltaic cells from damage. However, when these panels are discarded in municipal sanitary landfills or dumping sites, they do not merely increase the level of waste; they worsen long-term accumulation problems. This adds to existing landfill issues, such as space depletion and environmental hazards associated with solid waste that does not readily biodegrade over time.

Glass, a primary component of PV panels, exemplifies these challenges due to its durability and the difficulties associated with its disposal and recycling. Glass degrades extremely slowly, taking over 4,000 years to disintegrate in landfills (Siddique and Siddique, 2008; Yan et al., 2018). This slow degradation contributes to significant long-term environmental issues, especially as glass is often improperly disposed of or incinerated, worsening pollution concerns. This persistence in landfills and dumping sites adds to the closed landfill problems and exacerbates environmental hazards attributable to such non-biodegradable solid wastes.

Despite the unfavorable environmental implications, recycling glass from PV panels presents substantial challenges that further complicate its management. One of the most pressing issues is the lack of appropriate markets capable of processing recycled glass into usable material. Contamination during the recycling process lowers the quality and usability of the recycled product. Additionally, the logistics of transporting glass for recycling are costly, primarily due to its density; glass is approximately ten times denser than materials such as plastic or metal when comparing equal volumes. This high density not only increases transportation costs but also places greater strain on recycling machinery, leading to higher maintenance and operational expenses (Ran et al., 2016).

Furthermore, the fragility of glass poses another hurdle, as it is prone to breakage during handling and processing. This risk of damage during manipulation complicates recycling efforts and adds to the associated costs. These challenges underscore the intrinsic inefficiencies and environmental concerns linked to the improper disposal and recycling of PV panels, emphasizing the urgent need for sustainable waste management solutions.

Geotechnical Engineering Challenge

Geotechnical engineering has long struggled with the complex challenges of effectively managing clay soils, which are infamous for their difficult and unpredictable behavior. These soils, found in various geographical regions across the globe, present a unique set of challenges that can significantly obstruct construction and development efforts. Among their most problematic characteristics are their low bearing capacity, which limits the load-bearing potential of structures; swelling behaviour, which deals with significant soil expansion upon absorbing water and causing structural instability; high compressibility, which leads to settlement issues and can cause structural damage over time; and poor drainage capabilities, which contribute to water-logging, soil instability, and increased susceptibility to erosion and landslides. These issues not only complicate the construction process but also increase the risk of long-term maintenance problems and structural failures.

To mitigate these challenges, conventional soil stabilization techniques have been widely employed. These methods typically involve the addition of natural aggregates, such as gravel or sand, to improve the soil's mechanical properties or the use of chemical stabilizers, like lime or cement, to enhance the soil's strength and durability. Such interventions are designed to improve the overall structural integrity of clay soils, making them more suitable for construction purposes. However, despite their widespread use, these traditional approaches are not without significant disadvantages.

The environmental and economic implications of conventional soil stabilization methods have increasingly come under investigation. The extraction and transportation of natural aggregates contribute to the depletion of finite natural resources and can cause considerable environmental degradation, including habitat destruction, increased energy consumption, and pollution. Similarly, the production and application of chemical stabilizers, while effective in improving soil properties, are associated with high carbon emissions and other ecological impacts, such as soil and water contamination. These environmental costs, coupled with the often substantial financial outlay required for these stabilizing techniques, highlight the need for more sustainable and cost-effective alternatives (Behnood, 2018).

In Cyprus, the challenges posed by the prevalent clay soils are particularly serious, creating significant geotechnical obstacles, especially for infrastructure and road development projects. The region’s distinctive geological composition necessitates innovative approaches to soil stabilization that not only address the technical challenges but also align with the growing emphasis on sustainability and environmental aspects. As the demand for resilient and environmentally conscious infrastructure increases, there has been an intensive effort to explore and implement alternative soil remediation strategies.

One promising area of research involves the utilization of industrial waste products, such as glass powder derived from recovered photovoltaic panels and sintered gypsum, as soil stabilizers. These materials, which are often discarded as waste, hold significant potential for improving the geotechnical properties of clay soils. By incorporating these byproducts into soil stabilization practices, it is possible to enhance the strength, durability, and overall stability of clay soils while simultaneously addressing broader environmental concerns. The use of these materials not only provides a sustainable solution to the challenges of clay soil stabilization but contributes to waste management efforts by repurposing materials that would otherwise contribute to landfill waste.

It has been observed that the use of waste materials for enhancing soil texture has gained popularity over time. This movement aims to enhance the interrelated challenges of environmental preservation and matters of geotechnical engineering (Liu & Hung, 2023; Kheimi et al., 2022; Palansooriya et al., 2020). This study looks at the usage of glass powder from the cover layer of end-of-life photovoltaic (PV) panels and utilizes natural "sintered gypsum" to enhance clay soils. The scientific endeavor aims to solve a multidimensional problem, possessing the importance of large-scale and diverse effects.

According to recent studies, the average duration of PV or photovoltaic panels is estimated at between 20 and 25 years (Nagarajan et al., 2020). Growing use of PV panels in developed countries means that planning the effective disposal of solar panels in the end-of-life stage has become a challenge that has to be addressed (Wang, 2016).

However, despite the fact that these recycling processes are expensive, it has been shown that about 80% of a standard PV panel is composed of materials that will not go to waste at all due to recycling (Majewski et al., 2021). The National Renewable Energy Laboratory is predicting that it will cost about $20 to $30 to recycle a panel which is excessive compared to the disposal cost in a landfill of only about $1 to $2.

Agarwal (2023) notes that because of the economic disparity, it validates the challenges associated with the recycling of PV panels, and hence, reasons such as landfilling come to be less costly. The condition sounds bad with environmental concerns since there are heavy metals such as silver, lead, arsenic, and cadmium found in the solar panels, there is an environmental concern as well due to the dumping of the PV panels on land, which leads to land colonization (Vellini et al., 2017). Thus, the necessity of viewing these panels as wastes cannot be ruled out, and their last phase should be managed properly with regard to environmental issues and land resource ratio (Malandrino et al., 2017).

Statement of the Problem

Although around 80% of a standard PV panel is composed of materials that can be recycled, the process of dismantling them and extracting important components like glass, silver, and silicon is highly intricate and expensive (Majewski et al., 2021). According to the National Renewable Energy Laboratory, the cost of recycling a panel is projected to be around $20 to $30, which is significantly more than the cost of $1 to $2 for disposing of it in a landfill. The economic inequality highlights the practical difficulties linked to recycling PV panels, therefore making landfill disposal a more cost-effective option (Agarwal, 2023).

This condition not only presents environmental issues because of the existence of heavy metals like silver, lead, arsenic, and cadmium in solar panels, but it also raises worries about the colonization of land by discarded PV panels (Vellini et al., 2017). Therefore, it is crucial to regard these panels as waste materials and efficiently handle their end-of-life stage, considering both the environmental impacts and the efficient use of land resources (Malandrino et al., 2017).

Purpose of the Study

This study aims to repurpose the glass components of decommissioned photovoltaic panels by converting the glass shield sections into finely ground glass powder. Additionally, gypsum made from natural sources is aimed to be utilized to enhance the process. The goal is focused on addressing two interconnected challenges:

1. The major objective is to mitigate the environmental impact associated with the disposal of end-of-life PV panels by redirecting them away from overcrowded landfill sites. With the increasing demand for renewable energy solutions, there is a growing concern about the large number of expired PV panels. It is crucial to find ways to repurpose these waste materials, especially in civil engineering and geotechnical applications. The study introduces a pioneering way to manage waste from PV panels by extracting and using glass powder from the protective glass layers. This approach also presents a compelling end-of-life strategy for PV panels.

2. The second goal is to thoroughly assess how these recycled ingredients can enhance the structural and compositional soundness of clay soils. Glass powder and

sintered gypsum have the potential to improve soil characteristics and address challenges related to expansive behavior and excessive compressibility that often arise in construction and infrastructure projects. Incorporating these recycled materials is expected to bring several improvements, such as enhanced soil stability, better load-bearing capacity, reduced settling potential, and superior drainage qualities, among other benefits.

Utilizing glass powder and sintered gypsum innovatively makes it possible to significantly enhance the process of repairing challenging soils in geotechnical engineering. This study not only encourages the implementation of a circular economy by reutilizing resources that would otherwise add to environmental stress but also leads the way in adopting more efficient and economically feasible technologies for soil stabilization. Moreover, the objective is to thoroughly record the influence of these substances on soil functionality, providing helpful information to the discipline and bolstering the shift towards more environmentally friendly engineering methods.

Research Questions

To address the outlined challenges, this study will explore the following research questions:

Can sintered gypsum and waste glass powder be utilized as effective additives to enhance the geotechnical properties of clay soil?

To what extent can sintered gypsum and waste glass powder improve the mechanical properties (strength and stiffness) of clay soil?

What is the optimal dosage of sintered gypsum and waste glass powder for achieving the desired improvement in clay soil properties?

Does the effectiveness vary depending on the combination of these additives?

How does the incorporation of sintered gypsum and waste glass powder affect the microstructure of clay soil?

Can these microstructural changes be correlated to the observed improvements in geotechnical properties?

What is the environmental impact of using waste materials from end-of-life PV panels compared to traditional methods for clay soil improvement?

Does this approach offer a more sustainable solution from a life cycle perspective (LCA)?

Limitations

This study investigating the use of sintered gypsum and glass powder derived from end-of-life PV panels for clay soil improvement has several limitations to consider:

Laboratory Testing Constraints:

Limited Testing Duration: Laboratory experiments often have time constraints, which may not fully represent the long-term behavior of the amended clay soil under real-world conditions. Long-term durability testing may be needed to assess the effectiveness of these amendments over extended periods.

Another limitation of this study is the time-consuming nature of durability tests, which restricts the analysis to a single sample for each combination of additives.

Challenges with Waste Material Acquisition:

End-of-Life PV Panel Availability: Obtaining an end-of-life PV panel, particularly in areas with recent solar energy use, can be challenging. This may restrict the amount of material available for testing.

Glass Separation Challenges: Separating the glass shield from the rest of the PV panel can be a complex and labor-intensive process. Specialized equipment and safety protocols might be necessary, adding complexity to the study.

Health and Safety Concerns:

Glass Powder Inhalation Risks: Handling and processing glass powder can pose respiratory health risks due to the potential for inhalation of fine particles. The study should incorporate appropriate personal protective equipment (PPE) to mitigate these risks.

CHAPTER II

Literature Review

Research-related conceptual definitions, descriptions, and information related to the subject that already exists in the literature are given in this chapter.

This section establishes the context for the study by describing the specific type of clay from Cyprus that was utilized. Following a brief overview of several approaches to enhance the ground, the text subsequently delves into a comprehensive examination of previous studies on comparable methodologies employed in this investigation. This section also discusses the proper management of photovoltaic panels as solid waste at the end of their lifespan and the utilization of waste glass powder and gypsum to enhance soil quality. Ultimately, the chapter concludes by examining the impact of various ground improvement approaches on the environment.

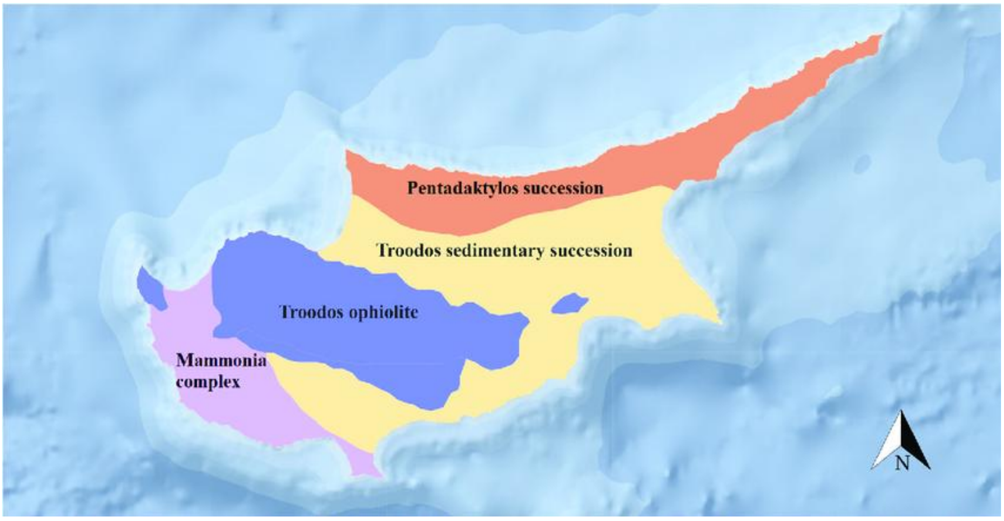
Cyprus Clay Soil and Geology

Cyprus, an island in the eastern Mediterranean, possesses a wide range of geological zones that testify to its intricate and abundant geological past (Figure 1). Comprehending these zones is essential, especially for distinguishing the different clay types present throughout the island.

The island can be categorized into three primary geological regions: the Troodos Ophiolite Complex, the Kyrenia Range, and the Mesaoria Basin (Department of Geological Survey, Ministry of Agriculture, Natural Resources and Environment, Cyprus, 2024).

Figure 1

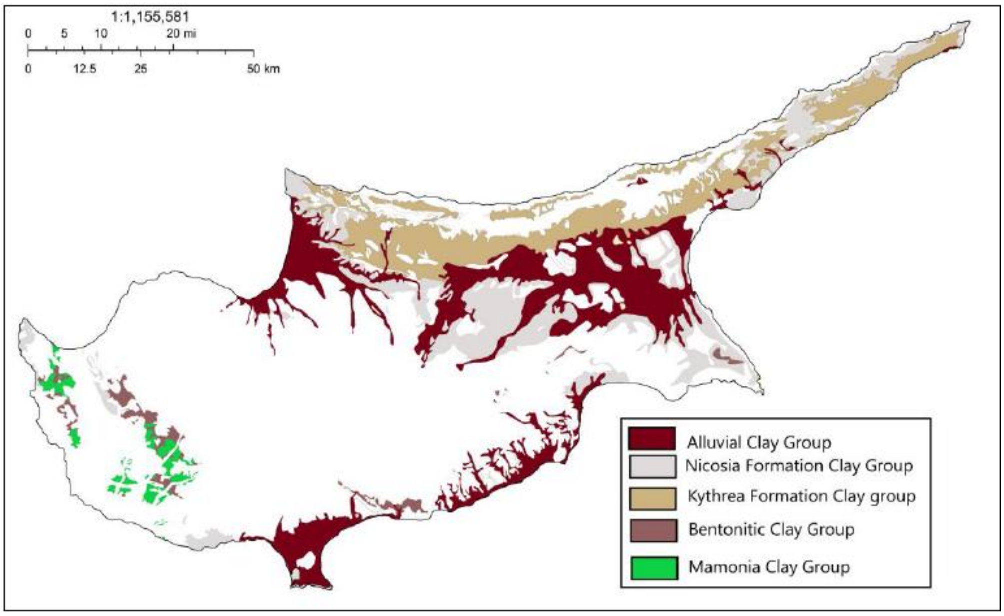
Geological Zone of Cyprus (Department of Geological Survey, Ministry of Agriculture, Natural Resources and Environment, Cyprus, 2024)



The Troodos Ophiolite Complex, located in the western portion of Cyprus, is a remarkable geological phenomenon. Created through the oceanic crust being forcefully pushed onto the bottom millions of years ago, this collection of oceanic rocks, such as mantle peridotites, basalts, and cherts, is highly distinctive. Figure 2 demonstrates a limited amount of clay in this area. However, some minor hydrothermal clays may be connected to the ophiolitic rocks.

Figure 2

Various Clay Soil Zone in Cyprus Island (Department of Geological Survey, Ministry of Agriculture, Natural Resources and Environment, Cyprus, 2024)



The Kyrenia Range, which extends along the northern shore, has a distinct geological contrast. This zone mainly consists of Mesozoic limestones and dolomites, with only a small amount of clay deposits available. Nevertheless, certain areas may contain terra rossa, a type of clay that remains after limestone undergoes chemical weathering (Mavrides, 1978).

The Mesaoria Basin, located in the center of Cyprus, is home to the island's most essential clay deposits and its most formidable obstacles. This basin is the result of crustal subsidence and is filled with sedimentary rocks that have accumulated over millions of years. The sediments consist of marl, marl limestones, and, notably, clays (Department of Geological Survey, Ministry of Agriculture, Natural Resources and Environment, Cyprus, 2024).

Two specific clay forms, bentonite and kaolinite, are particularly notable within the Mesaoria Basin. Bentonite, a type of clay with a high ability to expand, is commonly found in conjunction with volcanic ash layers formed during the Miocene epoch (Hughes, 2009). Kaolinite, a clay with a white appearance, is highly regarded for its ability to withstand high temperatures and its excellent ability to be moulded. It is found in weathered sedimentary rock formations (Murray, 2006).

Nevertheless, the narrative of Cyprus's clays stretches further than the Mesaoria Basin. The island's geological composition is more complex. The northeastern region, specifically the foothills, is renowned for its Cretaceous clays and sandstones. These clay deposits give rise to noticeable hills and are prone to erosion. Their composition exhibits variation, encompassing marl, limestone, and Miocene conglomerates.

It is important to take into account the existence of expanding clays in different areas of Northern Cyprus (Iravanian & Abdeh, 2020). These clays have unique properties that expand and contract when the moisture levels change, leading to significant movement and instability in the ground (Yoo, 2023). Their exceptional malleability and vulnerability to water render them formidable obstacles to development and infrastructure industries in these regions.

Soil Stabilization Methods

Methods for improving the ground in geotechnical engineering Field techniques encompass a range of methods used to improve soil characteristics, especially in regions where the ground conditions are suboptimal (Dai, 2005). The objective of these procedures is to enhance the stability and load-bearing capacity of the soil, thereby reducing settlement problems and assuring enough support for structures. This makes the soil appropriate for construction and other civil engineering activities (Szmechel et al., 2019). Common ground improvement techniques encompass compaction, preloading with surcharge, grouting, deep soil mixing, and stone columns (Szmechel et al., 2019; Mušec et al., 2018).

Deep soil mixing is a method used in civil engineering to stabilize soil. It entails using procedures to improve the engineering features of the soil, making it suitable for construction and other civil engineering tasks. A commonly employed technique for soil stabilization involves incorporating stabilizers, such as lime, cement, or fly ash, into the soil to enhance its strength and durability. The term used to describe this process is chemical stabilization. Another technique involves the utilization of geosynthetics, which are artificial materials inserted into or onto the soil to improve its characteristics (Nehab et al., 2014).

Traditional Soil Improvement Methods

Soil stabilization has traditionally used various established techniques that use easily accessible and affordable materials. Although lime, cement, fly ash, and bitumen have benefited civil engineering, their environmental consequences have been increasing. This part provides a more in-depth analysis of the recognized lime and cement stabilization techniques, examining both their efficacy and their environmental implications.

Lime, a commonly accessible and cost-effective substance, has been a fundamental component of soil stabilization for generations (Noor & Uddin, 2019). Its efficiency is based on its ability to react chemically with soil components, specifically clay minerals. The pozzolanic reaction raises the soil's pH level, decreasing its ductility and improving its overall strength (Al-Mukhtar et al., 2010; Bessaim et al., 2018).

Lime has advantages that go beyond immediate strength enhancements. Applying lime to soil can enhance its ability to resist water penetration, which is crucial for constructions exposed to the elements (Hezmi et al., 2019). Moreover, lime can function as a desiccant, expediting construction schedules in damp surroundings (Lemaire et al., 2013).

On the other hand, cement, as a hydraulic binder, offers a robust and versatile solution for soil stabilization. Upon contact with water, it undergoes a process of hydration, forming a strong and durable matrix that effectively binds soil particles together. This results in significant improvements in the compressive strength, shear strength, and overall stiffness of the material (Hillel, 2013). Cement's adaptability is showcased in its use in diverse civil engineering projects such as road building, foundation stabilization, and embankment reinforcement, inspiring its potential in various applications (Sounthararajah et al., 2016; Xuan et al., 2015; Castro et al., 2021).

Both lime and cement offer substantial benefits in soil stability. Lime's cost-effectiveness, user-friendliness, and positive impact on productivity make it an attractive choice. Similarly, cement provides significant strength enhancements and adaptability for a wide range of constructions. However, it's crucial to note that both materials share a common drawback-potential environmental impact. Lime manufacturing is a major contributor to greenhouse gas emissions, and it is the second largest source of carbon emissions from industrial processes, after cement production (Shan et al., 2016). On the other side, cement production is associated with high energy use. There are also concerns about the potential release of heavy metals from cement, which could aggravate soil pollution in the long term. This underscores the importance of considering environmental impact in construction practices (Soultanidis et al., 2022).

The future of soil stabilization hinges on achieving a harmonious equilibrium between efficacy and ecological accountability. It is essential to do further research on sustainable alternatives, such as bio-enzymes and geopolymers, while also improving established technologies to minimize their environmental impact. This is necessary for promoting responsible construction practices.

Modern and innovative soil Improvement Methods, Including Waste Material Utilization

Recently, several contemporary methods for soil stabilization, such as geosynthetics, microbial-induced calcite precipitation, electrokinetics, utilizing waste materials, and others, have been developed, providing distinct benefits compared to conventional approaches.

Marble Powder (MP)

One of the waste products being used as a new soil improvement technique is marble powder. In a recent study, the values of q_u and E_u of stabilized soil specimens showed a significant rise when marble powder (MP) content reached 5%. However, these values dropped as the MP concentration increased in highly plasticity silt with a plasticity index of 21 (Aydin et al., 2020).

Other experimental work by Sivrikaya et al. (2020) revealed that waste marble powders significantly improved soil stabilization. For high plasticity clays, the PI was reduced from 49 to 26, the expansion index from 45 to 20, the swelling index from 0.0030 to 0.0012, the compression index from 0.013 to 0.010, and linear shrinkage from 16.2% to 10.5%.

Construction and Steel Manufacturing Waste

Construction waste such as bricks, stones, tiles, and waste concrete is also one of the types of waste materials that can be recycled and used for soil enhancement. The investigation conducted by Bipasha et al. (2016) utilized grounds-granulated blast furnace slag (GGBFS) and construction waste (CW). The results show that the use of additives had a strengthening effect that bears a progressive increase over time. Under all curing conditions, the optimized additive ratios were 5% slag and 20% CW in the mix.

Granulated blast furnace slag (GBFS) and basic oxygen furnace slag (BOFS), which are the waste byproducts from steelworks, have been put to use in the stabilization of soft soils around industrial areas. For example, Goodarzi and Salimi (2015) demonstrated that dispersive clays can be stabilized with GBFS and BOFS which resulted in a decrease in the dispersivity of the soils, lower plasticity of the BOFS in particular, and higher compressive strength of the treated soils in general.

Plastic Waste

Using this material has always been a beneficial one for soil improvement. This is especially true in light of plastic waste management issues. In a recent study, it was observed that the undrained behavior of samples changed from contractive to dilative when plastic wastes reached a value over 1%. Shear strength and compressibility of clay were both positively impacted by the inclusion of plastic wastes above 1%.

Plastic waste materials have been beneficially included in soil stabilization techniques in semi-arid regions where alternative materials are hard to come by. It was shown in the research of Gangwar and Tiwari (2021) that the strength of sandy soils was improved and their erosion resistance was enhanced by the addition of plastic waste in shredded form. Their study revealed that improvement in the moisture-density relationship of soil was achieved through the replacement of 0.5% of plastic waste with the dry weight of the soil. In addition, plastic for 0.5% recoveries concentration corresponds to the maximum dry density of 1590 kg/m^3, and optimum moisture content reduces from 14.4% to 13.8% at peak concentration of 0.5% plastic.

This method not only offers a solution for plastic waste management but is also a low-cost method for improving soil properties in difficult conditions.

In another study, Hasanzadeh and Shooshpasha (2024) found that cemented sand with 0.5% SF and 0.75% PET fibers achieved the highest tensile strength at 42 days. SF increased stiffness, while PET fibers reduced it but enhanced energy absorption capacity.

Municipal Solid Waste İncinerator (MSWI)

In a study by Vaitkus et al. (2019), it was demonstrated the use of municipal solid waste incinerator (MSWI) ash in the stabilization of soft clay soils and remarked that it is possible to upgrade soil strength and reduce its plasticity by adding 2% of bottom ash. Moreover, the use of MSWI ash, which is a pozzolanic and cementitious-based material, also helps in the management of wastes and concurrently improves the quality of the soil properties.

Waste Tire Rubber

In recent years, the inclusion of ground tire rubber with the use of fly ash has emerged as a promising strategy for the stabilization of expansive soils. A more recent study has reported that the use of ground tire rubber and fly ash was able to improve the UCS and decrease the swell potential, thus providing two benefits of soil stabilization and waste management as well. Like this study, there is significant scope for improvement in methods for incorporating waste materials so as to get better results (Lv et al., 2022).

Wastewater Biosolids

On the other side, research done by Arulrajah et al. (2011) on biosolids-amended soils showed that it is rather effective in improving the shear strength of soils making thus roads quite feasible in poorly developed soils. The significant sustainable development provision is achieved when biosolids are processed and disposed of instead of being landfilled, as this contributes to soil enhancement.

Rice Husk Ash (RHA)

RHA is rice husk ash, an industrial waste from the rice milling industry that has attracted interest due to its use as a pozzolanic that contributes to the compressive strength and durability of stabilized soil. It was found in the previous study that the addition of RHA to a clay classified as CL would reduce the specific gravity as well as the plasticity, slightly increase the OMC and MDD, and improve the CBR value to about 130% at 6% RHA while enhancing the cohesion of clay but lower the shear angle (Ramadhan, 2020).

Geosynthetics

Geosynthetics have many uses caused by soil stabilization, such as stabilizing slopes, constructing embankments, and retaining walls (Kim et al., 2019; Bessaim et al., 2018). Geosynthetics can greatly reduce the amount of conventional additives relied upon in order to stabilize the soil, thereby making the process more cost-effective and eco-friendly. In a very recent study, in both coarse and fine soils, as well as in all reinforcement solutions in fine soil, the CBR test convincingly illustrated the advantages of a single reinforcement layer. It is correct to state that the factors that contributed to the above include the limitations that came about when the CBR of the coarse soil improvement by several layers was carried out (Carlos et al., 2024). Recently, the use of geosynthetics, in particular, geogrids, has shown the potential of improving soil strength. As an example, one can improve soil geosynthetic strength by up to 105% by using geogrids (Fakharian and Pilban, 2021).

Microbial-Induced Calcite Precipitation (MICP)

Microbial-induced calcite precipitation (MICP) is a recent method that is practiced to stabilize soil. It involves the use of bacteria and calcium solution injected into the soil to initiate a natural cementation process. They are responsible for the metabolism of urea, where they break urea into ammonia. This ammonia is combined with the calcium that is found in the soil, forming calcium carbonate precipitates. Other calcium carbonate materials also become organic as they adhere to the soil particles, causing a mineral-like effect that strengthens the ground more (Ali & Karkush, 2021). Normal construction practice encourages the use of MICP rather than conventional methods. This technique, which was advanced by Cui et al. (2022), is safe, cost-effective, and efficient in a way that makes it possible to reinforce different kinds of soil.

Electrokinetics

Electrokinetics is the current state-of-the-art technique to improve the stability of soil that involves the application of electric current to the soil such that its strength is improved and its permeability reduced. Electric fields are effective in causing the movement of charged items that are present in the soil, which transforms the soil's textural and chemical properties. In the area of soil stabilization, electrokinetic techniques have practices such as soil compaction, soil consolidation, and soil remediation (Azhar et al., 2017; Alshawabkeh, 2013).

Results were documented by Asavadorndej and Glawe (2005), where it was seen that clay silicates and aluminate ions interacted with calcium and hydroxide ions received during the electrokinetic process to form cementitious materials such as aluminum hydrates and calcium silicates. Such a technique's potential in enhancing soft soil stabilization was thus demonstrated with strength increases of as much as 570% after 7 days and 170% immediately after treatment.

Technics Comparisons. Electrokinetics and Microbial-Induced Calcite Precipitation (MICP) are two different soil improvement techniques. Electrokinetics helps to improve the stability of fine-grained soils such as clays, especially when wet or contaminated, using an electric field although it is expensive and difficult to implement on a broad scale. On the contrary, microbially induced carbonate precipitation carries out the process of calcite precipitation wherein soil particles get stumped together by microbial activity at low costs and is applicable to a wider variety of soils with the minimum possible environmental impact. MICP is well suited for large-scale applications, although its effectiveness may be low under adverse conditions.

Both MSWI ash and waste tire rubber are used in soil improvement but are very different from each other. MSWI ash, which is generated from burning wastes, is normally employed mostly as a soil stabilizer in construction, especially roadworks. It aids in the mitigation of waste from landfills. However, there are risks to the environment that might be presented in the ash that would require management. The waste tire rubber is usually made into crumb rubber that is added to the soil to improve its elasticity and reduce its weight. It is safe and efficient in the absorption of energy, making it suitable for applications against seismic disasters. It may, though, not be as effective as the binding MSWI ash.

Waste from both construction and steel production as well as plastic waste are also utilized in soil improvement operations, although they serve different functions.

Such construction and steel manufacturing wastes, e.g., slag and fly ash, are primarily used for soil strengthening and durability. Such materials offer good soil occlusion and load-bearing capacity and are thus appropriate for infrastructure applications. On the other hand, plastic waste in the form of either shredded or granulated plastic is used for soil modification, particularly in enhancing the flexibility of the soil and controlling its erosion. It's using the recycling of unnatural materials, which is rather unavoidable in this modern world, although fossilized waste can be adopted for soil-enhancing purposes with less strength than more probable construction and steel waste.

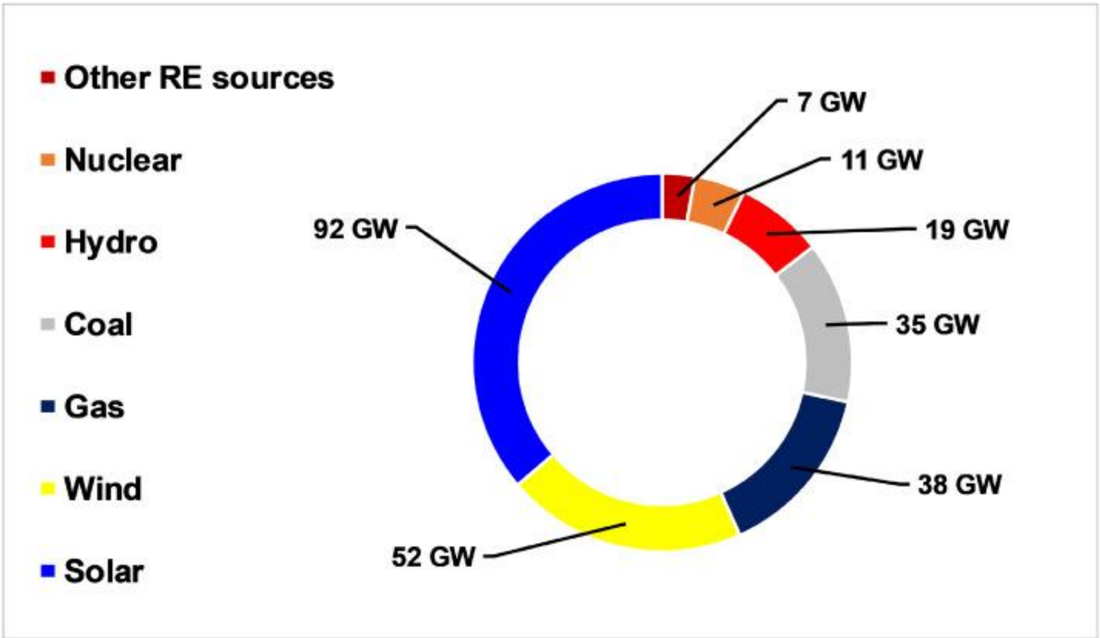
End-of-Life PV Panels

One of the main factors for this solid waste production increase over time is population growth and urbanization, including economic development, which now presents new challenges associated with landfill operations and waste recycling. It is indisputable that solid waste management has now turned out to be one of the most significant subjects of focus for stakeholders who are involved in the challenges of sustainability. In the recent past, geotechnical specialists have carried out extensive studies on waste minimization operations around the globe. These construction materials were then used in geotechnical practices for road pavement, walls, and building foundations. Another large-scale solid waste problem developing is how to recycle or up-cycle the end-of-life PV panels.

Solar energy production through solar photovoltaic (PV) ranks third in the world after hydropower and wind. Solar generation overtook the growth of nuclear and fossil fuel capacity installations owing to the rapid increase in solar PV structure, particularly in 2017 (Figure 3). However, with the increasing number of installations, the decommissioning, recycling, and recovery of end-of-life solar panels is becoming a significant environmental issue. In order to overcome these challenges and protect the future of this fast-growing industry, it is important to develop an appropriate policy and system for recycling PV cell materials (Chowdhury et al., 2020).

Figure 3

Capacity for the Generation of Electricity Installed in 2017 (International Energy Agency (IEA), (2018))



Over the past two decades, with nearly the entire population of the United States and many in China, including other nations embracing the installation of PV panels, different countries have been looking for innovative ways of dealing with PV panel waste. This implies extending the functional period and enduring nature of the photovoltaic (PV) panels by enhancing the structures' designs and toughness as well as improving the cost and availability of the recycling techniques (Li G. et al., 2012; Shen et al., 2013).

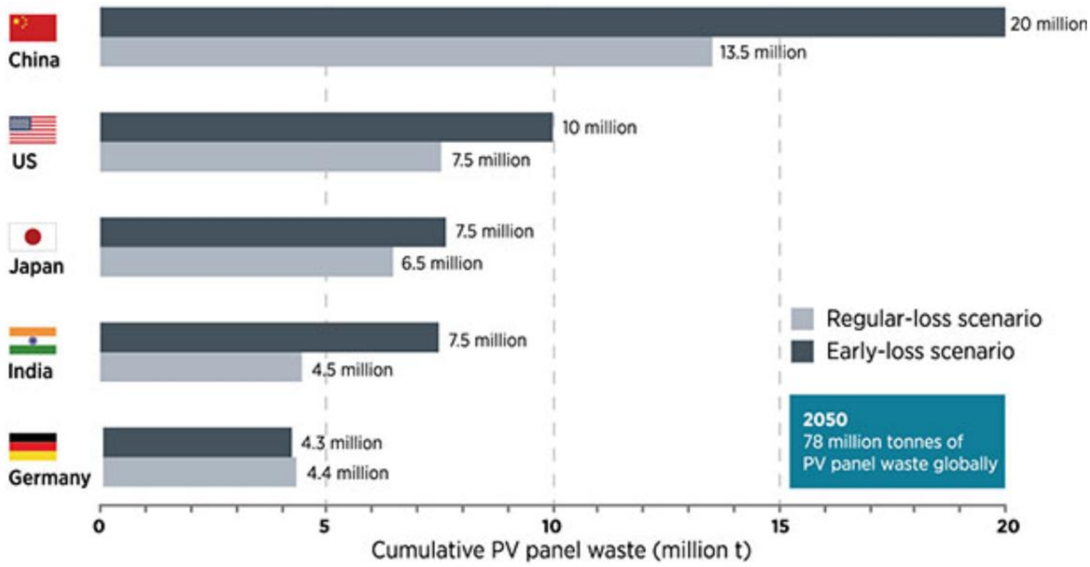
Some disposal cleantech strategies for photovoltaic (PV) panels have been developed by both the scientific community and industry. The advantages of renewable energy include the fact that countries like the United States and China deploy large numbers of solar panels. The current increase in the use of PV panels as a capital resource for clean energy generation has raised an emerging issue of what to do with these assets as they become obsolete.

Solar panel waste management technologies have concentrated around two aspects only: the enhancement of the lifespan and the reliability of the panels through their design and materials and the recovery technologies improvement and their economic aspect (Li G. et al., 2012; Shen et al., 2013). In order to reduce landfill disposal of solar panel waste, manufacturers conduct research on methods of improving the physical and mechanical properties of photovoltaic panels to extend their service life. At the same time, a lot of efforts have been made to develop efficient recycling technologies that would facilitate the recovery of materials from panels at the end of their useful life at an affordable price.

In order to harness solar energy in the generation of power, PV panels are specific devices that are pressed into the service of turning solar energy construction course. Yet, because of this expansion, the problem of solid wastes, in particular, sharply increases when these solar panels are considered out of service due to reasons of were mechanical damage or efficiency exhaustion (Shin et al., 2017). Further, the PV panels are still being manufactured, which explains the increasing generation of waste products from these systems. According to predictions (Figure 4), the total accumulated mass of renewable energy technologies containing hazardous materials waste facilities in the foreseeable future would attain an astronomical figure, quorum between 60 and59 million792 and 70,000,000 tons by the year 2050 (Ardente et al., 2019 IRENA, 2016).

Figure 4

Total PV panel waste by 2050, broken down by nation (IRENA, 2016)

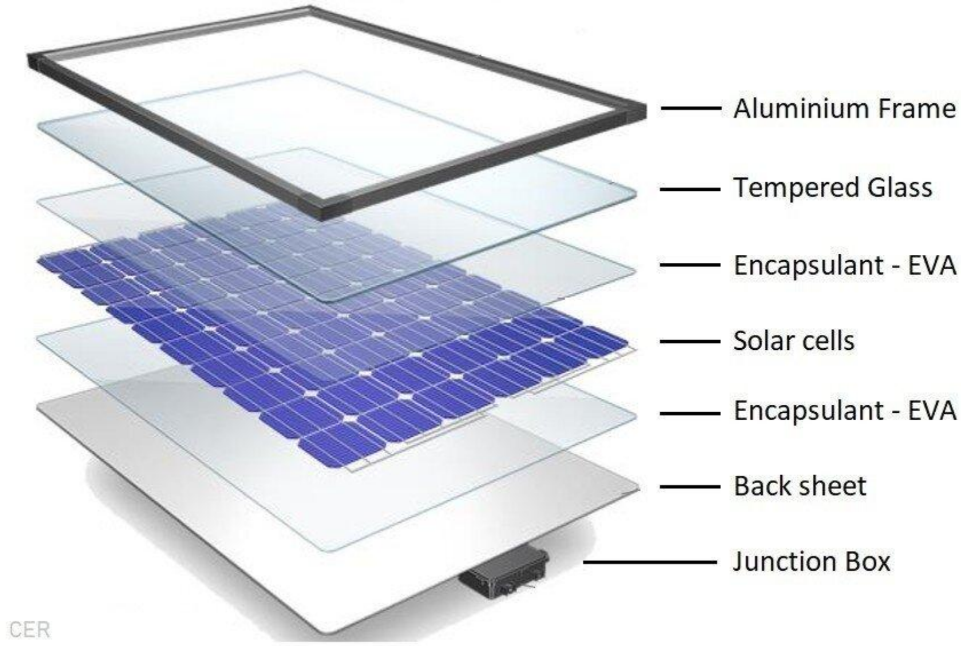


The main materials used for the construction of PV panels consist of silicon, glass, and metals, and excellent opportunities exist for recycling these components, as shown in Figure 5. However, they can be fully recovered. Most countries of the world still lack infrastructure development, which prevents the effective recovery of these waste materials and consequently limits the possible management of PV panel waste disposal. In addition, PV panels include many toxic substances that are extremely dangerous to health and nature (Mahmoudi et al., 2018; Fthenakis, 2004; Fthenakis & Moskowitz, 2000; Nieuwlaar et al., 1996; Phylipsen, 1995).

PV panels are found to contain some of the most alarming constituents, which have been considered hazardous, including Selenide (Se), Copper Indium Gallium Selenide (CIGS), often with cadmium (Cd), Lead (Pb), and Cadmium Telluride (CdTe) with cadmium and lead (Pb) in it. Crystalline Silicon (c-Si) panels have also been found to contain lead (Pb), thus complicating the safe disposal and recycling of the same (IRENA, 2016; Bang et al., 2018; Podoan et al., 2019; Mahmoudi et al., 2021). The need to minimize the environmental harm posed by the disposal of these panels has sparked a lot of research targeting these toxic materials. Such studies include the replacement of these materials with less hazardous substances, the use of more effective recycling practices to control the obtained materials, and an overall decrease in waste production from photovoltaic panels.

Figure 5

PV Panels' Different Parts (Quan et al., 2022)



About 70% of PV panels include a glass superstructure (Ziemińska-Stolarska et al., 2021). For a photovoltaic (PV) panel to be efficiently utilized and have a longer lifespan, the protection of the solar cells is to be ensured. The foremost layer of a photovoltaic (PV) panel, referred to as a glass shield, is integral in protecting the delicate solar cells enclosed within. Tempered glass is considered to be the best material for enclosing the above layers, owing to its strength and safety features, which prevent damage from external elements. In comparison to ordinary glass, tempered glass possesses four times the strength (Singh et al., 2023). These obstructions on the PV panels make them deformation-resistant to hailstones, hurricanes, and other climatic variations, thus reducing mechanical breakdown, promoting wear and tear-resistant materials, and enhancing operational performance over time (Ria et al., 2020). Also, due to safety reasons, tempered glass is preferred over regular glass since it does not shatter into sharp pieces but rather into tiny pieces with rounded edges, reducing the chances of cuts or injuries during installation maintenance or incidental hits.

Apart from rendering support, the protection afforded by the glass superstrate also determines the performance of a PV panel significantly. The manufacturers of premium-grade tempered glass utilize an antireflective coating so as to maximize the amount of light that passes through the glass layer and reaches the solar cells. Recent advancements in panels utilizing aluminum metal replace the glass base, which has an impact on the light trapping inside the panel, enhancing the overall energy absorption efficiency (Liu et al., 2022). Further research on other improved glass features, including the incorporation of self-cleaning and self-healing properties, would also see further performance and reliability improvements in PV panels.

Soil Stabilization Using Waste Glass

In the last few decades, there has been a growing focus on the usage of various contemporary waste materials, including glass powder, plastics, and electronic waste, in the management of soil quality improvement technologies. In 2019, India produced 2.48 million tonnes of glass powder, which shows the importance of glass as one of the global waste commodities (Rai et al., 2020). This method of mechanical stabilization is different from the more resource-intensive process of conducting laboratory tests. This strategy presents no potential environmental risks and, fundamentally, promotes the appropriate disposal of waste materials rather than utilizing conventional landfills (Tahmoorian et al., 2022).

Several research studies have been directed towards the use of waste material inside expansive soils so as to enhance their engineering characteristics such as shrinkage, swelling, deformation, and dispersion, among others and reduce the negative impact on the environment. These investigations have established waste glass as a suitable additive for soil stabilization, most often in combination with other binders.

Anglaaere et al. (2024) for instance, searched for the possibility of 50% reduction of the liquid limit of clay soil by mixing with glass powder and determined that glass powder appreciably influences the plasticity of clay soils. It was also realized that for the case when incorporating a larger amount of glass powder and rubber particles, the soil shear strength is statistically significantly improved. Their combination proved to be much more effective. A combination of 14% glass powder and rubber provides the optimal composition for shear strength.

Baldovino et al. (2020) implemented a soil improvement endeavor that involved Portland cement and glass powder. The unconfined compressive strength of the sample core, which consists of silt, cement, and GP powder, showed an upward trend with the increase of cement content, glass powder, curing period, and weight of dry molding. In particular, the achievements turned out to have unconfined compressive strength up to 15.5 kN/m^2 or increasing from 13.5. The optimum values were achieved after 90 days when 9% of cement and 30 % of GP additions gave the highest values.

In another experimental study on the performance of geopolymer, its practical application as an inorganic soil stabilizer based on glass powder has been evaluated. Bringing geo-polymer in soil samples has brought tremendous improvement in unconfined compressive strength as compared to soil that was not treated. More so, it was found that an even greater enhancement of UCS was achieved when the optimum glass powder content level was increased to 15%, thus supporting the claims for the use of geopolymer for strengthening and stabilizing the soil (Pourabbas et al., 2018).

The experimental investigation by Gowtham et al. (2018) focused on the determination of the impact of the usage of powdered glass and plastic waste on the properties of expanding soil. This was done to establish the optimum proportion that would best enhance the geotechnical properties by varying quantities of 2%, 4%, 6%, and 8% of pozzolana into the soil. It was found that a 6% ratio of glass powder to plastic waste was most effective in enhancing both physical and chemical.

In a study by Canakci et al. (2016), waste soda lime glass powder (WSLGP) was employed to cure clay soil in several proportions 3%, 6%, 9%, and 12% by weight. The results showed an increase in UCS (unconfined compressive strength) from 3% to 6% concentrations, but there was a drop in UCS from 6% to 12%. Similarly, in 2018, Mahdi and Al-Hassnawi did research where they examined the effects of some waste glass powder concentrations of 3%, 5%, 7%, and 9% by weight of dry soil on CBR and UCS tests. The findings of this research showed that optimal results were rated at 7% glass waste powder usage. Moreover, Babatunde et al. (2019) investigated the engineering properties of the black cotton soil BCS. The addition of 4% waste glass powder enhanced the load-bearing capacity of the researchers, owing to the increase in UCS and CBR values. The UCS value was recorded at 40 kN/m^2 for BCS without glass powder content, compared to a maximum value of 140 kN/m^2 with a 4% replacement of glass powder. Further percentage experiments of 2%, 6%, and 8% were conducted concerning dry soil weight.

An additional study was carried out by Al-Taie et al. (2023) using high percentages of recycled glass (RG). They proposed the entailing of sand-sized particles and increasing the RG content to 40%, producing a 30% reduction in the plasticity of the mixture. It was also observed that 25% of RG content contributed a significant enhancement of 45% in strength and also an impressive 130% enhancement in bearing capacity. It has also been noted that 6% glass powder content, when added, resulted in a complete 100% increase in strength and a 200% improvement in the bearing capacity.

Ibrahim et al. (2021) utilized glass powder in their study to make improvements to the expansive clayey soil. The amounts of glass powder assessed against dried soil weight included 6%, 12%, 18%, 27% and 36%. 27% waste glass powder was found to increase UCS significantly. On the other hand, the UCS was lowered using 36% waste glass powder.

Soil Stabilization Using Gypsum

Gypsum, formally known as calcium sulfate dihydrate: ($CaSO_4 \cdot 2H_2O$), is one of the carbonate minerals that has great potential as an additive that particularly improves soil. Some recent investigations indicated that the unconfined compressive strength (UCS) of clay soil can increase mildly with the addition of gypsum. The enhancement is considered to be a result of the chemical reaction of gypsum with clay minerals, which bond and thus enhance the geotechnical property of the soil mixture. Most of the studies have reported that the reason for the increased UCS of clay buried with gypsum is due to the cation exchange capability of these materials. This cation exchange mechanism comprises the replacement of high valent cations like calcium with monovalent cations like sodium residing in the interlayer of clay. This leads to a decrease in the plasticity of clayey soils due to this exchange, causing a less thick dispersive layer around clay grains (Zha et al., 2021; Ahmed et al., 2011). Such means that a different clay type will require a different amount of gypsum to stabilize and depend on the type of cations present in the clay.

Kuttah and Sato (2015) assert that the influence of gypsum on soil behavior may be unclear in gypseous soils. Prior gypsum presence may induce volume change due to hydration and dehydration cycles, an aspect which may compromise the durability of the modified soil. Such that, scope of soil chemistry and understanding of the role of gypsum with pertaining soils becomes beneficial for appropriate execution.

On the other hand, in the present work, Yilmaz (2001) observes that gypsum dissolves slightly in water, and subsequent exposure to water results in volume expansion swelling due to its hydroxyl mineral- anhydrite. However, in relation to the exceptional characteristic of gypsum that has been described above, in various studies, it was used together with other binders. The research undertaken by Salih and Shafiqu (2024) looked at the modification of clay soil strengthened with 6% lime by three different concentrations of gypsum, 2%,4%, and 8% of the dry soil. Thus, the most effective proportion for improving soil properties was found to be 6% lime together with 4% gypsum. This mixture demonstrates a reduction in the plasticity index from 33% to 29%. There was an increase in the UCS value (doubled) for curing times of 0, 7, and 14 days.

Recent research by Sharifi Teshnizi et al. (2024) reports that a highly plastic and swellable clay was chemically treated with different amounts of RHA (5-20%) and gypsum (2-6%) and left to cure for periods of 7, 15, and 30 days. From the tests done, shear strength was noted to have improved, and the plasticity and swelling pressure were reduced. In particular, after curing for 7 days, the UCS of the clay that was stabilized with 15% RHA and 2% gypsum increased by 1.46 times when compared to the controlled clay. When the gypsum content was raised to 6%, the unconfined compressive strength of RHA-gypsum-modified clay was 1.90 times that of untreated clay.

Other studies have been conducted to understand the effectiveness of gypsum on clay soil without any additives. As part of the research by Mesfin et al. (2023), which generally incorporated spent grain (BSG) ash and gypsum, it was found that the optimum additive dosage was 20% of the BSG ash added to the soil. This was, however, after the inclusion of gypsum content of 5-20% by the dry weight of the sample.

In other studies conducted recently, the cement-stabilized clay was further developed by incorporating gypsum, where they adopted the gypsum-to-cement ratio (G/C). In this work, when the ratio of G/C increases from 0% to 20% after 60 days of curing, the final water content of the treated soft clays decreases by 7.8% for 50% of the initial water contents and 11.2% for 70% of initial water contents after a 60-day curing period respectively. However, the last dry densities of 10.5% and 12.3% increase above these groups for the final dry density increase for these two groups, respectively. This indicates that the total water content and dry density are largely dependent on the amount of gypsum. Cation exchange under conditions when gypsum is present is claimed to have important implications (Wu et al., 2022).

Despite wide research efforts on soil stabilization using gypsum, it seems that not much attention has been directed toward sintered gypsum. Sintered gypsum is made of gypsum subjected to a heating process, and it has pozzolanic properties. Pozzolans are materials that enter into a chemical reaction with Calcium Hydroxide ($Ca(OH)_2$) produced when gypsum is hydrated and incorporated within cementitious compounds, increasing the capacity of the soil mixture. The pozzolanic process can also take place with the $Ca(OH)_2$ produced by the hydration of gypsum and by the hydration of one of the most popular construction binders, Portland cement, which is sometimes used in advanced ground enhancement methods. Soil stabilization using both cement and lime on sulfate soils, Barman and Dash (2022) noted that there were significant changes in the engineering properties of the stabilized soils. This study also focused on the beneficial aspects of using the pozzolanic reaction of gypsum in such cases.

Research Gaps

Despite significant progress in the field, numerous key research gaps remain in the extant literature. To begin with, while current research mostly focuses on short-term strength, the impacts of gypsum and glass powder-treated soils and their endurance in diverse environmental situations are still limited. The performance of these soils throughout wetting and drying cycles, which is an important feature in building, particularly in flood-prone areas, has not been adequately explored.

Moreover, whilst previous studies investigated in controlled laboratory conditions, there is too much shortage of spaced evaluations. It is essential to go beyond laboratory outcomes to the field where practical, skeptical people exist, particularly on the elements of research like constructability, etc. Besides the abovementioned, little attention is paid to the economic efficiency of implementing glass powder and sintered gypsum technologies in the literature. The elimination of such deficiencies will bring about a better understanding of the practicality of these materials in the field of civil engineering design.

This particular study assesses end-of-life solar panel material (glass shield) to determine its potential for stability; however, areas of further work should be on investigation into the other possible recyclable materials from PV panels, such as silicon chips and polymers for stabilization purposes, which have not been studied before. This may lead to the discovery of additional ways of engineering materials sustainably.

Critical Analysis

An increasing amount of research has proven the feasibility of the use of waste glass and gypsum on an integrative basis concerning the stabilization of soil. Most of these findings have been inconsistent due to the variations in the methodologies, soil types, and the surrounding environment. Canakci et al. (2016) reported substantial improvements in the unconfined compressive strength with the incorporation of waste glass powder in suitable amounts. These limits were focused on one type of sandy clay soil with high plasticity, and after mounding, few such results are extendable to other types of clay soils, especially with low plasticity or with distinct mineral compositions.

Mahdi and Al-Hassnawi (2018) confirmed these findings by obtaining similar results despite varying curing times and soil types. The variations in findings between studies highlight the need for a more systematic understanding of the interactions between glass powder, gypsum, and different clayey soils. Moreover, while glass powders have been generally accepted to enhance pozzolanic activity, further analysis is required in order to understand the different types of gypsum used, their curing period, and their effect on the resultant treated soils' strength and performance over an extended period of time.

This work seeks to fill these gaps by performing a thorough series of laboratory investigations of sintered gypsum with finely ground glass powder under controlled conditions. It aims to enhance the accumulated comprehensive information of the effects of these things on clay soils, consequently refining the soil stabilization approach with recycled waste materials.

Global Relevance of Soil Stabilization Using Glass Powder and Gypsum

Recent research predominantly concentrates on hot and arid environments, where glass particles and gypsum have improved soil strength, flexibility, and load-bearing ability. Studies conducted by Canakci et al. (2016) in arid regions indicate that the incorporation of waste glass powder can enhance the load-bearing capacity of clayey soils, while Al-Taie et al. (2023) demonstrated considerable increases in soil strength in temperate climates using recycled glass. These efforts provide a robust rationalization of the core stabilization reactions. However, given this, the geographic diversity of the soil types and the climatic aspects of environments tackled remain on the shallow side.

Soils in many climatic zones exhibit significant variability in behavior, particularly under conditions of moisture stress, freeze-thaw cycles, and extended saltwater exposure. It should be noted that the knowledge of soil stabilization methods must include not only the controlled conditions, under which laboratory experiments are carried out but also the field conditions for different climatic and environmental factors. The performance of these stabilized soils in different conditions is one of those factors that can either render the techniques useful or be opposed to the recommendation of their use in a global context.

In regions that are prone to high rainfall, flash flooding, or the effects of coastal features, soils are subjected to a high moisture content, which, after improvement, may reduce the strength and intention of cohesion in the stabilized soils. However, studies conducted by Baldovino et al. (2020) and Ibrahim et al. (2021) have recorded quick improvement in soil strength with the inclusion of glass powder and gypsum. However, the lasting effects have not been fully studied, especially for soils exposed to repeated wetting under moderate conditions. Arid regions serve as appropriate experimental testing conditions as the external environmental conditions are minimized with the aim of hiding the shortcomings of the stabilized attains that may be experienced in conditions that are less stable.

In addition, the association between soil stabilizers and environmental variables, including freeze-thaw cycles in cold regions, is likely to determine the field performance of the stabilized soils. The freeze and thaw cycles contribute to the expansion and contraction of soil matrices, which may, in turn, deteriorate the bridges or bonds formed by glass powder and gypsum. Presently, available studies on the suitability of these materials under such harsh environmental conditions are limited, thereby limiting the application of these materials in polar or subpolar areas where the need for building infrastructures is becoming increasingly high due to changes in land use patterns caused by global warming.

In this way, while there is important research in specific directions utilizing waste materials such as glass powder, gypsum, etc., it quite still remains narrow. It is equally necessary to understand the interaction of these kinds of stabilizers with the specific properties of the climate in various climatic regions for advancing infrastructure that is resilient to the increasing threats of climate change. It stands to reason that since tropical nations, polar countries, and coastal countries are in their efforts to combat these threats, additional studies should be done to quantify the effectiveness of these stabilization approaches under adverse and extreme conditions, enhancing and climatic conditions.

It is known that some of the studies had shortcomings that should be addressed, particularly examining in greater detail the degree of interaction between the materials presented in the study, like sintered gypsum, glass powder, and clay soils, each in its own individual environmental conditions simulating climatic conditions of different regions. This will improve the understanding of the strength and efficiency of using waste materials for soil stabilization, thus helping in the effective planning of future construction projects.

Environmental Impact Evaluation Regarding the Soil Improvement Methods

Geotechnical engineering is essential in the building business as it deals with the difficulties and dangers related to soil stabilizing procedures. Construction activities have huge environmental impacts based on their energy consumption and utilization of materials (Roohnavaz et al., 2018). It is because of these problems that the interest in sustainable development in geotechnical engineering has been growing. To mitigate these problems, it is also important to understand and minimize the potential of soil stabilization methods toward the adverse environmental impact.

The consumption of energy and materials, particularly cement, significantly affects soil stabilizing processes. Cement is one of the widely used materials in the process of soil stabilization, and it also contributes notably to the emission of carbon dioxide in the civil engineering industry (Henry & Kato, 2009).

Consequently, there is a demand for more research and the implementation of Life Cycle Assessment (LCA) methodologies to address these environmental impacts and develop advancements in geotechnical engineering. LCA is a proposed analytic framework that evaluates all the relevant environmental impacts of a product or activity in all of the stages, from production to disposal, including raw materials extraction and end-of-life disposal. With the LCA, it is possible for geotechnical engineers to assess the impact of soil stabilizing activities in terms of energy and materials such as cement consumed in the process. This enables them to spot weaknesses and implement sustainable improvements (Verma et al., 2021). In addition, such a tool could enable geotechnical engineers to find greener materials and practices like recycled content or new technologies where construction processes can be spared (Henry & Kato, 2009). Thus, the application of LCA strategies in geotechnical engineering will positively impact and promote sustainable construction practices by mitigating the adverse effects associated with soil stabilizing practices (Orak et al., 2022).

Novelty of the Study

The significance of this study is crucial in understanding the possible applications of glass powder, especially in geotechnical engineering. However, little research has been done in this way by adding glass powder and sintered gypsum for the stabilization of clay soil. In addition, it is also expected that current applications of tempered glass, which is a waste material from PV panels in geotechnical engineering, are limited.

The geotechnical application of EoL photovoltaic (PV) panels is used in one more inventive aspect of this work. This technique provides an innovative concept that could help solve the problem of the disposal of end-of-life photovoltaic (PV) panels and their management in the long term.

CHAPTER III
Methodology

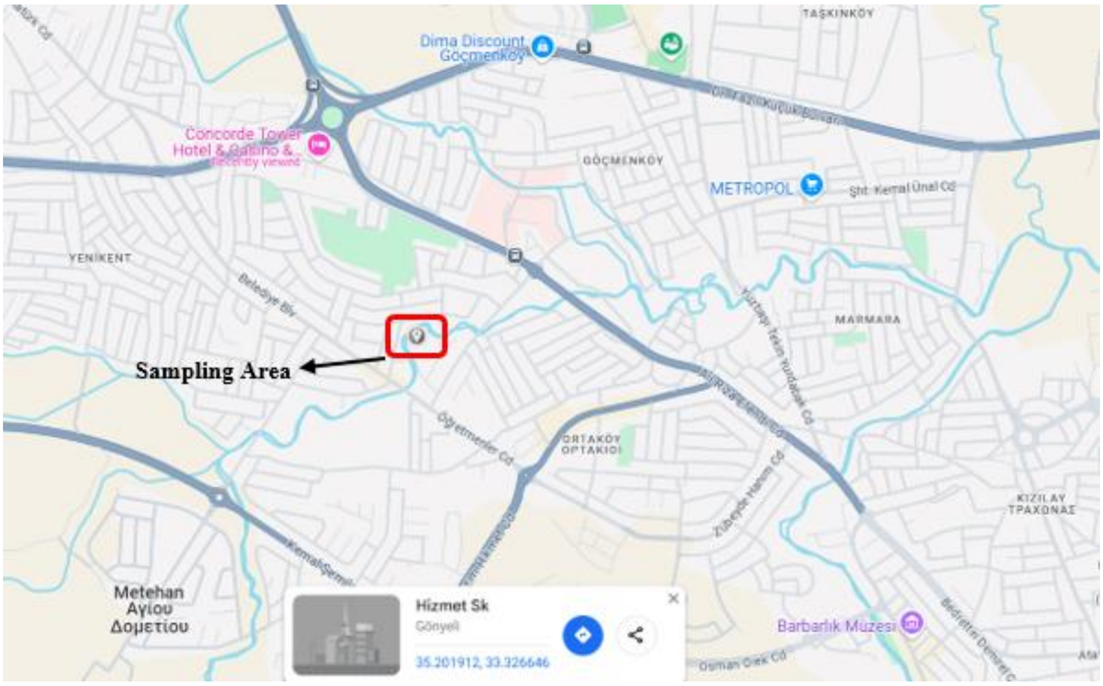
Material

Clay

The clay soil utilized in the current study was provided from a particular site located in the northern part of Nicosia within the central region of Cyprus. A site for the soil excavation was picked since it was within a river basin that was well known for alluvial deposits. In order to make sure that the soil samples were taken from subsurface conditions, the soils were taken at a depth of 2 meters, which is a level that has not been disturbed by human or industrial activities. The sampling location coordinates are shown in Figure 6.

Figure 6

Sampling Location Coordinates



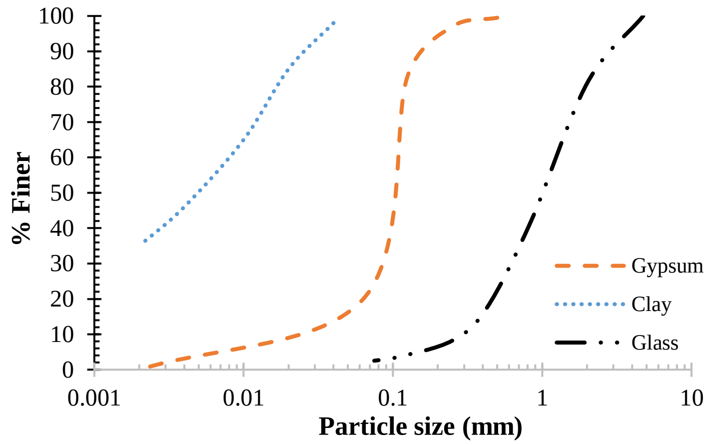
Once collected, the soil sample was underwent to a fixed 105°C drying temperature in oven. The objective of the drying step was to remove moisture content in the sample which would interfere with laboratory tests.

In order to thoroughly define the physical characteristics of the soil, specific tests in the laboratory following the appropriate ASTM standards were performed. Atterberg limits were established in accordance with the procedures from the (ASTM D4318–17e1) and serve as supplemental values to the plasticity and liquid limits of the soil. Sieve analysis, according to (ASTM D6913 / D6913M–17), explored the grain size distribution in great detail, giving information necessary for the analysis of the soil textural composition. In addition, the determination of specific gravities using (ASTM D854–14) gave a specific gravity value of 2.66, which is important in determining both the density and porosity of the soil.

Based on these results, the soil was assigned a classification under the Unified Soil Classification System, USCS (ASTM D4318–17e1). The soil has been classified with low plasticity and non-organic clay. This classification represents fine-grained soil and low compressibility and, therefore is fit for the experimental works highlighted in the current study. The particle size analysis of clay soil and the additives are shown in Figure 7.

Figure 7

Particle Size Analysis for Clay Soil, Sintered Gypsum, and GP



Glass Powder (GP)

The glass material utilized in this investigation was taken from end-of-life solar panels. This decision was motivated by the desire to look for economic and ecological solutions. Solar panels present significant challenges in discarding the strong adhesion of the glass to the solar cells. Such adherence makes the separable out procedures difficult as the recycling of such panels becomes very challenging.

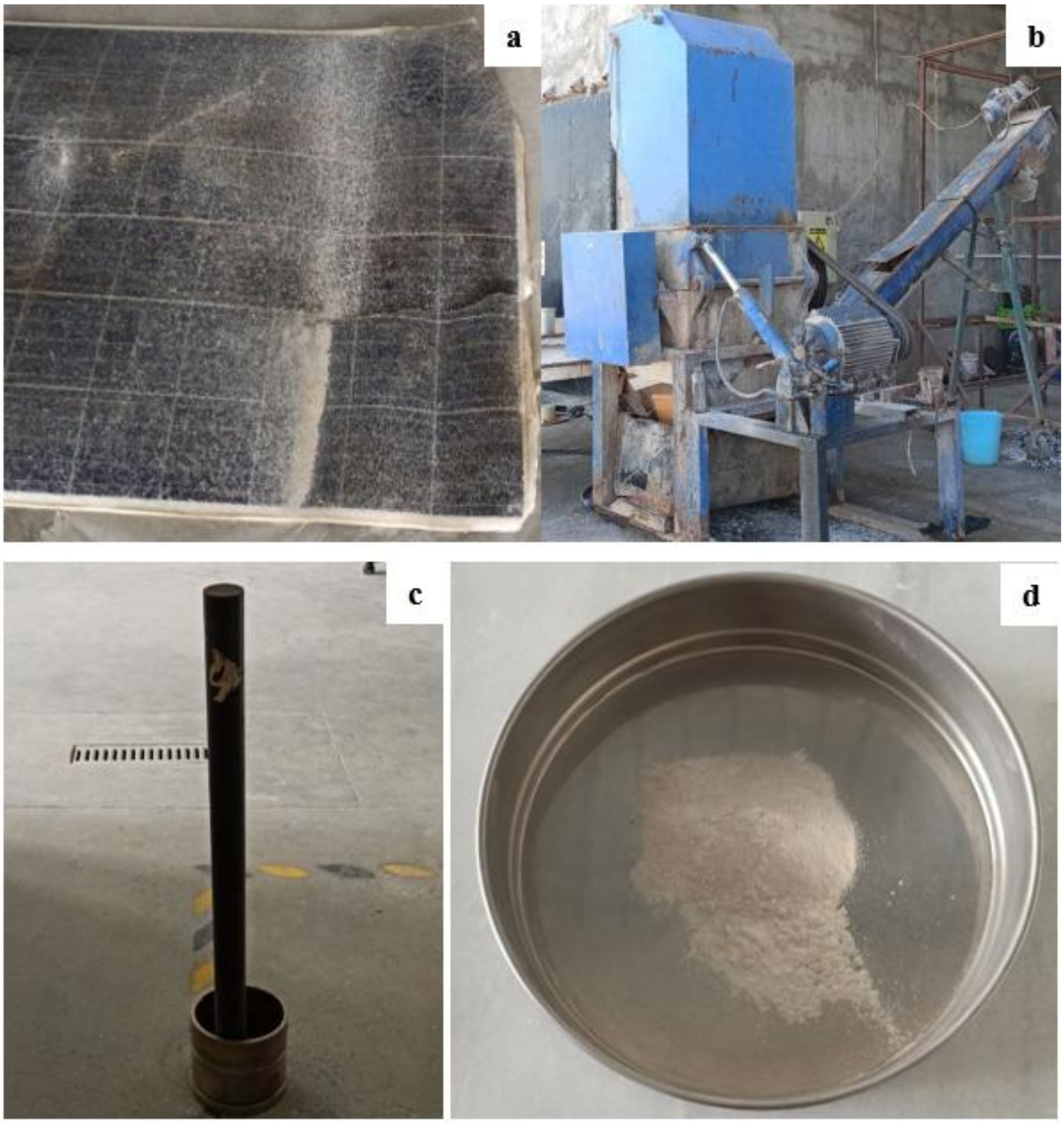
In order to solve this problem, a chopper machine was first required to assist in the removal of the top layer of glass from the solar cells. This mechanical operation complemented the explicit disadvantage of taking apart the panels efficiently.

After the first separation, the separated glass pieces were further size reduced. This was done by putting the glass pieces in a hollow cylindrical rod and pounding them with a hammer. The addition of a hollow plate aided in preventing the wastage of material whilst ensuring that the glass was pulverized to the required grade.

As soon as the glass acquired the proper size, a sieve was used to separate out the desired fineness of particles. To be precise, the glass was sieved with sieve number 230, where the aperture is 0.045 mm. This sieving procedure was important in producing GP that contained the finer particles for subsequent experiments. It is critical to ensure that the GP is manufactured with consistently sized particles to allow for consistency in the blending of materials, which would guarantee accuracy in the tests that followed. The order steps of the target GP are presented in Figure 8.

Figure 8

GP Driving from EoL PV Panels Procedure: (a) Providing Eol PV Panel from the Landfill, (b) Shredding by a Chopper Machine, (c) Crushing the Glass Particles after Division from the Solar Cell, and (d) Target GP after Sieving by Sieve Number 230



Sintered Gypsum

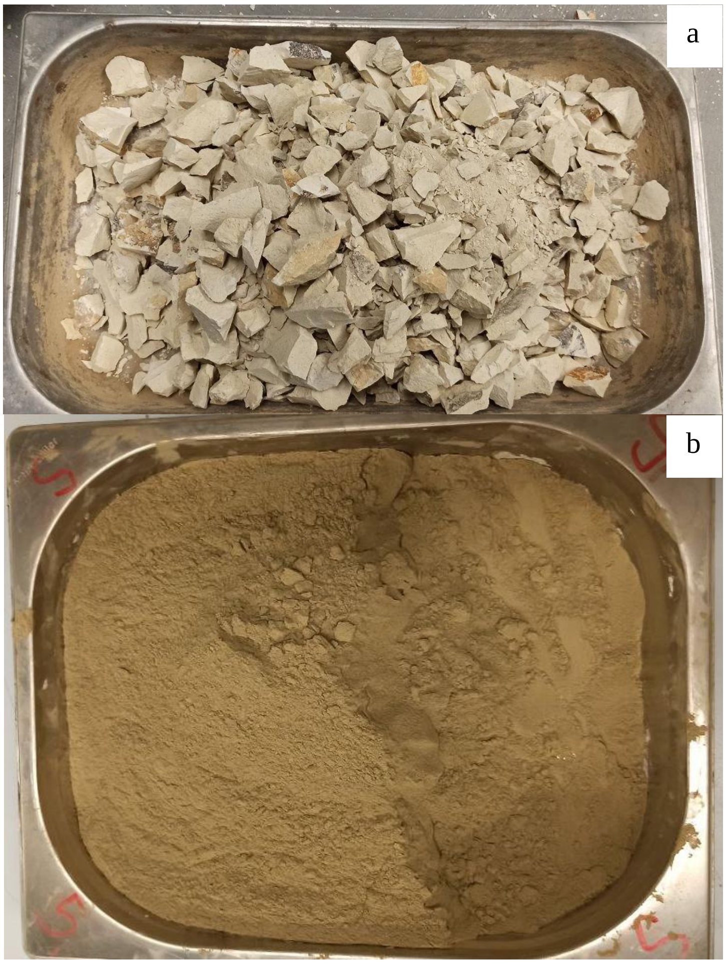
The gypsum rock, which was used as the raw material in this research, was carefully collected from the associated field site near Nicosia, which is present in Cyprus. Gypsum rock, called raw gypsum, was first made into a moderately coarse powder with a hammer (Figure 9a) and then processed through Los Angeles apparatus. The preliminary stages of crushing were followed by classification, using sieve number 120 of mesh size 0.125 mm. Afterward, the finely weighed and cycled gypsum was also placed into a kiln with a temperature of 1050 degrees Celsius for 24 hours, with the aim of enhancing the pozzolanic properties of the material.

After the sintering of raw gypsum, the material was subjected to an additional sieving. This part was performed to remove any undesirable particles or impurities that may have formed or accumulated during the high-temperature sintering operation. By conducting this step, the purity and consistency of the gypsum were further ensured, providing a high-quality material for the experimental analysis (Figure 9b).

The reason why 1050°C was selected as the sintering temperature for gypsum is that it markedly affects the pozzolanic properties of the material. At this point, the gypsum is thermally dehydrated, producing calcium sulfate hemihydrate, which is more active when mixed with water and other constituents. It is reported that when the reaction temperature is changed, the level of pozzolanic activity is also reported to vary, and in some studies, the effective temperature range is said to be between nine hundred and thousand degrees Celsius. If the temperature rises more than 1050ºC, then there will be excess dehydration, which will reduce the reactivity of the material as the amount of anhydrite will be increased in the materials (Elert et al., 2023). Concerning energy consumption and the environmental aspect, this procedure should also be followed.

Figure 9

Sintered Gypsum Preparation: (a) Crushed Gypsum Stone by Hammer and (b) Desirable Sintered Gypsum after Crushing by Los Angeles Machine and Oven Sintered at 1050 Degrees Celcius



The selection of sieve sizes, namely 0.125 mm and 0.045 mm, was determined by their efficacy in attaining the requisite particle size distribution for both the glass powder and sintered gypsum. The chosen opening diameters were intended to optimize the surface area of the particles, hence boosting the pozzolanic reaction with clay soil. Comparative literature indicates that smaller particles enhance the mechanical properties of stabilized soil by occupying voids and improving adhesion. The 0.045 mm sieve size facilitates the elimination of larger, less reactive particles, so ensuring that the material utilized in the blends corresponds with the requisite standards for optimal performance.

Methodology Overview

A sieve analysis and a physical characteristics examination of the clay soil, gypsum, and glass waste powders (GP) were the experimental procedures that began the work. This stage was important for getting familiar with the initial characteristics of every material. In this study, gypsum was introduced in the amounts of 0%, 5%, 10%, and 15%, and GP was added in the proportions of 0%, 4%, 8%, and 12%, respectively. All these percentages were figured out in relation to the dry soil mass so that there would be no differences in the samples. This systematic investigation sought to determine the effects of various mixtures of gypsum and GP on the engineering properties of the soil.

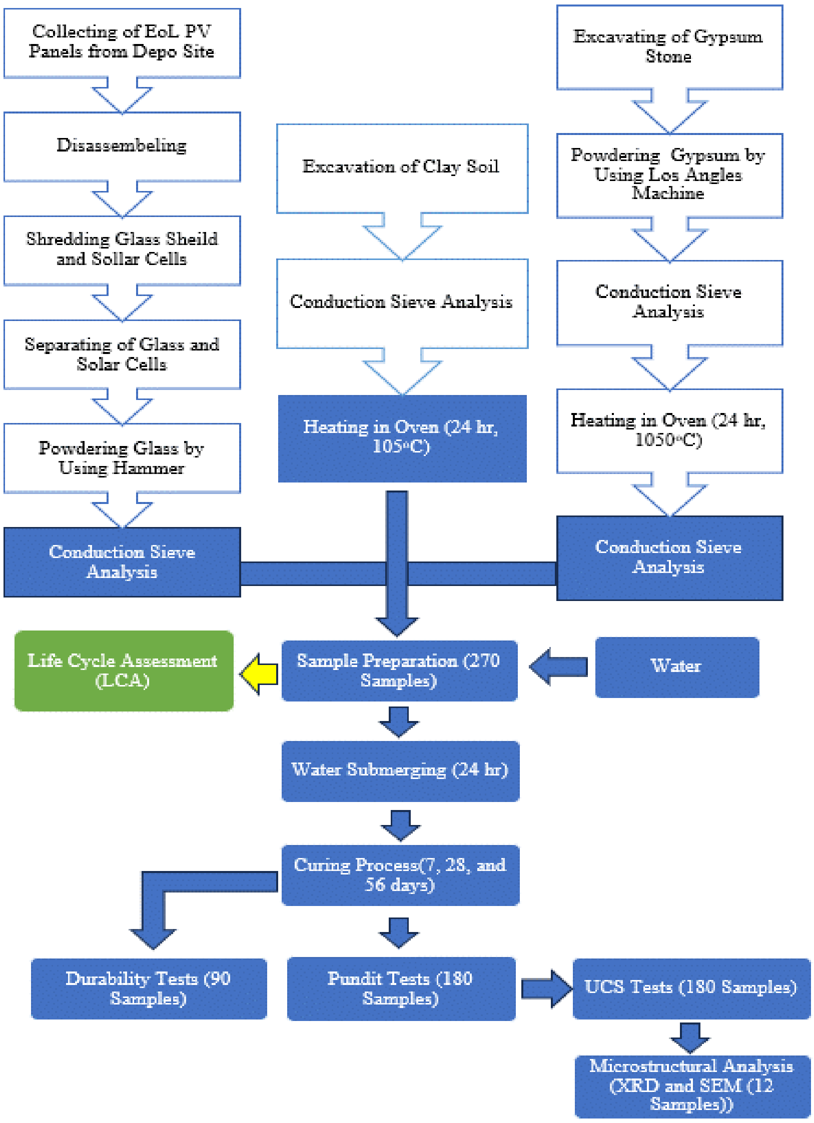
The compaction procedure of the prepared materials took into account the design dry densities of the aimed 1500 kg/m^3 and 1700 kg/m^3. The latter value of 1700 kg/m^3 is the maximum dry density that can be attained under the current conditions. For loose samples, 1500 kg/m^3 was considered appropriate since less energy isn't exerted than other density configurations. These densities were strategically selected to indicate varying degrees of compaction. This move was undertaken to enable an in-depth evaluation of the effectiveness of the composite materials under varying compaction efforts. Compacting such samples to two different densities makes it possible to understand how compaction affects some of the key characteristics of the samples being studied.

Key performance characteristics of the specimens were subjected to an extensive testing schedule to assess the influence of these compaction levels as well as the durability of the samples. Three different curing periods of 7, 28, and 56 days were selected for analysis as they studied the change in properties over a period of time. Strength and durability were assessed on the cured specimens using a series of accurate test methods. These tests consisted of initial shear modulus, uniaxial compression tests, and ultrasonic pulse velocity, which were performed individually in order to gather enough information on the mechanical properties of the material. Further assessment of the durability was done by using wetting–drying cycle tests that were done in order to replicate simulated environmental conditions and evaluate the material's resistance to degradation over time.

At the same time, microstructural assessments were performed in order to formulate a more profound comprehension of the changes that occur in the materials on the microscale. X-ray diffraction (XRD) analyses were performed to assess the presence of crystalline phases within the samples in order to comprehend the chemical alterations caused by both the compaction and curing processes. The particle shape, distribution, and structure of the bonds between the particles were described by scanning electron microscopy (SEM). The overall process in this study has been presented in Figure 10.

Figure 10

Diagram of Experimental Process in this Study



Methods

Molding and Curing Specimens

To conduct UCS testing, precise cylindrical specimens were carefully crafted, possessing a diameter of 50 mm and a height of 100 mm, adhering to the guidelines outlined in (ASTM C39/C39M-20). Initially, specific dry densities were targeted for the specimens. In this study, two target densities were selected: 1500 and 1700 kg/m^3, aligning with the maximum dry density of the clay at its optimal moisture content (17%). To accomplish this, the soil samples were first dehydrated in an oven at a temperature of 105 degrees Celsius for 24 hours. It was followed by the process of pulverization using the Los Angeles apparatus. Subsequently, the clay material was passed through sieve number 18 (with an opening of 1 mm).

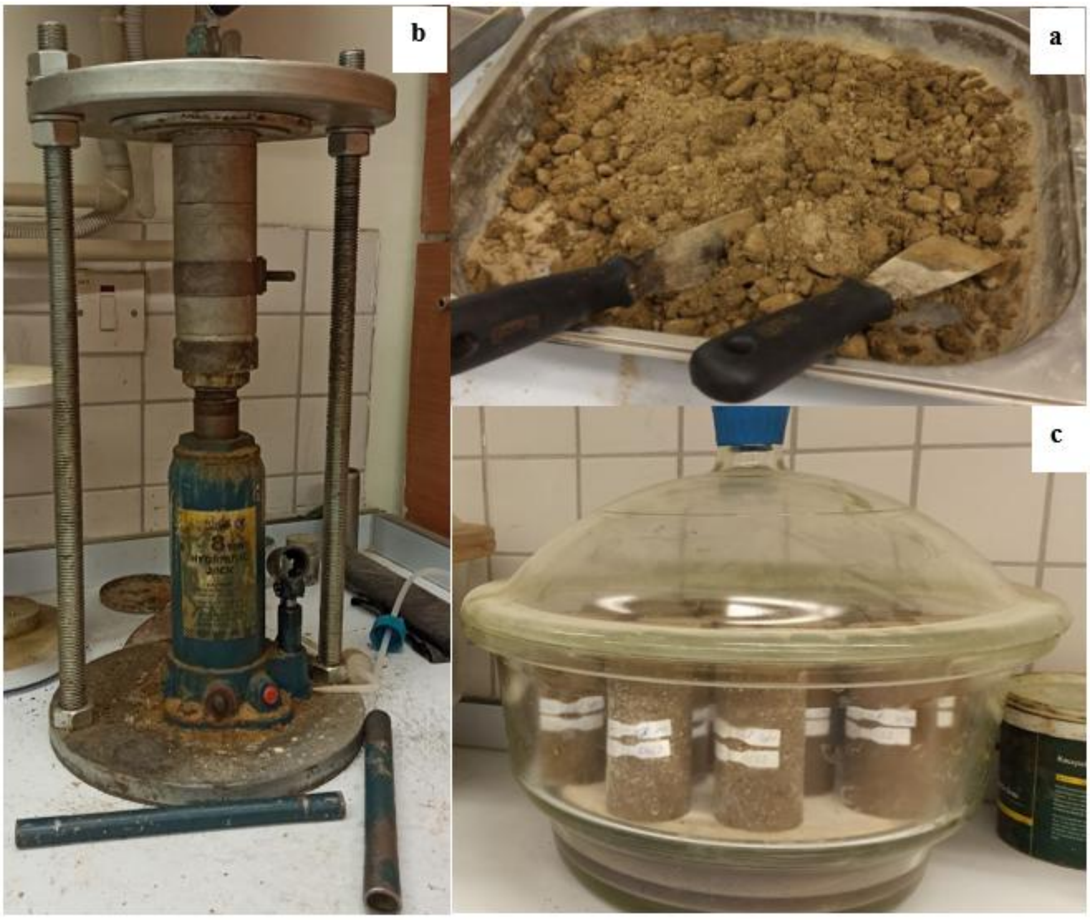
Adhering to the predetermined density requirements, the proportions of clay, GP, and sintered gypsum were then accurately considered. The specified quantities of dry materials were blended in a moisture-free environment until a consistent dispersion was attained, which usually required at least 5 minutes. After this, a predetermined quantity of water was incrementally added and mixed with the binder materials until a uniform blend was achieved. The amount of water used was based on the clay's compaction curve, which showed two different densities: the highest density (1700 kg/m^3) and a lower density (1500 kg/m^3). Three samples were prepared for each mixture. Two of them were subjected to the UCS test, while one was tested for the durability test. The UCS results for each combination were calculated as the average of the two sample results.

The blend was later divided into three equal layers and then compacted using a split mold to reach the appropriate density, following the compaction procedure proposed by Ladd (1978). Subsequent to molding, the sample was delicately removed from the mold, and its dimensions were measured. Following this, the specimens underwent a curing process by (ASTM C511-19) for different durations of 7, 28, and 56 days. The sample preparation procedure for the testing is illustrated in Figure 11.

The developed curing conditions, which consisted of sustained relative humidity control which is 100% and a normal room temperature of 25°C, were chosen in accordance with the literature, which claims that these factors significantly influence the hydration and pozzolanic activity of gypsum. This technique ensured that the weather was maintained constant and hence did not allow the temperature to dry rapidly or surface defects to be induced early, which would otherwise affect the mechanical properties of the samples.

Figure 11

Sample Preparation Procedure: (a) Incorporating Additives into Soil and then Moisturising and Homogenising, (b) Using a Static Compaction Apparatus to Compact the Sample's Three Layers, and (c) Placing in the Desiccator for the Duration of the Curing Process



After the curing process, each sample was submerged in water for 24 hours, ensuring the highest degree of saturation and assessing its capacity to withstand this long immersion without failure.

A total of 288 samples were designated for preparation to account for the test variables. Consequently, owing to the failure of the control samples (at both densities) after 24 hours of immersion in water, the total number of prepared samples was decreased to

270. Every combination of test variables has been paired with three produced samples. Two samples are prepared for UCS and G_0 tests, while one sample is designated for the ALM test. Table 1 provides comprehensive information on specimen preparation, additive compositions, and the tests performed.

Table 1.

Testing Schedule

Soil type	GP content (%)	Gypsum content (%)	Curing (Days)	Molding dry density (kg/m^3)	Test types
Clay	0	0, 5, 10 and 15	7, 28 and 56	1500 and 1700	UCS, G_0, Durability, SEM, XRD
	4	0, 5, 10 and 15	7, 28 and 56	1500 and 1700	UCS, G_0, Durability, SEM, XRD
	8	0, 5, 10 and 15	7, 28 and 56	1500 and 1700	UCS, G_0, Durability, SEM, XRD
	12	0, 5, 10 and 15	7, 28 and 56	1500 and 1700	UCS, G_0, Durability, SEM, XRD

Porosity was determined using a modified variation of Equation 1, as initially put forth by (Consoli et al., 2020), taking into account the dry density. (ρ_d), and the masses of the clay (M_s), sintered gypsum (M_{gyp}), and GP (M_{GP}). The corresponding unit-specific gravities for these components were denoted as Gs_s, Gs_{gyp}, and Gs_{GP}, respectively.

$$\eta = 100 - 100[\frac{\rho_d}{total \cdot mass \cdot of \cdot solid}][\frac{M_s}{Gs_s} + \frac{M_{gyp}}{Gs_{gyp}} + \frac{M_{GP}}{Gs_{GP}}] \quad (1)$$

Consoli et al. (2016) introduced a correlation for predicting the performance of cement-treated soils, employing the porosity-to-cement index (η/C_{iv}). Subsequently, Ekinci et al. (2019) proposed a more inclusive index (X_{iv}) that considers all components of binders to forecast the strength of different mixtures. The porosity-to-binder index (η/X_{iv}) is utilized in this study to evaluate the clay modification when it is mixed with sintered gypsum and GP. The calculation of X_{iv} is defined by Equation 2:

$$X_{iv} = \frac{V_{gyp} + V_{GP}}{V} \tag{2}$$

Unconfined Compressive Strength (UCS)

Regarding the ASTM D1633-17, methods were followed to assess the impact of additives on the compressive strength of clay by the UCS test.

For the UCS testing, an electronically controlled load frame was utilized. This load frame is equipped with a maximum load capacity of 23 kN and is calibrated to an accuracy of 0.005 kN, ensuring precise application and measurement of the load during testing. The testing protocol was designed to adhere strictly to the specifications detailed in the ASTM D1633-17 standard, including maintaining a constant strain rate of 1 mm/min throughout the testing process.

Before the commencement of the tests, each sample was completely saturated by immersing it in the water for about 24 hours at room temperature. The importance of this saturation process would be to reproduce the situations that the specimens were likely to identify where the result of the tests would be a true reflection of the properties of the material in realistic conditions. After the saturation period was completed, samples were taken out of the water, and the dimensions and weights of the samples were measured prior to the UCS test. These measurements were very important as they were used in calculating the bulk density and standardizing the test samples.

All the values of vertical displacement and load data were recorded during the UCS testing. This data was examined to derive the maximum load and the appropriate strength values for the specimens. After testing was done, the stress-strain data obtained was analyzed to acquire the values of the modulus of elasticity for every specimen. This was done by using the stress-strain values in the elastic limit curve, which was derived using the relationship in equation 3, which is essential to understanding the material's stiffness and deformation characteristics under load.

$$E = \frac{\Delta_{\sigma}}{\Delta_{\varepsilon}} \tag{3}$$

In this equation, $\Delta\sigma$ represents the alteration in the vertical stress, while $\Delta\varepsilon$ signifies the modification in the vertical displacement.

Durability Test (Wet/Dry Cycles)

Once the samples had been cured completely, the specimens were then submerged in water for 6 hours to reach proper saturation with water and simulate conditions that would potentially cause moisture damage when in service. After this wetting phase, the specimens were placed in an oven where drying was done under controlled conditions. The drying period to be maintained was 74°C ± 2°C for a period of maximum period of 42 hours. This temperature and time period were selected based on the ASTM D559 standard.

After each wetting and drying cycle, the surfaces of the specimens were carefully scratched to remove any loose material. This scratching was performed with a force equivalent to 15 N to simulate the mechanical effects that might occur during handling or environmental exposure.

Following each cycle, the mass of each specimen was precisely recorded. This data was essential for calculating the loss of mass associated with each wetting and drying cycle, a key indicator of the material's durability. By tracking the mass loss after each cycle, the study was able to determine the ALMts for each specimen after completing a maximum of twelve cycles. The ALM provided a quantitative measure of the material's resistance to cyclical environmental stressors.

Ultrasonic Pulse Velocity Tests (Pundit)

Initially, the UPV tests were accomplished on all specimens to evaluate their shear modulus before the UCS tests, following the guidelines of the ASTM C597-02 standard. A MATEST Ultrasonic Tester Model C368 was employed for these tests. It was equipped with two transducers for emitting and receiving ultrasonic waves along the specimen's length. The two transducers were securely affixed to the top and bottom of the specimen using silicon lubricant to ensure consistent wave transmission (ASTM C597-02). The waves' recorded velocity (Vs) considered the sample's length as the travel distance. Equation 4 was employed to derive the maximal shear modulus (G_0) from the sample's density (ρ).

$$G_0 = \rho \times V_s^2$$

(4)

Microstructural Tests

In this study, the pozzolanin response made from soil additives and the clay soil was checked by means of a series of microstructural tests, focusing on the use of clay soil with the sintered gypsum and GP in the presence of water. There was a need to describe the chemico-physical changes on the micro level in order to further justify the characteristics of improvement mechanisms being based on pozzolanic reactions.

In order to achieve these objectives, such techniques as X-ray diffractions and scanning electron microscopy (SEM) were used. The SEM analysis was performed on a field-emission scanning electron microscope (QUANTA 400F), which was chosen for its imaging system's high-resolution capabilities. Small sample pieces measuring about 10 mm in dimension were prepared for SEM testing and were put on aluminum stubs for stability when under an electron beam. Thin gold targets were also coated on the samples to reduce surface charging, which would affect the better image results. With this coating, a super advantageous view with higher visibility was obtained.

For the SEM analysis, images having different levels of magnification ranging from 1 K to 10 K were taken for better views of different microstructural features. These images were helpful in understanding the structure and composition of the soil-additive matrix, more so how different clay particles bond to the sintered gypsum and GP.

The analysis in this work included an X-ray powder diffractometer using the Bruker AXS D8 Advance Model. This instrument was selected for high accuracy and efficiency in the detection and quantitative analysis of crystalline phases in the samples. Also, the diffractometer was equipped with a high-speed position sensitive detector (PSD) called Vantec-1, and it was used with a Cu-Kα X-ray source. This configuration gave some important advantages in phase and structural analysis.

Areas of scanning include a 2-theta area of 2-90 degrees, which is comprehensive enough for all the relevant diffraction peaks. The scanning was carried out at 2 degrees per minute with 0.02-degree steps to make sure that the small peaks could be detectable and examined. All the operational parameters were defined with careful consideration, with the device functioning at 40 kV and 30 mA, and settings were structured to improve the proximity and detail of the diffraction information obtained.

In order to analyze the XRD data, the International Center for Diffraction Data's (ICDD) database was searched through the Crystal Impact Match Software, Version 3.11.1. This program allowed for the comparison between the diffraction patterns obtained from the samples and the ones available in the database, thus enabling the quick and precise determination of the crystalline components within the samples. Furthermore, all diffractograms obtained from the XRD analysis were subjected to some improvement and understanding through the use of HighScore (Plus version 3.0.5), which provided more advanced data processing and peak-picking features.

Life Cycle Assessment (LCA)

Investigating the environmental impacts associated with the utilization of GP derived from EoL PV panels and sintered gypsum for soil stabilization is critical, given the significant energy and material consumption involved. The LCA was conducted following the standards of the International Standardization Organization (ISO) 14040 and 14044. Following these standards, the environmental impacts of different blends in this study were systematically evaluated through four phases:

- Goal and scope definition phase
- Inventory analysis phase
- Impact assessment phase
- Interpretation phase

Goal and Scope Definition Phase. The objective of the LCA was to evaluate the environmental implications linked to the utilization of recycled GP from end-of-life PV panels and sintered gypsum in soil stabilization. The functional unit (FU) was established as one cubic meter of the mix, facilitating a consistent comparison across various material combinations. The system boundaries were defined to include the entire process, from the manufacturing of GP and sintered gypsum to the formulation of the final blend utilized in soil stabilization. This border encompasses material processing, transportation, and energy consumption related to both material manufacturing and on-site preparation, thereby facilitating a thorough examination of environmental implications.

The study concentrated on a midway curing duration of 28 days to guarantee that the comparison of material blends is both significant and rigorous. This decision signifies the pivotal moment when mechanical properties settle, offering a pertinent overview of the environmental impact linked to this stage of material development. The product system of this study has the following main processes:

- Producing GP from EoL PV panels
- Preparing sintered gypsum
- Preparing the blend (mixing, homogenization, and compaction)

Preparing the Blend (In The Field). To prepare the blends, clay, water, sintered gypsum, and GP are added to the mass specified in Table 3. The blend's preparation and homogenization involve using various pieces of equipment. A motor grader was used to create a flat surface during the grading process. An additive spreader was used to mix additives with soil, and a water spreader was employed to disperse water in the soil. Finally, compaction was achieved using a pad-foot roller.

Table 2.

Mass of the Additives in Different Samples

Sample ID	Mass of soil (kg)	Mass of GP (kg)	Mass of Gypsum (kg)	Mass of water (kg)
1.7GP0GYP5	1619.0	0.0	81.0	356.3
1.7GP4GYP5	1559.6	62.4	78.0	356.3
1.7GP8GYP5	1504.4	120.4	75.2	352.4
1.7GP12GYP5	1453.0	174.4	72.6	348.7
1.7GP0GYP10	1545.5	0.0	154.5	356.3
1.7GP4GYP10	1491.2	59.6	149.1	352.2
1.7GP8GYP10	1440.7	115.3	144.1	352.5
1.7GP12GYP10	1393.4	167.2	139.3	348.9
1.7GP0GYP15	1478.3	0.0	221.7	356.3
1.7GP4GYP15	1428.6	57.1	214.3	352.3
1.7GP8GYP15	1382.1	110.6	207.3	348.4
1.7GP12GYP15	1338.6	160.6	200.8	349.1
1.5GP0GYP5	1428.57	0.00	71.43	431.94
1.5GP4GYP5	1376.15	55.05	68.81	428.21
1.5GP8GYP5	1327.43	106.19	66.37	424.83

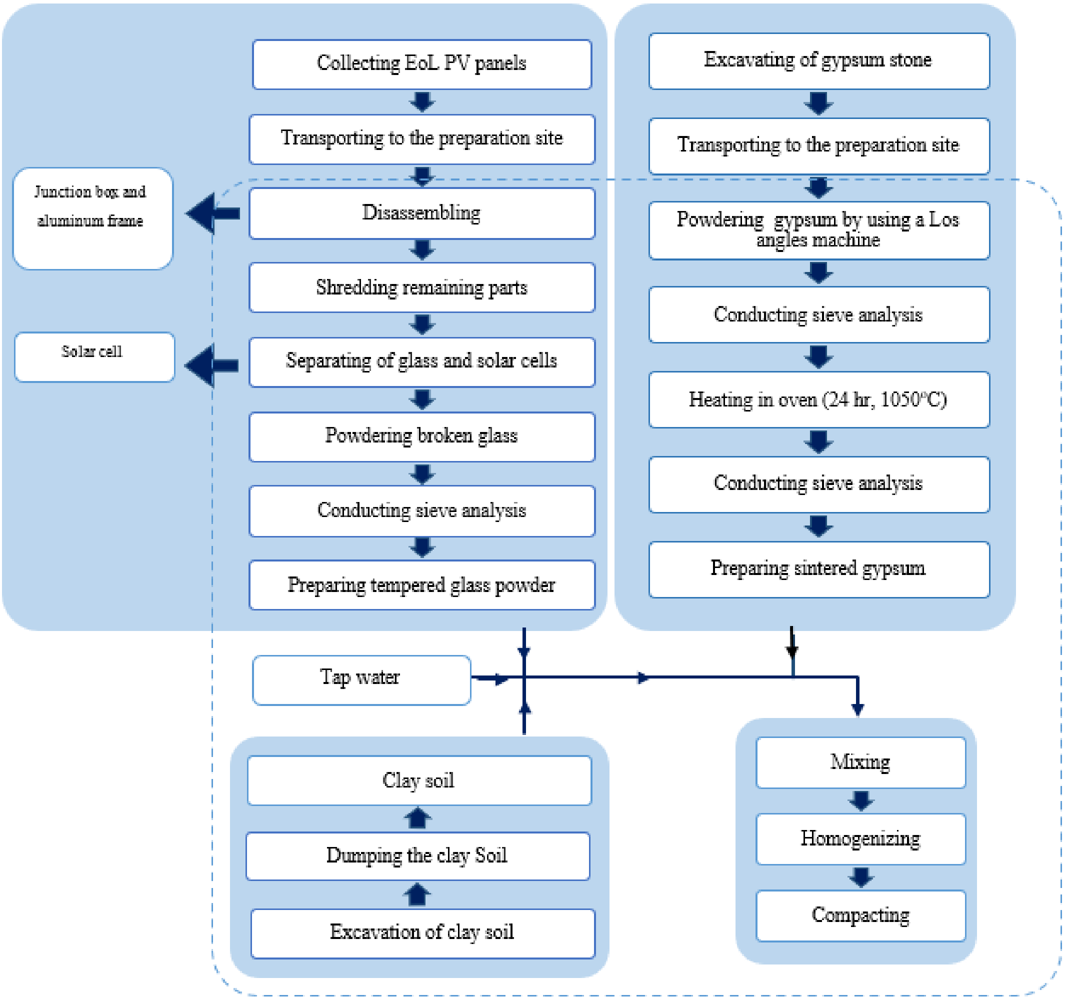
Table 2 (Continued).

1.5GP12GYP5	1282.05	153.85	64.10	431.94
1.5GP0GYP10	1363.64	0.00	136.36	428.33
1.5GP4GYP10	1315.79	52.63	131.58	425.06
1.5GP8GYP10	1271.19	101.69	127.12	431.93
1.5GP12GYP10	1229.51	147.54	122.95	428.45
1.5GP0GYP15	1304.35	0.00	195.65	425.28
1.5GP4GYP15	1260.50	50.42	189.08	431.93
1.5GP8GYP15	1219.51	97.56	182.93	428.56
1.5GP12GYP15	1181.10	141.73	177.17	425.48

System Boundary. The system boundaries of this study are shown in Figure 12.

Figure 12

System Boundaries



Life Cycle Inventory Analyzing (LCI) Phase. The inventory analysis examined not only the energy but also the materials consumed per process stage in detail. The investigation featured the array of material characteristics of the end-of-life photovoltaic panels during GP creation that depends on the panel's age and the manufacturer (Singh et al., 2021). The average weight of a photovoltaic panel is 18 kg, which normally has a recyclability of around 56% due to the problems in the recycling of the solar cell's attachment glass, particularly remaining attached. This efficiency metric was obtained through observations of the processes and processes related to sourcing relevant literature, ensuring reliability in the assessment of the externalities. Table 3 summarizes the EoL PV panels' share of the material for this study, including the composition mentioned above.

Table 3.

Mass Composition of PV Panels

Material	Percentage	Weight (kg)
Glass	70	12.6
Aluminum	13.7	2.466
Polymers	9.2	1.656
Silicon	3.7	0.666
Copper	3.2	0.576
Silver	0.055	0.0099
Zinc	0.09	0.0162
Others	0.055	0.0099

The energy associated with the separation processes was defined in terms of the average electricity consumption that was known (18 kW) and the time spent processing each panel. A duration of 2 minutes is required in the process of glass extraction from an individual PV panel. Table 4 explains the energy consumption for GP production.

The energy required for the production of the sintered gypsum was computed based on the kiln's power of 1.6 kW, where the gypsum was sintered at 1050 degrees Celsius for a period of 8 hours (net time of the kiln's working). These computations were very significant in, and indeed necessary, assisting in helping to improve the procedures of assessing the extent of energy spent in material preparation, as shown in Table 5.

$$E_{kWh} = P_{kW} \times T_h \tag{5}$$

Table 4.

Inventory Data for GP Generation

Output flow	Input flow	Amount
GP	PV Panel (number)	1
	Electricity (kWh)	0.6

Table 5.

Inventory Data for Sintered Gypsum Production

Output flow	Input flow	Amount
Sintered Gypsum	Gypsum (kg)	30
	Electricity (kWh)	12.8

The machinery working hours to prepare 1m^3 are shown in Table 6.

Table 6.

Machinery Working Hours for Preparing 1 m^3 of the Blend (Al-Subari et al., 2023)

Equipment	Power (HP)	Time (Hours/m^3)
Soil Excavation	150	0.0105
Dumping Truck	220	0.069
Pad-foot Roller	115	0.0092
Water Spreader Truck	220	0.0039
Gypsum/GP spreader	115	0.0042
Motor Grader	185	0.0133
Total		0.1101

Life Cycle Impact Assessment Phase. The LCA was performed using the OpenLCA (version 2.1.1). The Ecoinvent 3.7 database was used in this study because it is one of the best databases in terms of life cycle inventory (LCI) characteristics.

For the purposes of impact evaluation in this study, the ReCiPe midpoint (H) was employed to evaluate various environmental issues and outcomes. The ReCiPe midpoint H method, as applied in the software OpenLCA, was claimed to be a modernized life cycle impact assessment method that incorporates recent developments in science (Veronese et al., 2020). This method permits an evaluation of the relative environmental impacts of alternative products, services, or processes (Iswara et al., 2020).

In this study, environmental problems with ozone depletion, particulate matter creation, urban land use, global warming, water use, and fossil fuel use were selected because they are the most relevant problems involved with glass and sintered gypsum powder as construction materials. Ozone depletion issue is included as it concerns the amount of harmful substances that can be lowered with the use of prefabricated units. Particulate matter creation is likewise important as anything that can help replace these traditional materials can help reduce air pollution. Urban land occupation is emphasized, as finite sources and land area can be conservatively allocated in case the materials used are greener. Climate change is aggravated, therefore, by less emission of gases that lean more on more energy-consuming materials. Water depletion is dealt with when issues of selective use of reclaimed materials or materials requiring less water are addressed. Fossil depletion is also tackled by this approach, as it is possible to minimize energy inputs by using low-energy-embodied materials. As a result, decreasing the consumption of non-renewable energy sources.

CHAPTER IV

Findings and Discussion

This section aims to show the major results obtained by data analysis and give a detailed discussion. The first section includes the physical properties of clays used, GP, and gypsum as the two other main materials. This is then followed by a subchapter devoted to the properties of the composite materials from a mechanical point of view, which contains a detailed statistical analysis. Then, the durability of the mixes is covered. This is explored, and in this case, it discusses procedures and trends. The chapter explores and covers the macro-level outcomes of the mixtures and their behavior in the macro scope. Finally, the LCA discussion will take place.

In this part, to provide a comprehensive context for these investigations, Table 7 presents a detailed overview of the physical characteristics of the clay soil, gypsum, and GP used as additives in the experimental program. This table includes essential parameters such as specific gravity and Atterberg limits, which are fundamental to understanding the behavior of the materials under different compaction conditions.

Table 7.

Physical Characteristics of Clay Soil, Sintered Gypsum, and GP

Properties	**Clay**	**Sintered Gypsum Powder**	**GP**
Consistency Limits			
Plasticity index (%)	26	-	-
Liquid limit (%)	46	-	-
Specific gravity	2.66	2.33	2.64
Particle-Size Distribution			
D_{50} particle diameter (mm)	0.005	0.1	1
Clay (diameter < 0.002 mm) (%)	40	-	-
Silt (0.002 mm < diameter < 0.075 mm) (%)	54	25	2.53
Fine sand (0.075 mm < diameter < 0.425 mm) (%)	6	75	25
USCS classification	CL	-	-

Table 7 (Continued).

Standard Proctor Compaction Characteristics			
Maximum Dry Density (kg/m^3)	1700	-	-
Optimum moisture Content (%)	17	-	-

Effect of Test Variables on Mechanical Behavior

The study conducted a statistical analysis of the dry densities (1700 and 1500 kg/m^3), glass-powder contents, gypsum contents, and curing durations. This assessment explains the distinct effects of individual factors on the (UCS), as shown in Figure 13a–c, (G_0) depicted in Figure 13d–f, and (E) represented in Figure 13g–i. Regardless of other factors' influence, the calculated factors exhibited a noticeable increase when the specimens were compacted to a greater dry density. It is attributed to the porosity reduction and enhanced interaction of soil particles and additive materials in denser specimens. The increase in gypsum content resulted in a consistent improvement across all strength and stiffness features. It is worth noting that the increase was more significant in denser samples than in less dense ones.

On the other hand, the behavior of the glass-powder content was inconsistent across all strength and stiffness features. It was observed that, for all mentioned features (UCS, G_0, and E), increments from 0% to 8% led to a decrease, and suddenly, for the 12% content, a shift to an increasing trend was noted. It highlights the significance of a 12% glass powder content in the samples, implying a critical threshold for this material.

Examining the variables test, it is also reported here that the test variables particularly have the most effect on the G_0 compared to E.

The results from statistical analysis revealed that there was a significant relationship between all test variables and strength as well as the stiffness of the samples. It was observed that the performance of these characteristics was greatly influenced by the presence of gypsum in the blend.

Figure 13

Effect Assessment of Test Variables on Mechanical Properties: (a) UCS-Gypsum, (b) UCS-GP, (c) UCS-Curing Days, (d) G_0-Gypsum, (e) G_0-GP, (f) G_0-Curing Days, (g) E-Gypsum, (h) Es-GP, (i) E-Curing Days

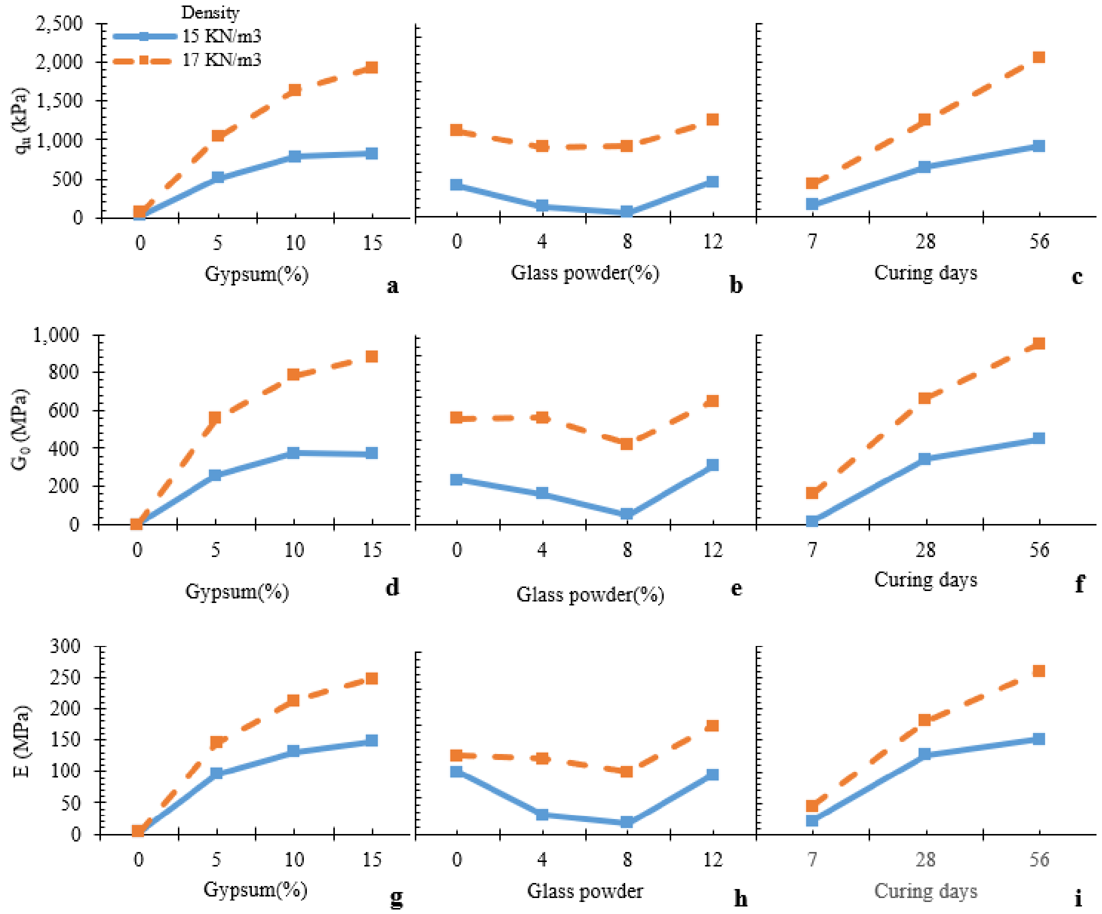
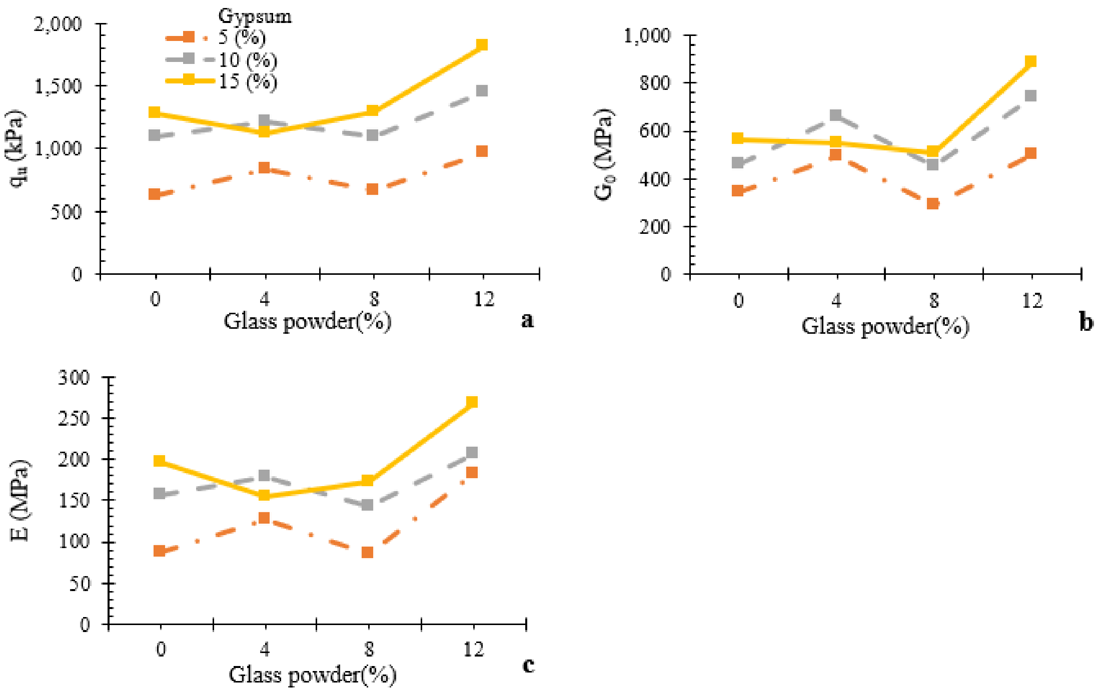


Figure 14

Effect Assessment of GP on Mechanical Properties in Presence of Different Percentages of Sintered Gypsum: q_u -GP (a), G_0-GP (b), E-GP (c)



ANOVA, in this case, has been performed to evaluate the variation in mechanical property with the variation of GP content within each sintered gypsum composition, which has been shown in Figure 14. A comparison of Figure 14 with Figure 14 shows that for the case of varying proportions of sintered gypsum, there is clear scope for the interrelationship of strength, stiffness, and GP content at all times in focus.

Figure 14 shows the apparent trend that samples incorporating 5% and 10% sintered gypsum possess enhanced physical properties with a rise in GP amount from 0% to 4%, after which a decline is observed up to 8% GP content. In addition, there is an increase in the physical properties when the content of GP is raised to 12%. In contrast, the behavior changes remarkably for the composition of sintered gypsum 15%. Here, both strength and stiffness increase with the increase from 4% to 12% of GP content, and after a small decrease with an increase from 0% to 4%. However, in Figure 13, the general tendency traced in eight figures is very different, and mechanical properties are the lowest in the figures with a GP content of 8%. This highlights the crucial influence of sintered gypsum in parallel with GP content, which needs careful evaluation when the effect of GP content on complete mechanical properties is assessed.

Consequently, the noted variations signify the extent to which GP and sintered gypsum combine in the content of the samples, implying a more complex relationship that affects the physical characteristics of the sample, such as those outlined through the ANOVA test. These findings propose a more embedded consideration for the joint impact of GP and sintered gypsum on the mechanical properties, which helps facilitate material formulation and design in broader areas of general applications.

Table 8.

Results from an ANOVA Test with Respect to UCS, G_0, and E

Dependent Variable:	**Unconfined compressive strength**				
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Corrected Model	151489329.444[a]	89	1702127.3	127.376	0.00
Intercept	130794753.119	1	130794753.1	9787.829	0.00
D	17695110.023	1	17695110.0	1324.187	0.00
GYP	42456101.576	3	14152033.9	1059.046	0.00
GP	3472118.292	3	1157372.8	86.610	0.00
CD	37869655.204	2	18934827.6	1416.959	0.00
D * GYP	7025662.280	3	2341887.4	175.252	0.00
D * GP	625951.690	3	208650.6	15.614	0.00
D * CD	4874786.442	2	2437393.2	182.399	0.00
GYP * GP	1746039.792	8	218255.0	16.333	0.00
GYP * CD	16479886.292	6	2746647.7	205.541	0.00

Dependent Variable:	**Initial shear modulus**				
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Corrected Model	39784267.379[a]	89	447014.2	340.431	0.00
Intercept	29567775.475	1	29567775.5	22517.828	0.00
D	4068424.330	1	4068424.3	3098.376	0.00
GYP	10162954.510	3	3387651.5	2579.922	0.00
GP	1378642.975	3	459547.7	349.976	0.00
CD	10740360.514	2	5370180.3	4089.749	0.00
D * GYP	1698067.081	3	566022.4	431.064	0.00
D * GP	172557.216	3	57519.1	43.805	0.00
D * CD	1017736.952	2	508868.5	387.537	0.00
GYP * GP	838923.232	8	104865.4	79.862	0.00
GYP * CD	3994036.753	6	665672.8	506.954	0.00

Dependent Variable:	**Elastic modulus**				
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Corrected Model	2911854.592[a]	89	32717.5	47.854	0.00
Intercept	2640246.253	1	2640246.3	3861.746	0.00
D	157156.407	1	157156.4	229.864	0.00
GYP	862859.492	3	287619.8	420.686	0.00
GP	136815.911	3	45605.3	66.704	0.00
CD	798672.510	2	399336.3	584.088	0.00
D * GYP	79807.964	3	26602.7	38.910	0.00
D * GP	22050.839	3	7350.3	10.751	0.00
D * CD	38338.135	2	19169.1	28.038	0.00
GYP * GP	60974.242	8	7621.8	11.148	0.00
GYP * CD	309229.567	6	51538.3	75.382	0.00

Table 8 (Continued).

GP * CD	2628889.806	6	438148.3	32.788	0.00	**GP * CD**	1261044.178	6	210174.0	160.062	0.00	**GP * CD**	145217.173	6	24202.9	35.400	0.00
D * GYP * GP	1063823.949	8	132978.0	9.951	0.00	**D * GYP * GP**	124527.962	8	15566.0	11.855	0.00	**D * GYP * GP**	15155.226	8	1894.4	2.771	0.01
D * GYP * CD	3754889.588	6	625814.9	46.832	0.00	**D * GYP * CD**	557516.957	6	92919.5	70.764	0.00	**D * GYP * CD**	28513.195	6	4752.2	6.951	0.00
D * GP * CD	666631.074	6	111105.2	8.314	0.00	**D * GP * CD**	146741.093	6	24456.8	18.626	0.00	**D * GP * CD**	49867.779	6	8311.3	12.156	0.00
GYP * GP * CD	1989402.569	16	124337.7	9.305	0.00	**GYP * GP * CD**	1114011.902	16	69625.7	53.025	0.00	**GYP * GP * CD**	64208.460	16	4013.0	5.870	0.00
D * GYP * GP * CD	1789875.079	16	111867.2	8.371	0.00	**D * GYP * GP * CD**	577233.152	16	36077.1	27.475	0.00	**D * GYP * GP * CD**	39693.976	16	2480.9	3.629	0.00

Table 8 presents a statistical interpretation regarding the relationship of the samples with the test variables (additives, densities, and curing days) and the mechanical parameters (UCS, G_0, E). For each of the entries given in the Table, the significance (P value) is less than 0.05, meaning that there is a meaningful relationship between the test variables and the mechanical properties of the samples. On the contrary, the corrected model provides a great F-statistic supporting the interdependence of the test variables and mechanical properties. It has been illustrated in Table 8 that the test variables have the most notable effect on G_0 and much less on E.

Figure 15

Correlation Between Different Additive Combinations and UCS Amounts for Two Densities: (a) 1500 kg/m^3 And (b) 1700 kg/m^3

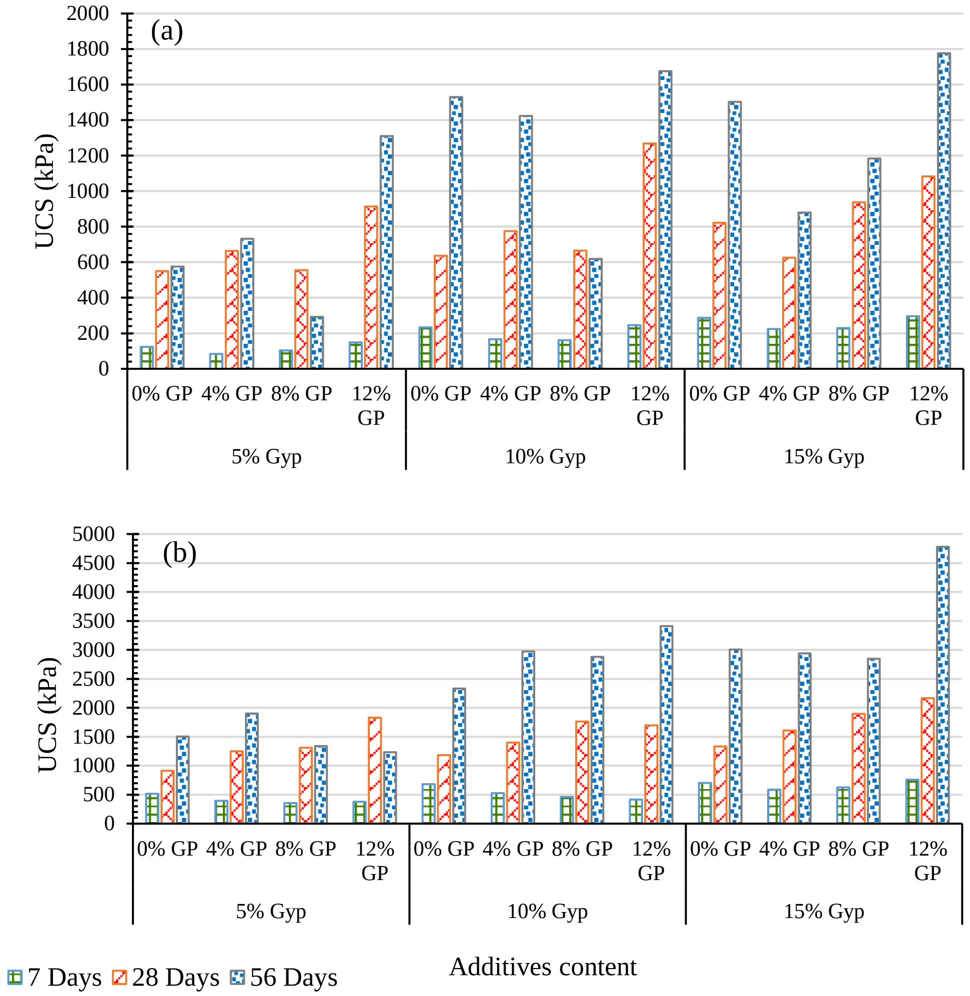


Figure 15 provides the coherent correlation between the soil strength and test variables. Regarding the effect of sintered gypsum content, the unconfined compressive strength (UCS) of the specimen consistently improves over various soil densities. This shows a general trend of improving soil strength with the increasing sintered gypsum content. Particularly, this improvement is seen mostly in the denser soils. Also, curing periods of 28 and 56 days are important factors that need to be taken into account in that the impact of the additives is further pronounced during any of these particular periods. On the other hand, the GP content effect on UCS does not show a constant behavior.

For example, at 5% sintered gypsum content, UCS increases incrementally from 0% to 4% GP, followed by a decrease at 8% GP and subsequent increases at 12%

GP. This irregular trend underscores the sophisticated influence of GP on soil strength, suggesting that its effectiveness depends upon specific proportions and interactions with other additives.

Figure 16

Correlation Between Different Additive Combinations and G_0 Amounts for Two Densities: (a) 1500 kg/m^3 and (b) 1700 kg/m^3

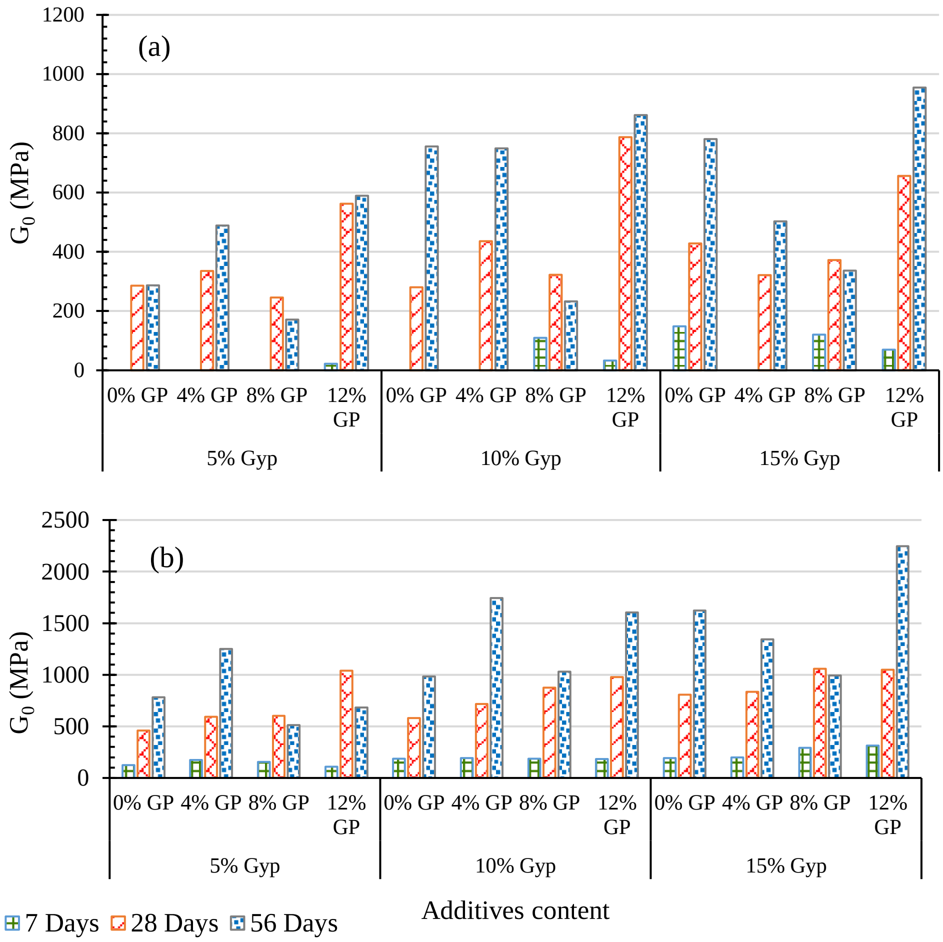


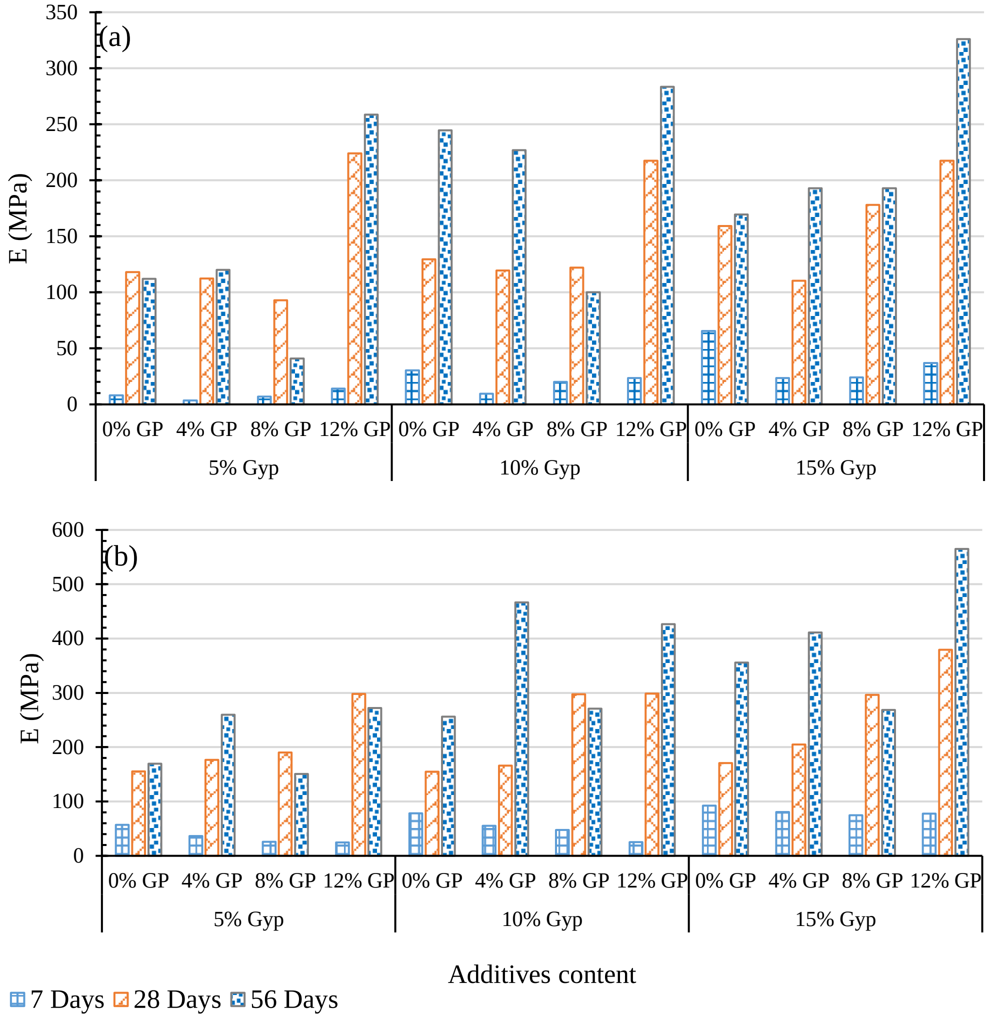
Figure 16 reveals that the G_0 values for the samples with seven curing days are low, particularly for the lower density ones. The trend of increasing stiffness follows a pattern similar to the UCS Figures. However, a low GP content aggravates the stiffness of the samples, especially in high-sintered gypsum content samples. It seems that there is a minimum limit for GP percentage that must be considered to improve stiffness.

In loose samples, higher G_0 values are associated either without GP or with 12% GP. An interesting finding from Figure 16b is that among samples with 5% and

10% sintered gypsum content, higher G_0 values are expressed in those with 4% GP compared to others. However, the greatest stiffness is observed in samples with the highest sintered gypsum content, in those with 12% GP across all tested specimens. In addition, Figure 16 shows that in samples with 8% GP, higher G_0 is observed in specimens cured for 28 days compared to those cured for 56 days.

Figure 17

Correlation Between Different Additive Combinations and E Amounts for Two Densities: (a) 1500 kg/m^3 and (b) 1700 kg/m^3



Additionally, E in relation to samples which cured for periods of 28 days showed increasingly higher values than those that had cured for periods of 56 days (Figure 17), particulary in the analysis of this section for 8% GP content specimens.

One of the main points that can be deduced from the UCS, G_0, and E bar charts is that, in both densities, samples containing 4% GP content demonstrate an enhanced condition compared to those with 0% and 8% GP content. This implies that even with the limited availability of GP, clay improvement is still feasible initially. Moreover, the utilization of waste GP holds significance in terms of solid waste management practices.

Influence of Porosity/Binder Index on UCS

Figure 18 illustrates the correlation between the UCS and the corrected porosity/binder (P/B) ratio (η/X_{iv}^{α}) for various samples with varying additives, densities, and curing durations.

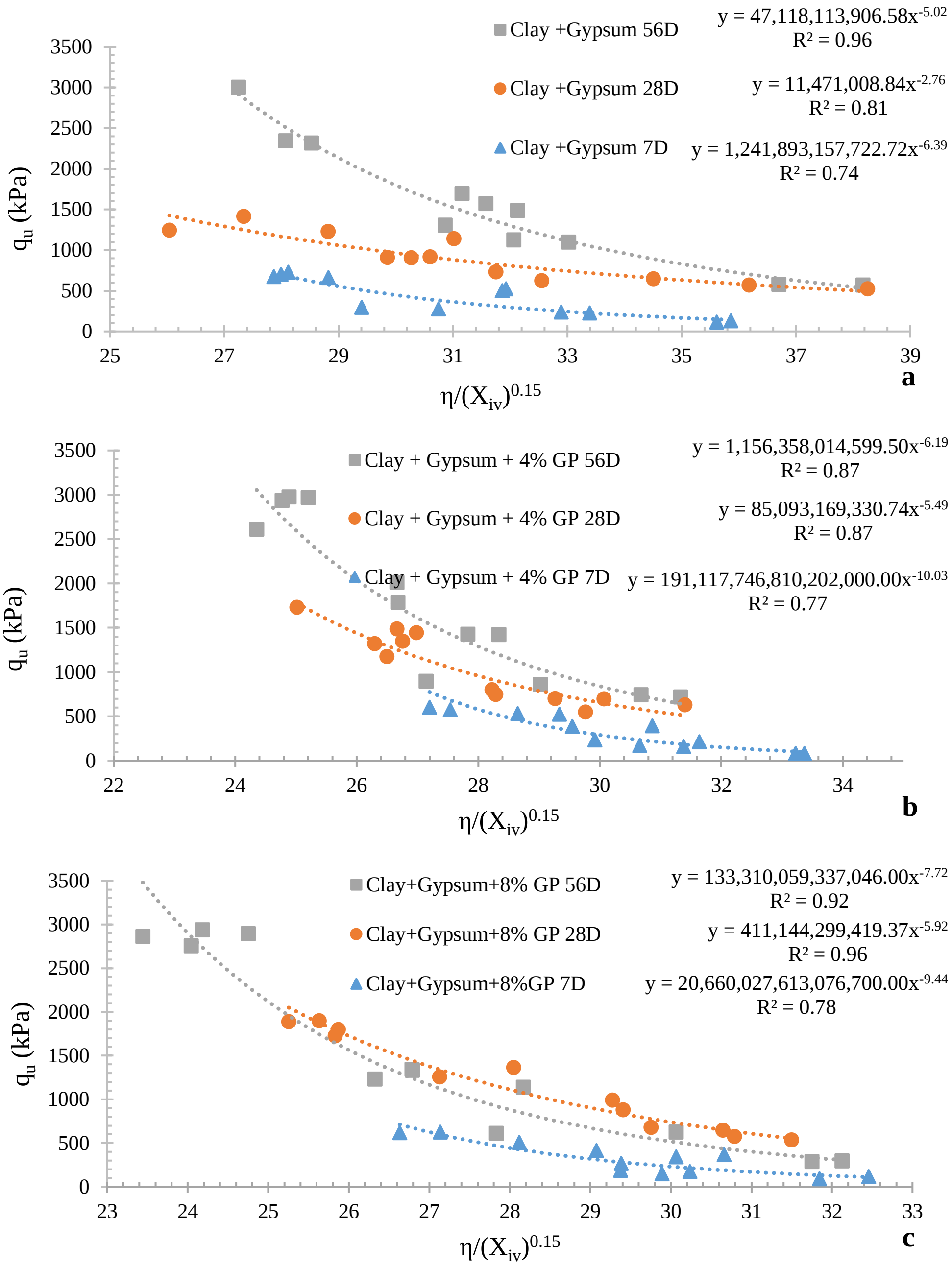
This study shows that porosity significantly impacts blend behavior, as evidenced by the power coefficient α. It is consistent with prior research findings (Filho et al., 2021). When α assumes a value of less than 1, it implies that porosity has a more significant influence (Hanafi et al., 2022). Within the present investigation, the optimal fit was at $\alpha = 0.15$. It aligns with earlier empirical studies, where α values typically ranged from 0.12 to 0.35, primarily depending on the specific soil type, as demonstrated in previous research.

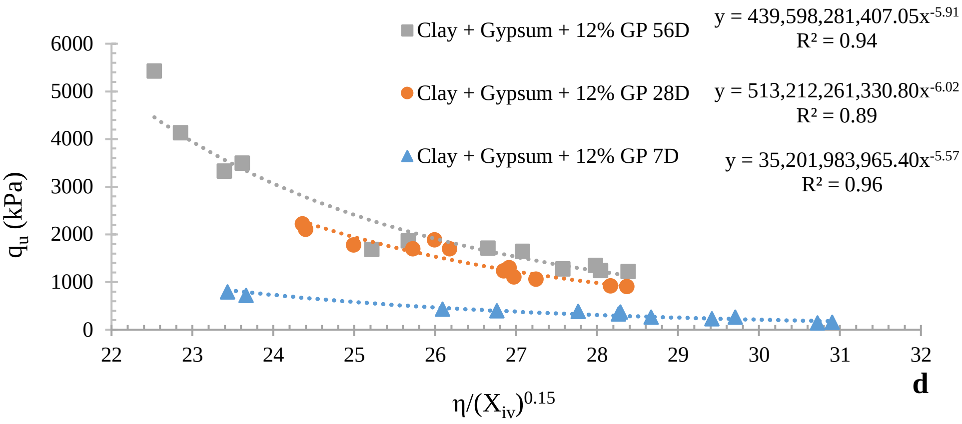
As can be seen from Figures 18a to 18d, by increasing the porosity index, the decrease of q_u has been achieved that aligned with prior studies (Consoli et al., 2007; Ekinci et al., 2019 and Ekinci et al., 2020). Considering the amount of GP, it was revealed that samples with 12% GP, compared to the other percentages of GP, have a lesser range of porosity that yields higher amounts of q_u. This jump from 8% to 12% of GP is because of a higher reduction in porosity investigated in the microstructural analysis. On the other hand, the high regressions of curvatures in Figures 18a to 18d represent a significant relation between q_u and porosity in all samples.

Moreover, regarding the graphs in Figure 18, curing days play a significant role in sample strengthening. As shown in Figures 18a to 16d, graphs of 7, 28, and 56 curing days are positioned above each other, respectively, except for samples with a GP content of 8%. In addition, graphs related to 7 curing days are notably distinguished from the other two graphs in each chart regarding the distance, especially at high porosities. The growth of q_u by increasing the curing days is predictable; however, the case of GP content of 8% is discussed in the microstructural analysis part.

Figure 18

The Associations Between the UCS and the Modified P/B Index were Analyzed for All Curing Durations and Different Amounts of Sintered Gypsum with (a) 0% GP, (b) 4% GP, (c) 8% GP, and (d) 12% GP for Both Samples' Dry Densities





d

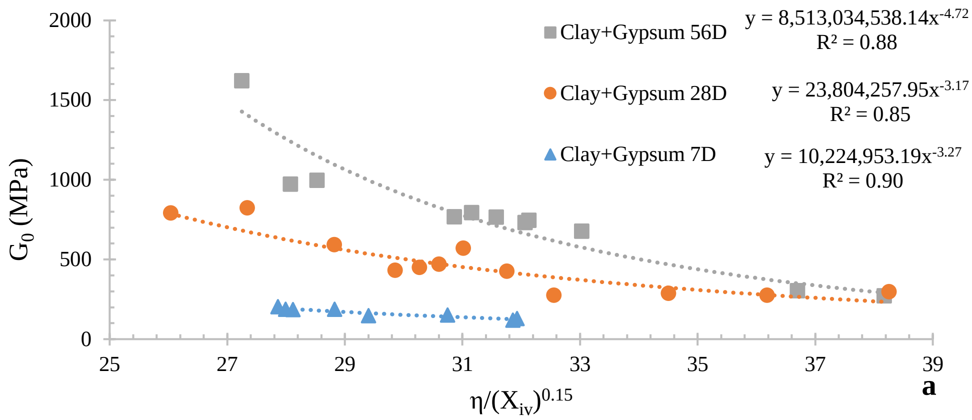
Influence of P/B Index on G_0

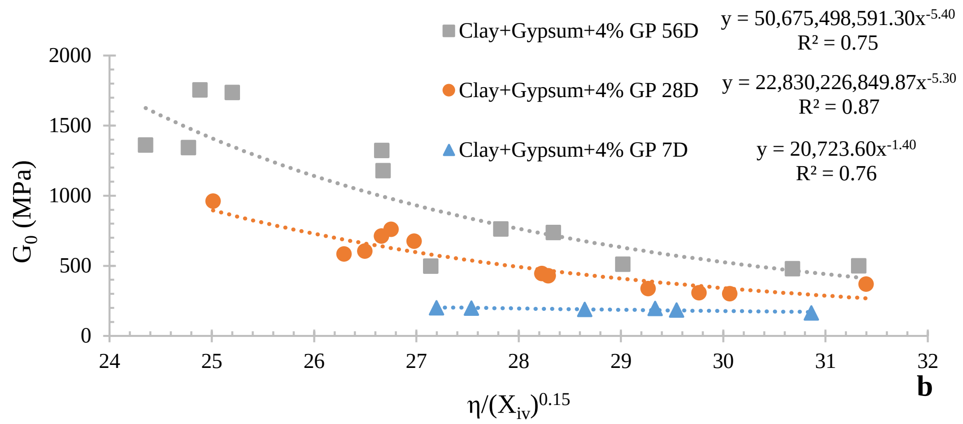
Figure 19 illustrates how the G_0 relates to the modified porosity-to-binder index ($\eta/X_{iv}^{0.15}$). In contrast to the findings of the UCS test, the diagrams show lower regression coefficients. Due to the regression status of the charts, there is an excellent correlation between the porosity index and stiffness; again, graphs with 12% GP have the highest regression coefficient among the other GP percentages.

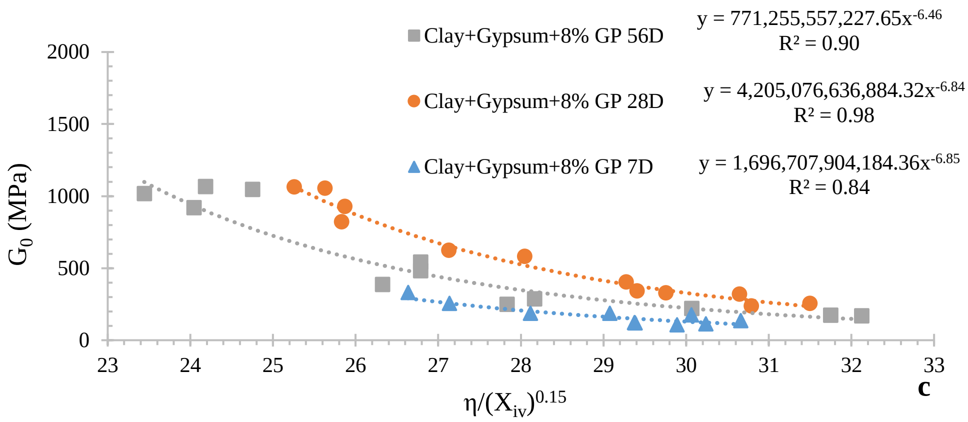
Here, similar to the previous part, the graphs' positions are predictable, which means that an increase in curing periods increases the samples' stiffness, except for the chart related to samples with a GP content of 8%. Furthermore, the results for the seven-day-cured samples are not close to the 28- and 56-day curing duration results, and the behaviors of these samples are more linear in comparison with the q_u graphs. In other words, the additives' effects on soil improvement are negligible on short curing days. However, the chart with 8% GP exhibits an exception again.

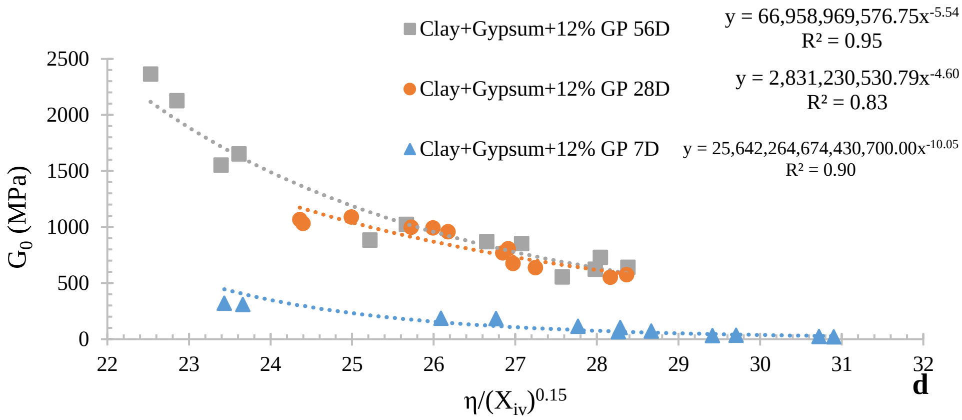
Figure 19

The Associations Between the G_0 and the Modified P/B Index were Analyzed for All Curing Durations and Different Amounts of Sintered Gypsum with (a) 0% GP, (b) 4% GP, (c) 8% GP, (d) 12% GP for Both Samples' Dry Densities





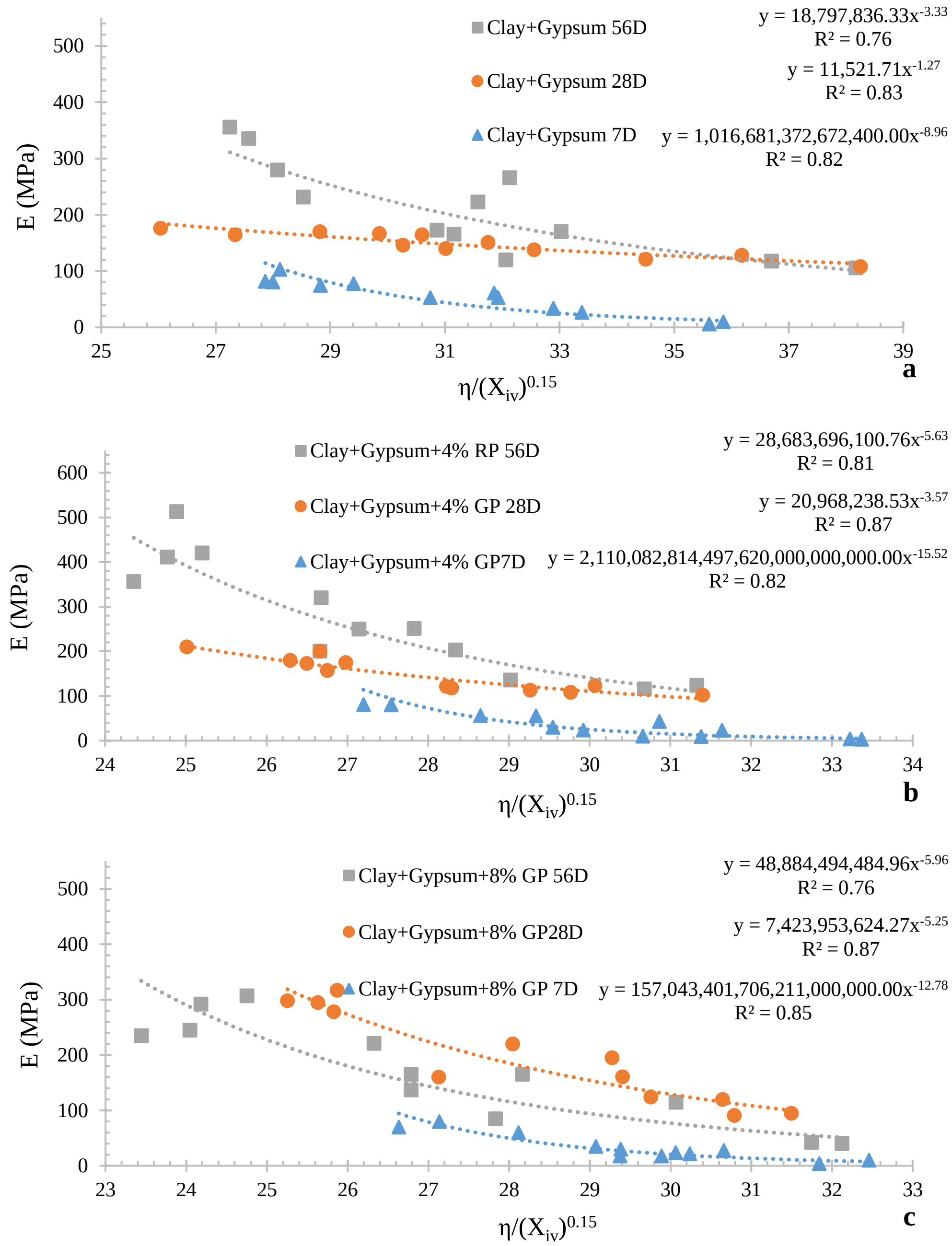


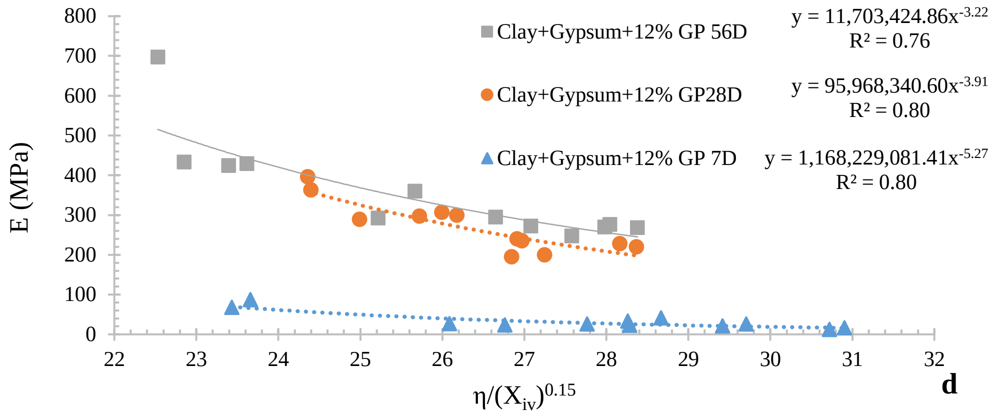


Considering Figure 20 reveals that elastic modulus expresses semi-linear behaviour for GP content of 0 and 4 percent. Regarding Figure 20 d, in high content of GP, curation plays a major role in these samples, while 7 days cured samples are far from samples with curing days of 28 and 56. The special behaviour of samples with 8% of GP followed by previous sections.

Figure 20

The Associations Between the E and the Modified P/B Index were Analyzed for All Curing Durations and Different Amounts of Sintered Gypsum with (a) 0% GP, (b) 4% GP, (c) 8% GP, (d) 12% GP for Both Samples' Dry Densities





Influence of P/B Index on Normalized UCS, G_0 and E

Figures 21, 22, and 23 express the sample normalized results of UCS, G_0, and E, respectively. On top of that, enhanced predictive capabilities and better understanding have been achieved as a result of this normalization process. In this case, equations 6, 7, and 8 also display regression coefficient values of R^2 = 0.87, R^2 = 0.82, and R^2 = 0.76, respectively. Regardless of the amount of additives and the curing length, these statistical relationships are important and valid in finding q_u, G_0, and E associated with a specific blend by one test. It is recommended to do this test with three similar samples to achieve a typical strength amount for the selected value of $\eta/X_{iv}^{0.15}$, represented as ∇, for improved accuracy. The decision to use ∇ amounts near 25 was made in this work because it is recommended in recent studies on different materials (Ekinci et al., 2019; Ekinci et al., 2020).

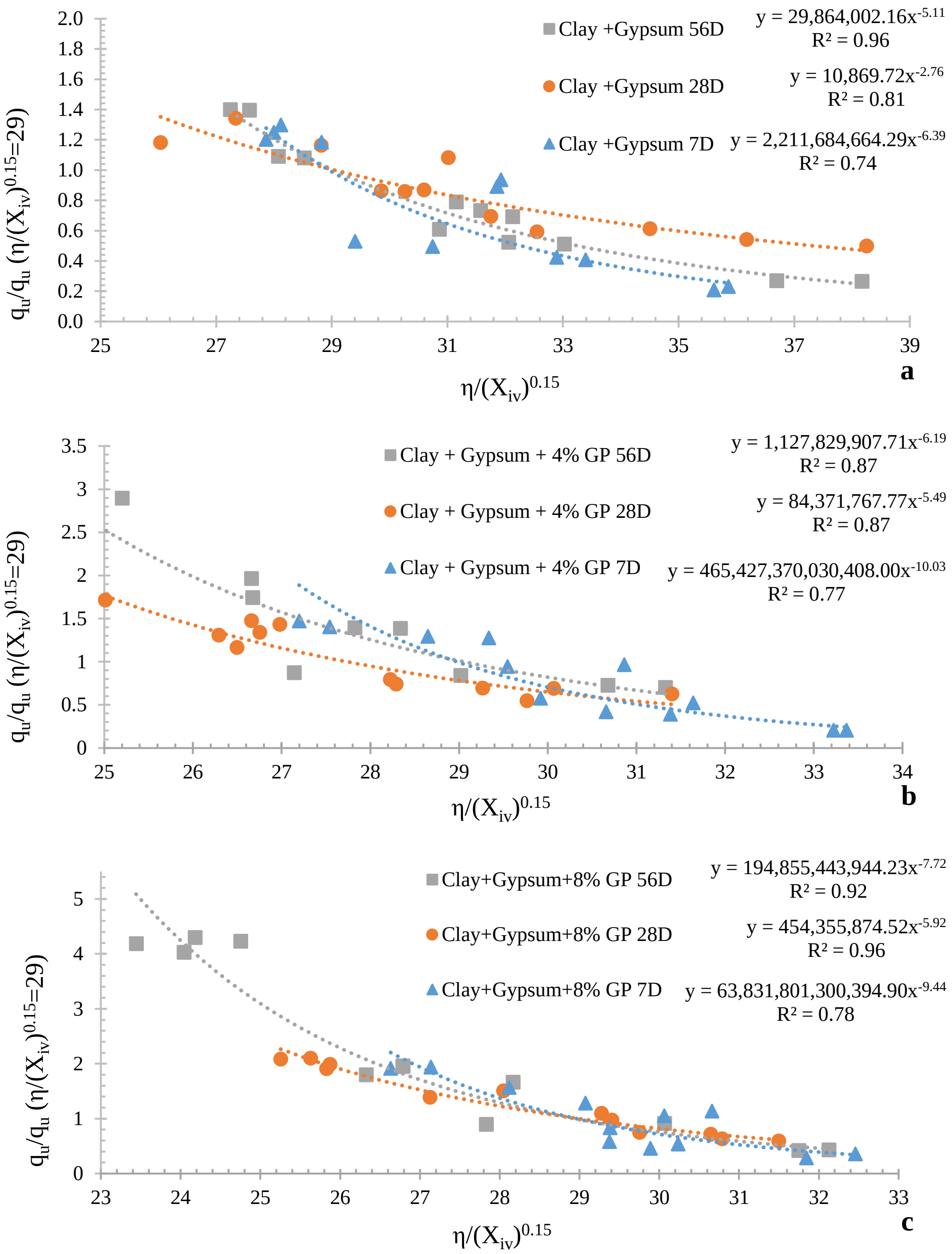
$$q_u = q_{u_{(\eta/X_{iv}^{0.15}=29)}} \times (10,044,565,830.22)\left(\eta / X_{iv}^{0.15}\right)^{(-6.87)} \tag{6}$$

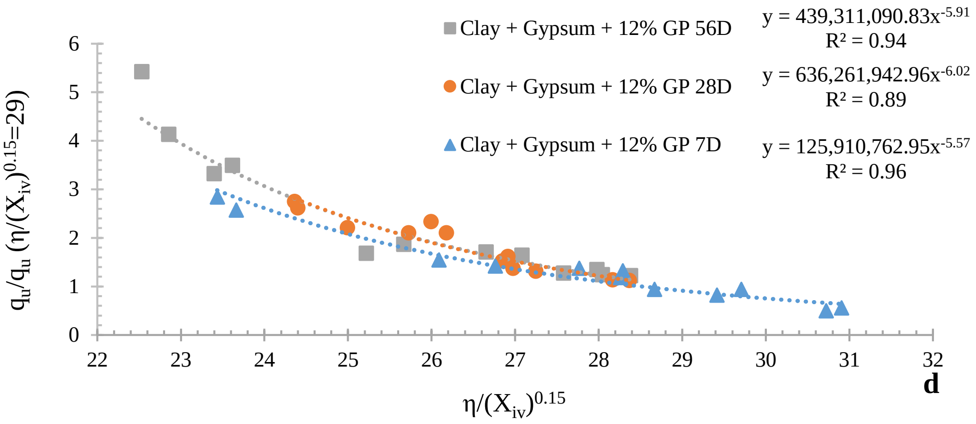
$$G_0 = \mathrm{G}_{0_{(\eta/X_{iv}^{0.15}=29)}} \times (1,679,377,468.80)\left(\eta / X_{iv}^{0.15}\right)^{(-6.33)} \tag{7}$$

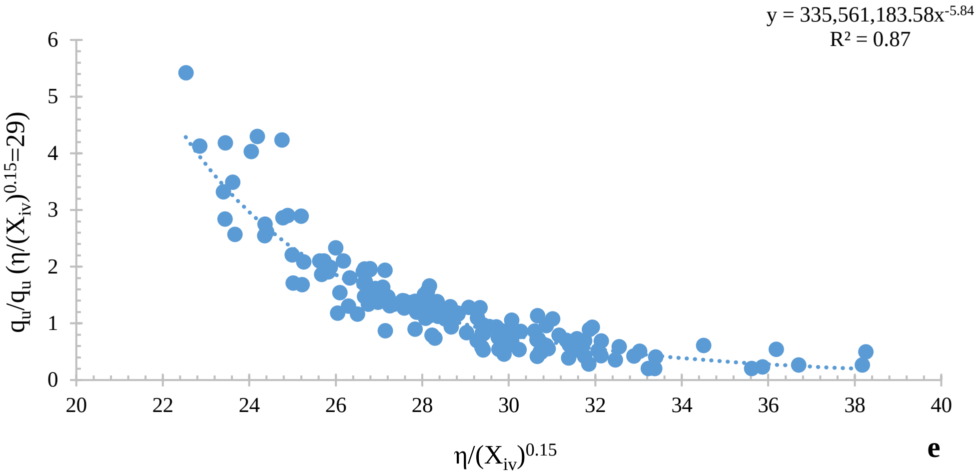
$$E = \mathrm{E}_{(\eta/X_{iv}^{0.15}=29)} \times (3,139,109,314.76)\left(\eta / X_{iv}^{0.15}\right)^{(-6.54)} \tag{8}$$

Figure 21

The Relationships Between the Normalized UCS and the Modified P/B Index for All Curing Durations and Different Amounts of Sintered Gypsum with (a) 0% GP, (b) 4% GP, (c) 8% GP, (d) 12% GP, (e) All Tested Samples in One Chart, and (f) All GP-Improved Samples with Additives in One Chart for Both Samples' Dry Densities




Clay + Gypsum + 12% GP 56D
Clay + Gypsum + 12% GP 28D
Clay + Gypsum + 12% GP 7D
y = 439,311,090.83x^-5.91
R² = 0.94
y = 636,261,942.96x^-6.02
R² = 0.89
y = 125,910,762.95x^-5.57
R² = 0.96
q_u/q_u (η/(X_iv)^0.15=29)
η/(X_iv)^0.15
d


y = 335,561,183.58x^-5.84
R² = 0.87
q_u/q_u (η/(X_iv)^0.15=29)
η/(X_iv)^0.15
e

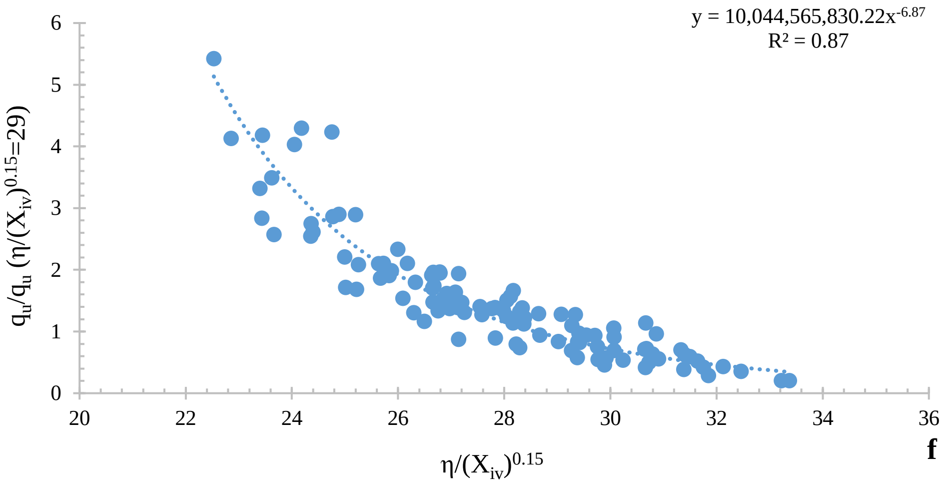
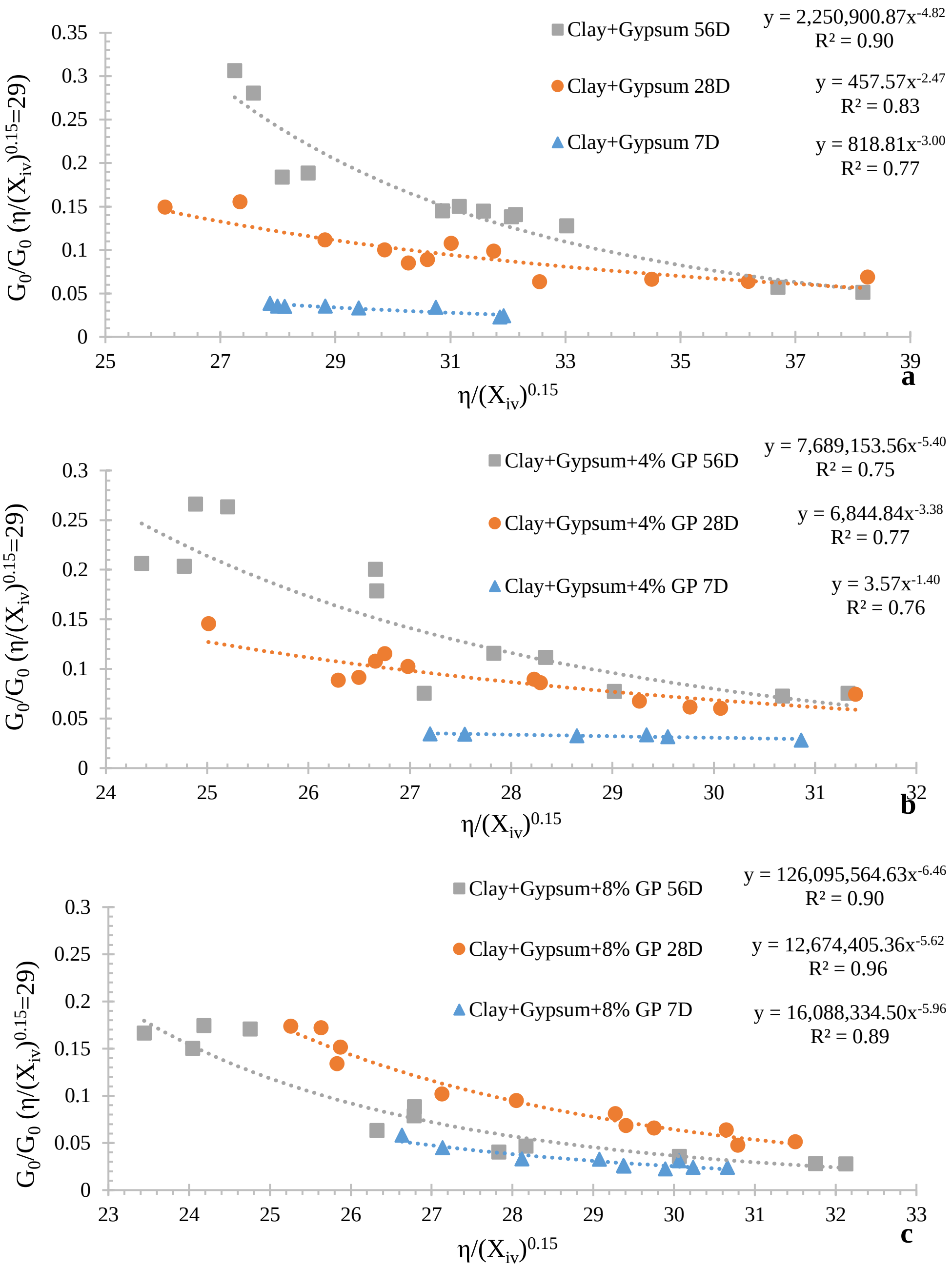
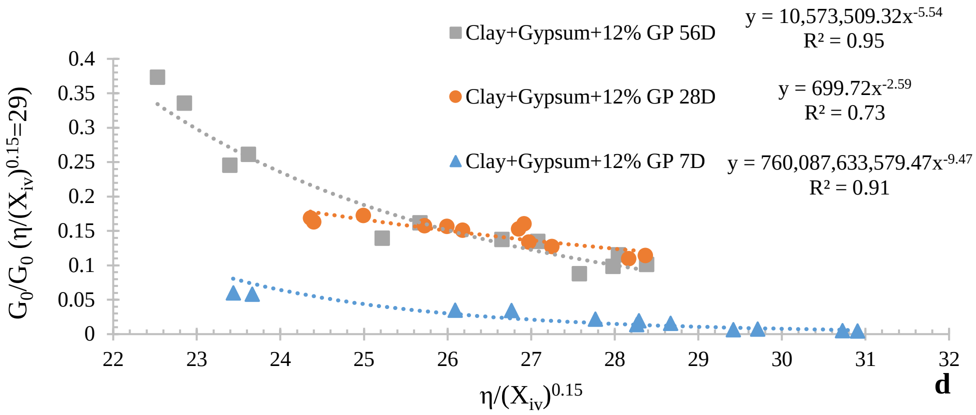

y = 10,044,565,830.22x^-6.87
R² = 0.87
q_u/q_u (η/(X_iv)^0.15=29)
η/(X_iv)^0.15
f

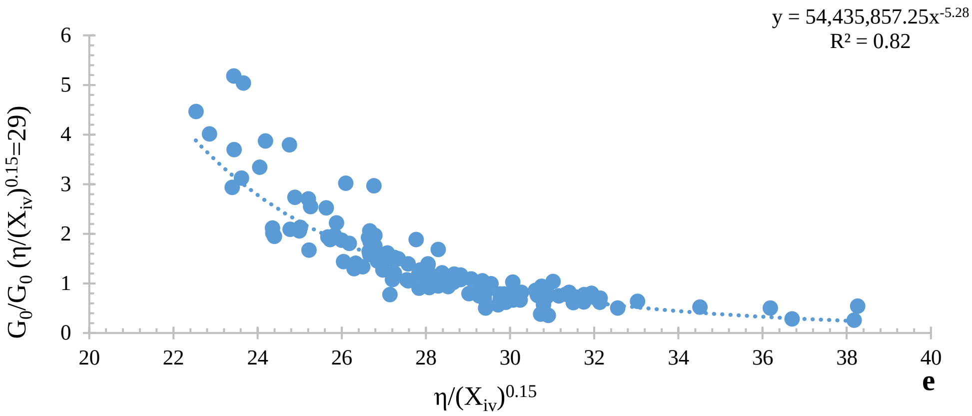
Figure 22

The Relationships Between the Normalized G_0 and the Modified P/B Index for All Curing Du-Rations and Different Amounts of Sintered Gypsum with (a) 0% GP, (b) 4% GP, (c) 8% GP, (d) 12% GP, (e) All Tested Samples in One Chart, and (f) All GP-Improved Samples with Additives in One Chart for Both Samples' Dry Densities

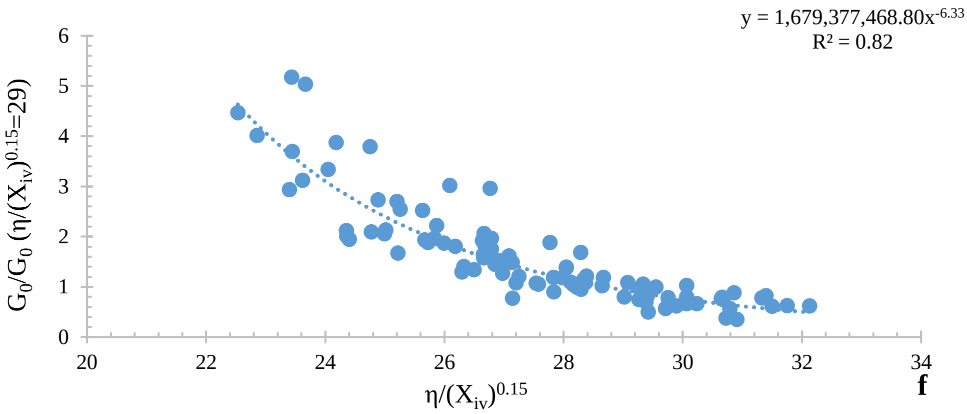




Clay+Gypsum+12% GP 56D
y = 10,573,509.32x-5.54
R² = 0.95
Clay+Gypsum+12% GP 28D
y = 699.72x-2.59
R² = 0.73
Clay+Gypsum+12% GP 7D
y = 760,087,633,579.47x-9.47
R² = 0.91
G0/G0 (η/(Xiv)0.15=29)
η/(Xiv)0.15
d



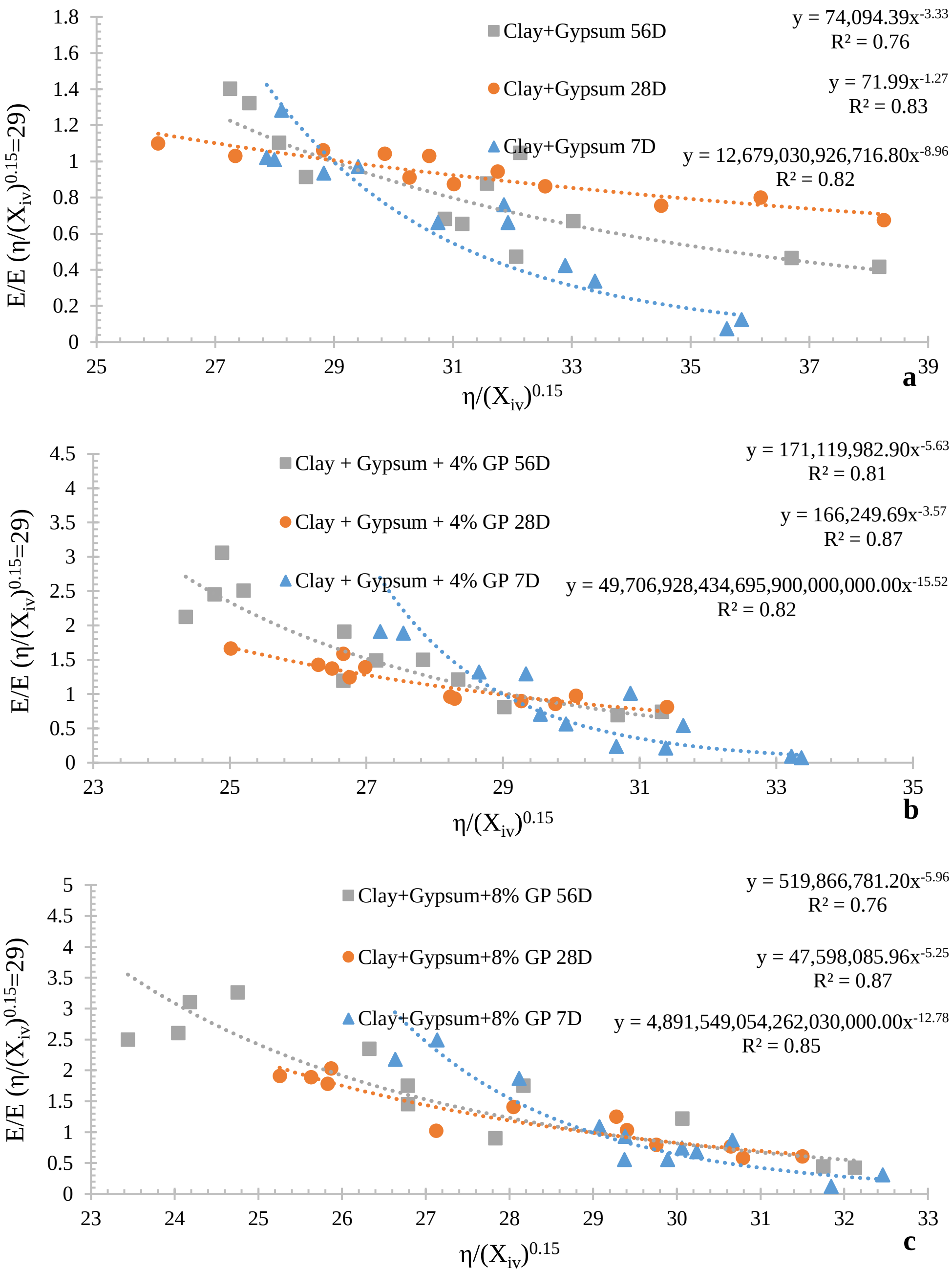
y = 54,435,857.25x-5.28
R² = 0.82
G0/G0 (η/(Xiv)0.15=29)
η/(Xiv)0.15
e

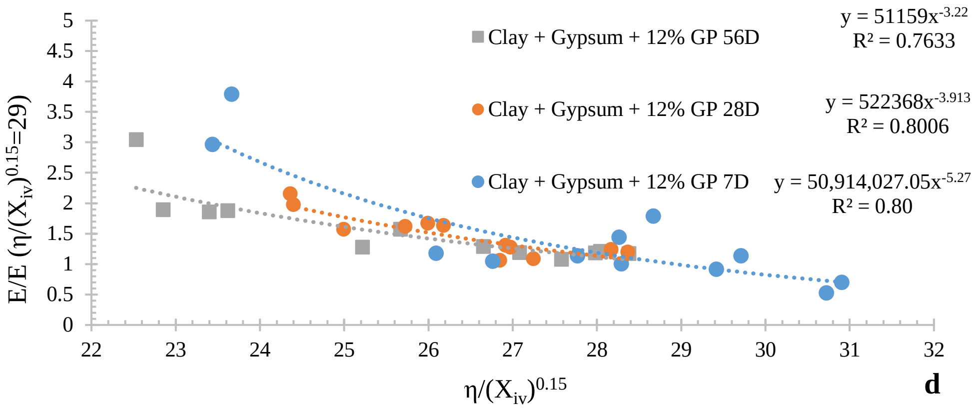


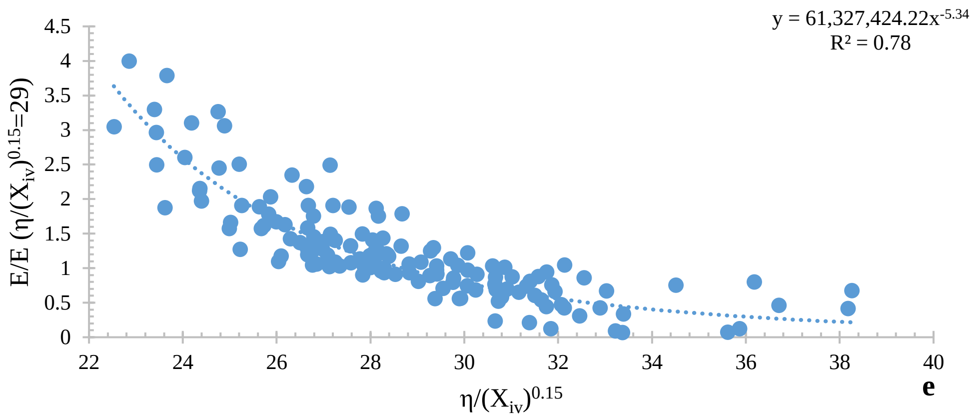
y = 1,679,377,468.80x-6.33
R² = 0.82
G0/G0 (η/(Xiv)0.15=29)
η/(Xiv)0.15
f

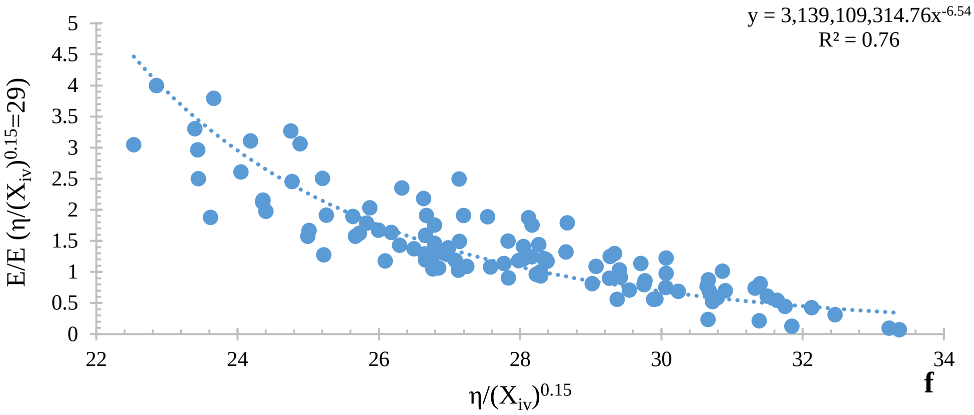
Figure 23

The Relationships Between the Normalized E and the Modified P/B Index for All Curing Du-Rations and Different Amounts of Sintered Gypsum with (a) 0% GP, (b) 4% GP, (c) 8% GP, (d) 12% GP, (e) All Tested Samples in One Chart, and (f) All GP-İmproved Samples with Additives in One Chart for Both Samples' Dry Densities









Mechanical Properties' Relations

Figure 24 reveals a strong correlation between physical properties characterized by high regression values. A well-fitted power diagram effectively represents the relationship between the q_u-G_0 graph in Figure 24a and Equation 9, exhibiting a high regression coefficient ($R^2 = 0.89$). Furthermore, Figure 24c illustrates the relationship between E and G_0 for all the mixtures under examination, as described by Equation 10, which displays a power diagram with a notable coefficient of regression of $R^2 = 0.88$.

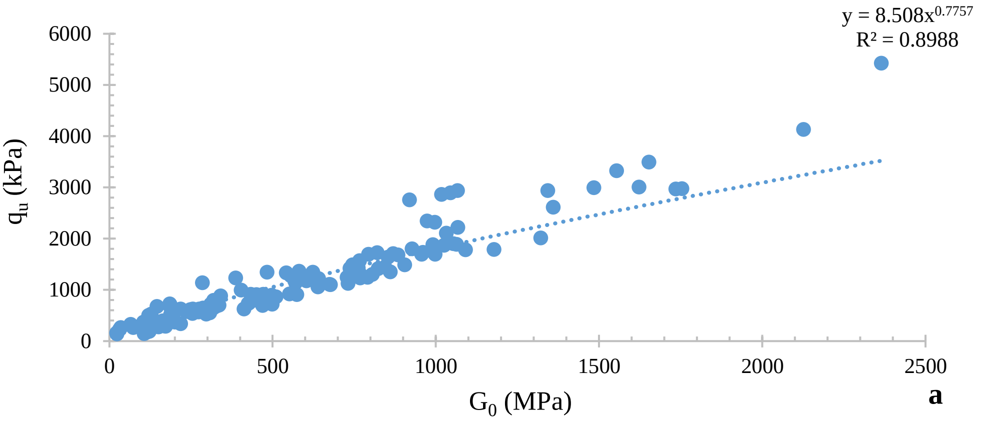
Equation 7 plays an essential role in determining the G_0 of specimens prepared at the specified value of $\eta/(X_{iv})^{0.15} = 29$, and they are linked to the relevant parameters of UCS and E in Equations 9 and 10. The significance of Figures 24a and 24c lies in the fact that at different GP and sintered gypsum amounts, q_u and E can be determined using Equations 9 and 10 for various clay blends over specific curation through the non-destructive assessment of G_0.

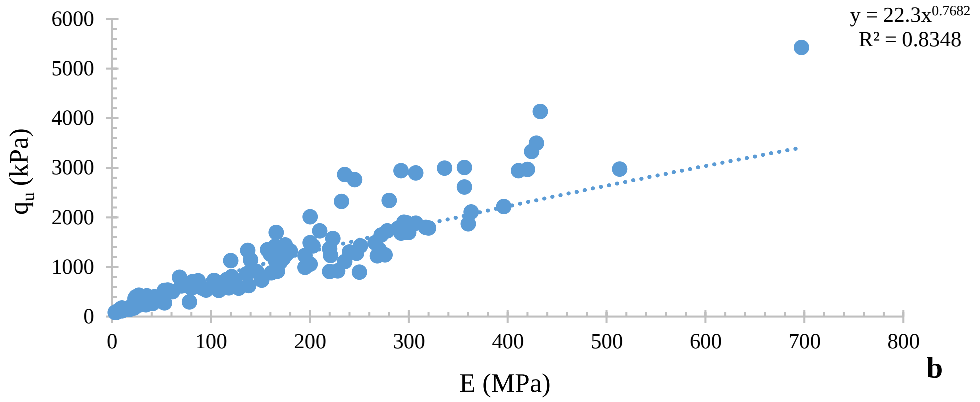
$$q_u = 8.508 G_0^{0.7757} \tag{9}$$

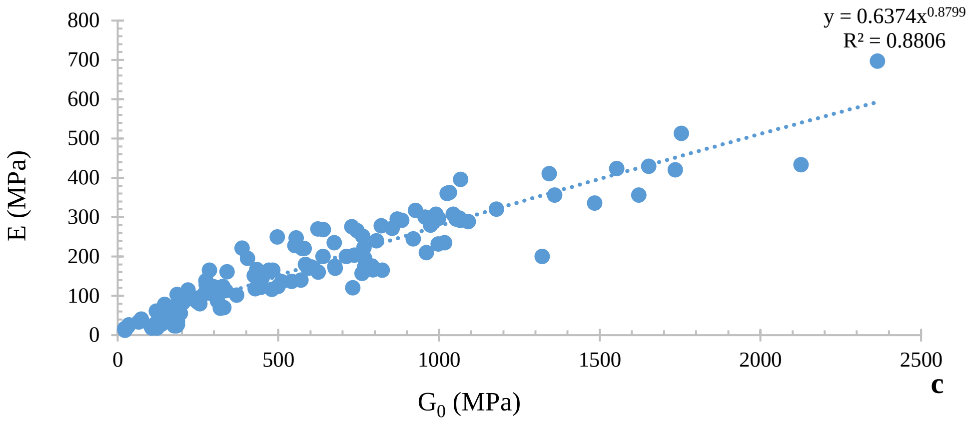
$$E = 0.6374 G_0^{0.8799} \tag{10}$$

Figure 24

Correlation Between (a) UCS and G_0, (b) UCS and E, and (c) E and G_0





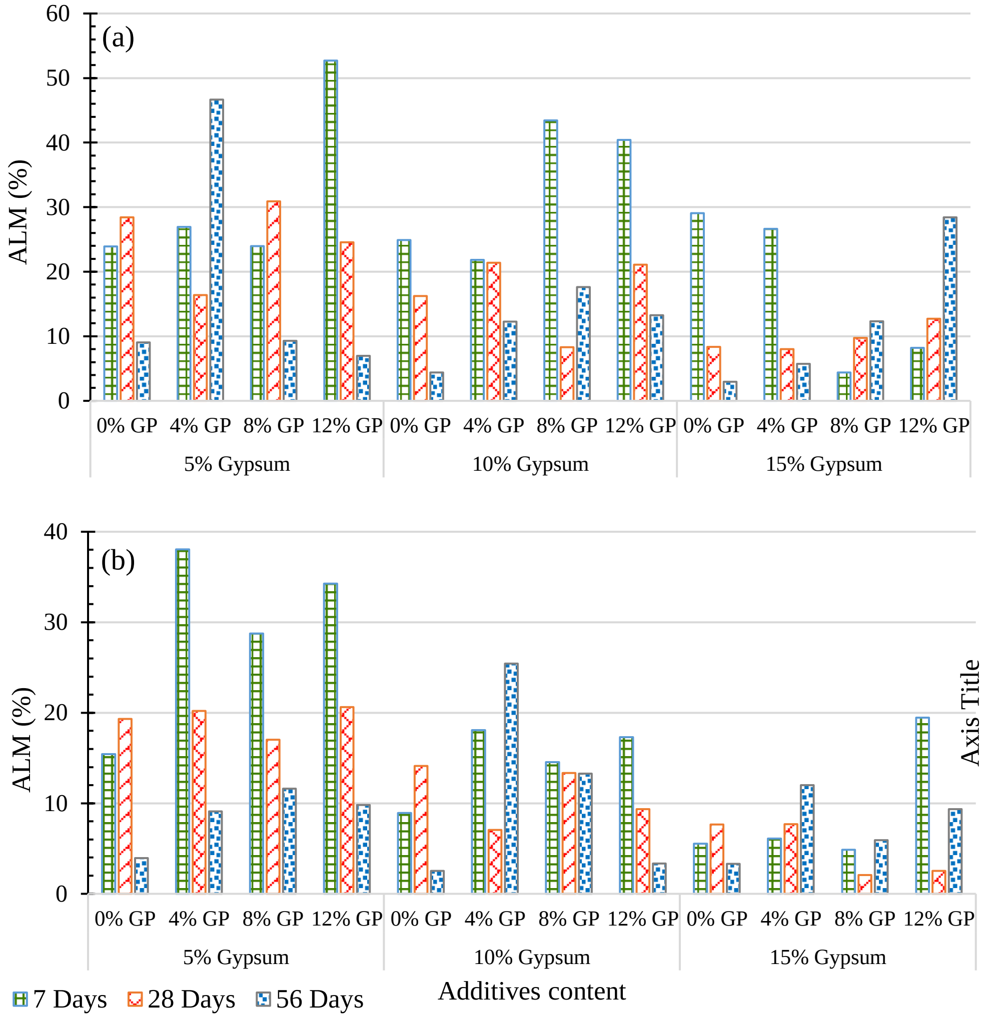


Durability Assessment of Soil Samples by Sintered Gypsum and GP

Figure 25 illustrates the effect of each blend's composition on durability. As predicted from the UCS, $G_{0,}$ and E results (Figures 15, 16, and 17), ALM decreases with increasing strength, although the pattern is inconsistent. Considering the GP content reveals that ALM increases by increasing the GP content. This is due to the inherent properties of GP, which is a cohesion-less material and provides a brittle status for the sample. On the other hand, the increase of sintered gypsum results in a decrease of ALM by applying a cementitious condition by pozzolanic reactions.

Figure 25

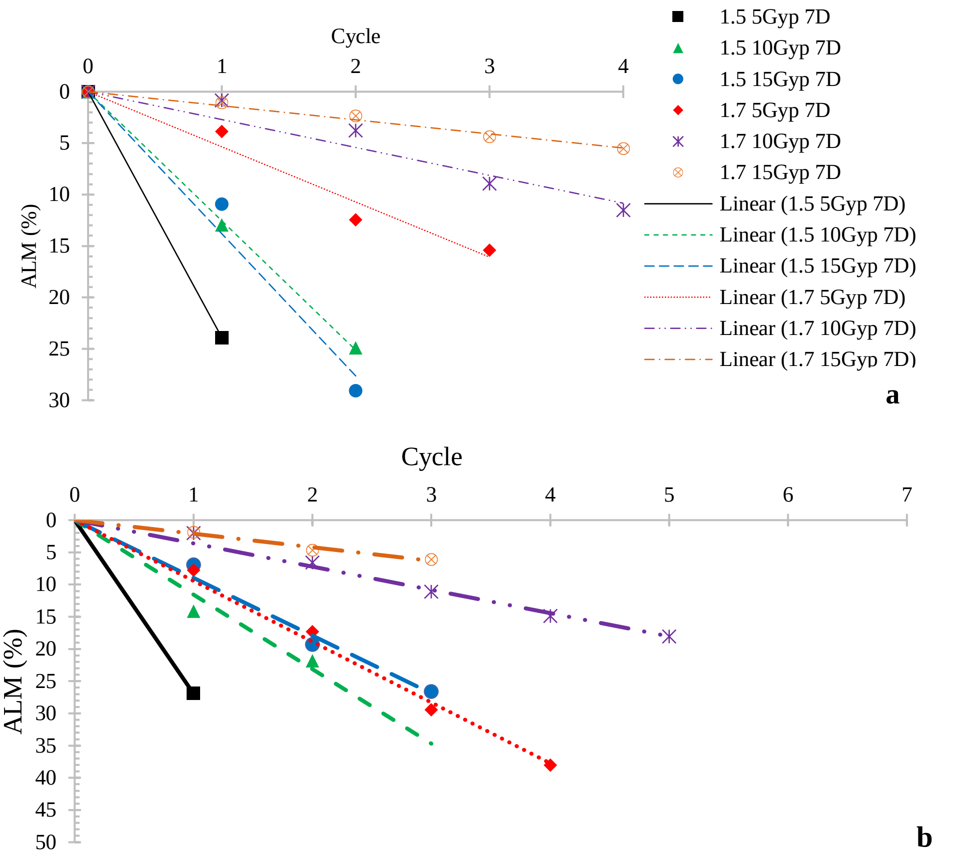
Correlation Between Different Additive Combinations and ALM Amounts for Two Densities: (a) 1500 kg/m³ and (b) 1700 kg/m³

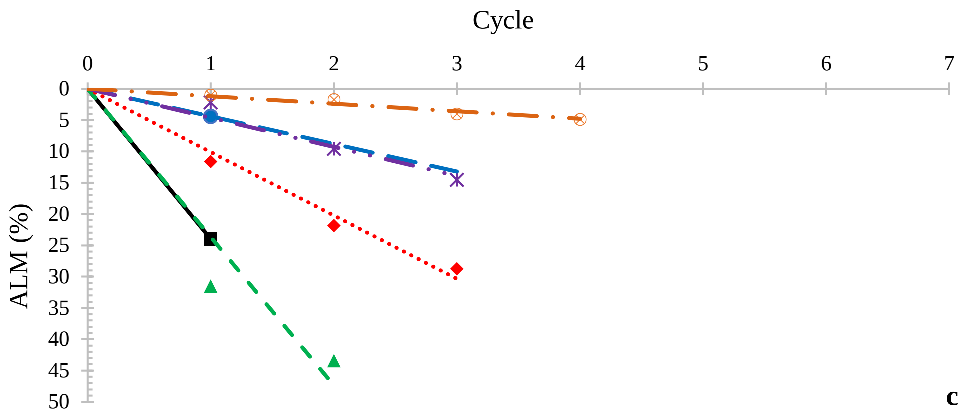


Figures 26, 27, and 28 show variations in the accumulated loss of mass (ALM) of all prepared specimens at each cycle for curing periods of 7, 28, and 60 days, respectively. In general, a linear trend can be established between the ALM and the wet/dry cycles, as the rate of ALM is particularly constant throughout the cycles. It is clear from the graphs that the ALM is reduced with respect to increasing the curing period. Regarding all the graphs, the line related to the sample with 5% sintered gypsum and 1500 kg/m^3 is the closest one to the vertical axis, which means it has less durability status, and the line related to the sample with 1700 kg/m^{3,} and 15% sintered gypsum is the closest line to the horizontal axis which means the highest durability feature. On the other side, the blue line (samples with 15% sintered gypsum and 1500 kg/m^3) is over the red line (sample with 5% sintered gypsum and 1700 kg/m^3), which means that for durability improvement, adding more gypsum can cover the effect of compaction in the blend.

Figure 26

The Accumulated Loss of Mass (ALM) Over the Wet/Dry Cycles for Blends Containing (5, 10, And 15%) Sintered Gypsum Content (1500 kg/m^3 and 1700 kg/m^3) Dry Densities and Cured for 7 Days for (a) 0% GP, (b) 4% GP, (c) 8% GP, and (d) 12% GP





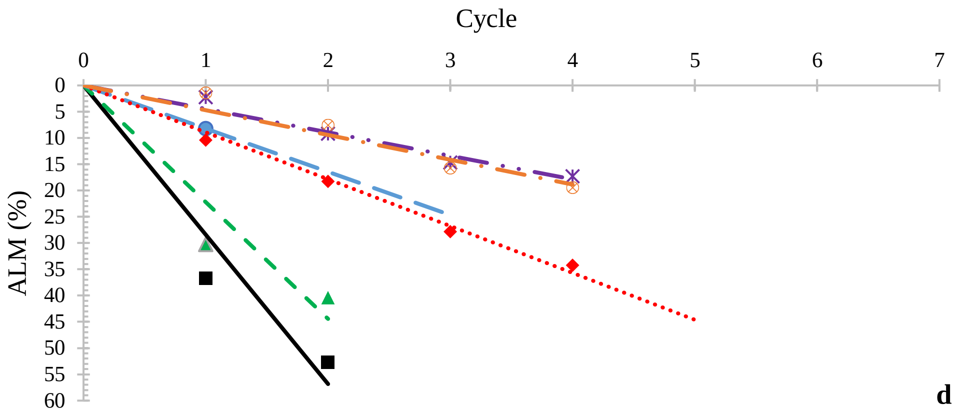
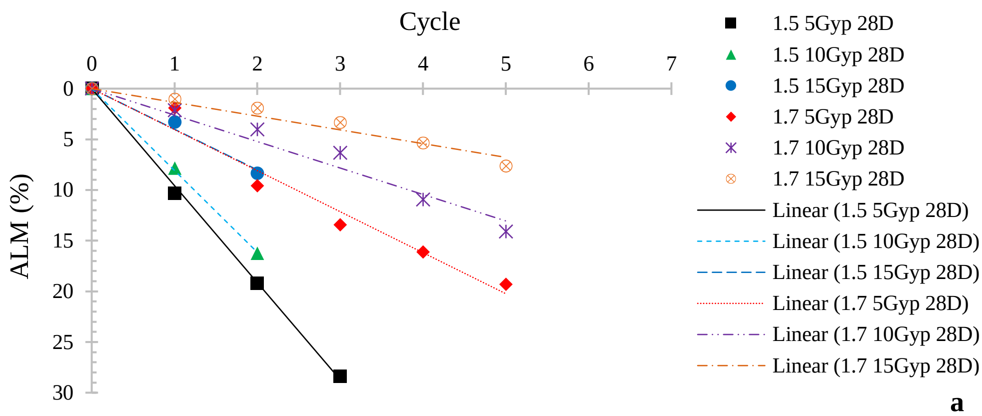
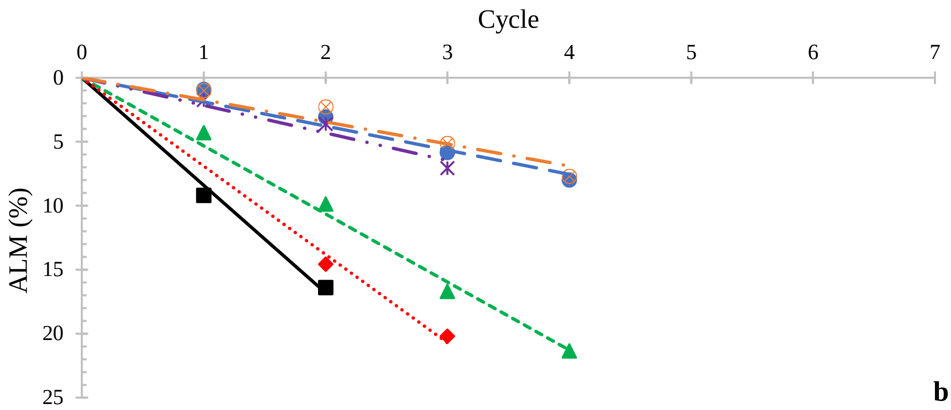


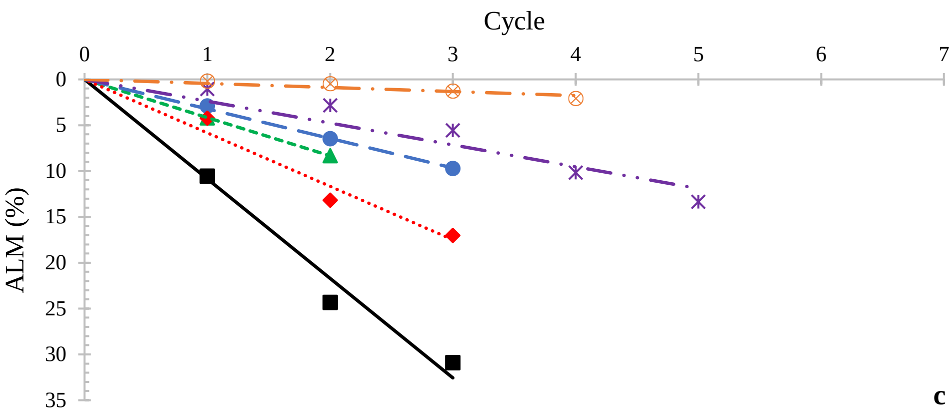
Figure 27

The Accumulated Loss of Mass (ALM) Over the Wet/Dry Cycles for Blends Containing (5, 10, And 15%) Sintered Gypsum Content, (1500 kg/m^3 And 1700 kg/m^3) Dry Densities and Cured for 28 Days for (a) 0% GP, (b) 4% GP, (c) 8% GP, and (d) 12% GP

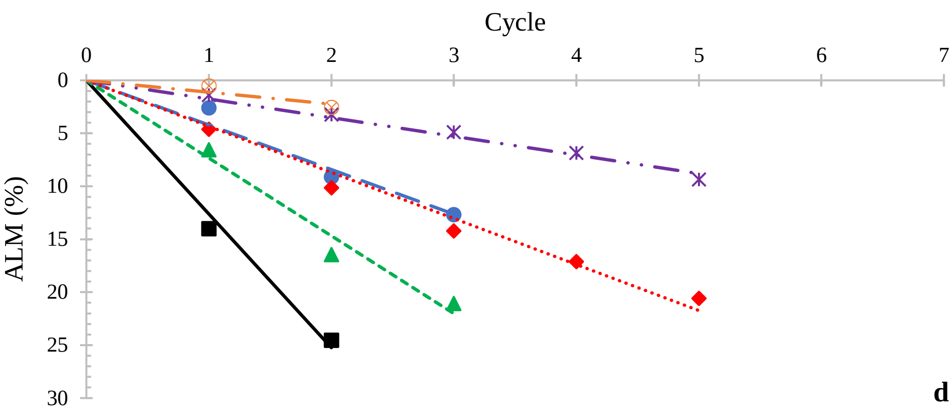



Cycle
0
1
2
3
4
5
6
7
0
5
10
15
20
25
ALM (%)

b


Cycle
0
1
2
3
4
5
6
7
0
5
10
15
20
25
30
35
ALM (%)

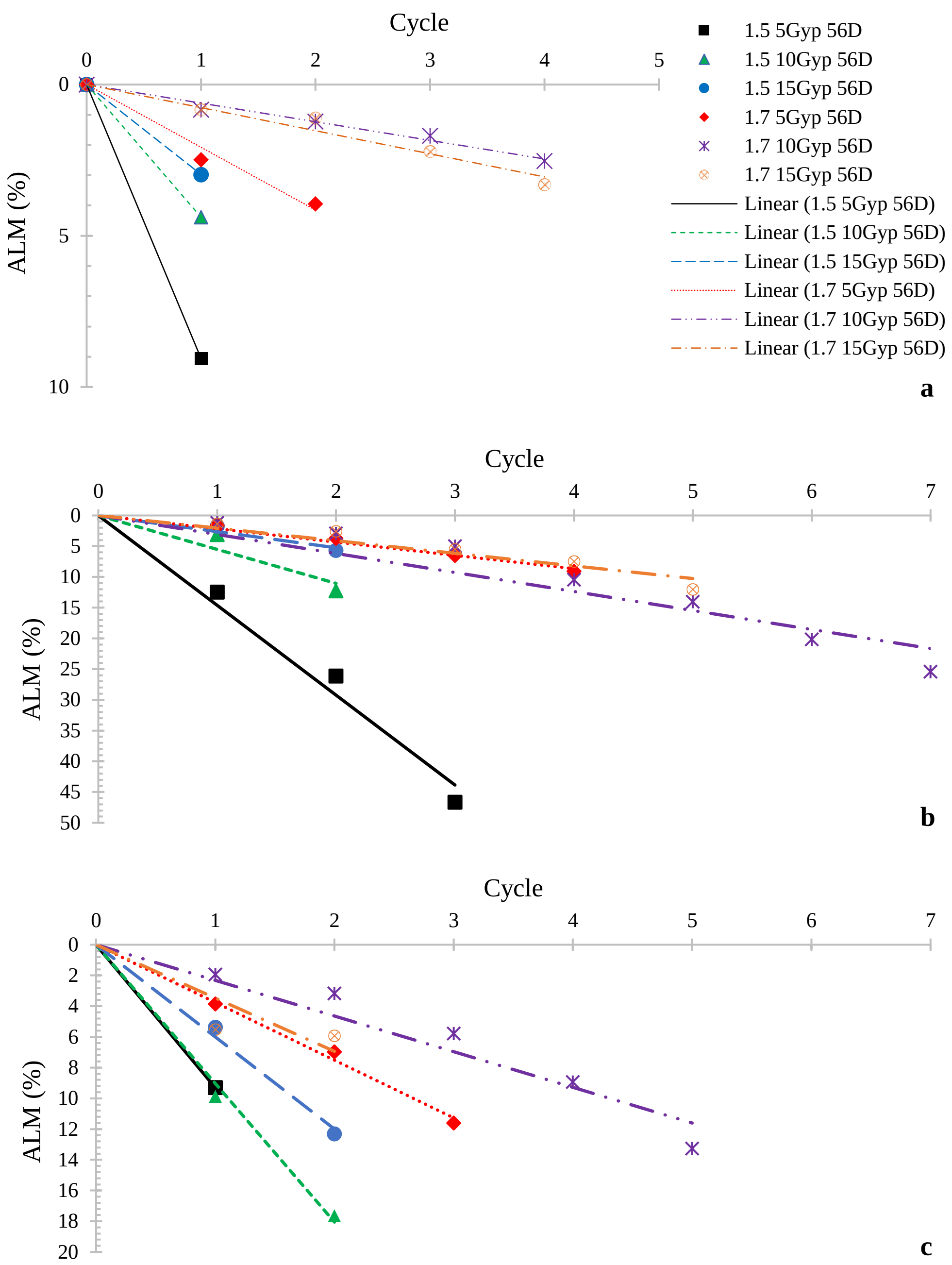
c

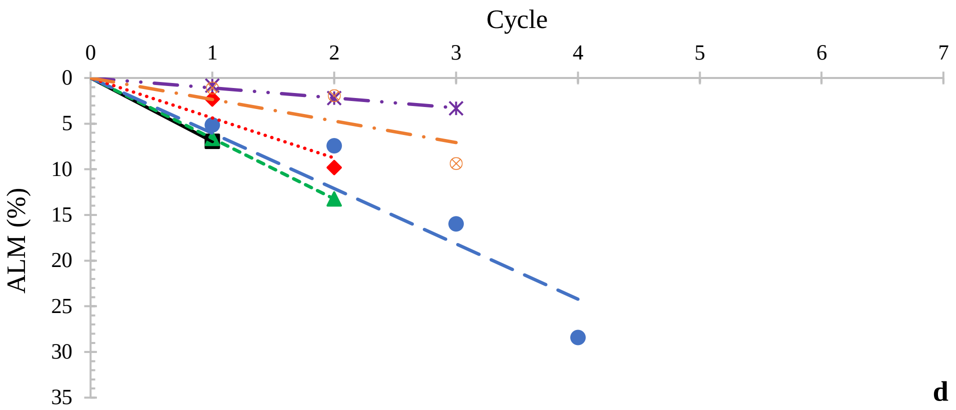

Cycle
0
1
2
3
4
5
6
7
0
5
10
15
20
25
30
ALM (%)

d

Figure 28

The Accumulated Loss of Mass (ALM) Over the Wet/Dry Cycles for Blends Containing (5, 10, And 15%) Sintered Gypsum Content (1500 kg/m^3 and 1700 kg/m^3) Dry Densities and Cured for 56 Days for (a) 0% GP, (b) 4% GP, (c) 8% GP, and (d) 12% GP





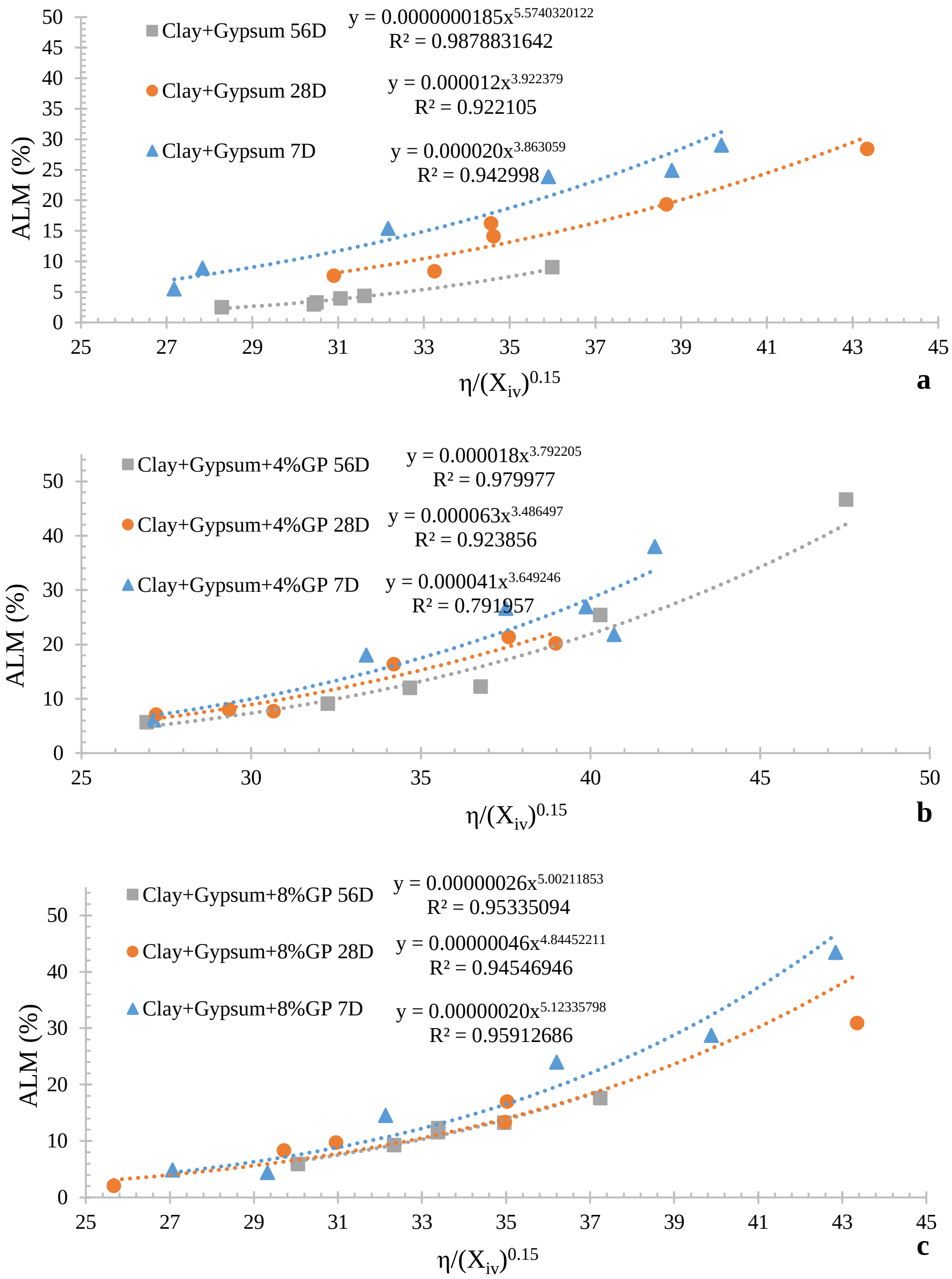
As shown in Figure 29a–d, the presence of GP aggravates the durability factor of mixed samples. However, by increasing the GP content from 4% to 12%, the porosity decreases slightly, and it is declared that the worst GP content for durability is 4%. Regarding the charts, samples with more curing days express less ALM (%), which means that pozzolanic reactions between additives and the clay soil continue over 56 days. It is discussed in the microstructural analysis. As seen from the high regression values of the ALM graphs, the relation between the ALM and porosity in this study is meaningful. After normalization of the ALM graph for all durability tests and comparing Figures 29e, f, an increase of 1% is apparent, strengthening the link between the ALM and the porosity index.

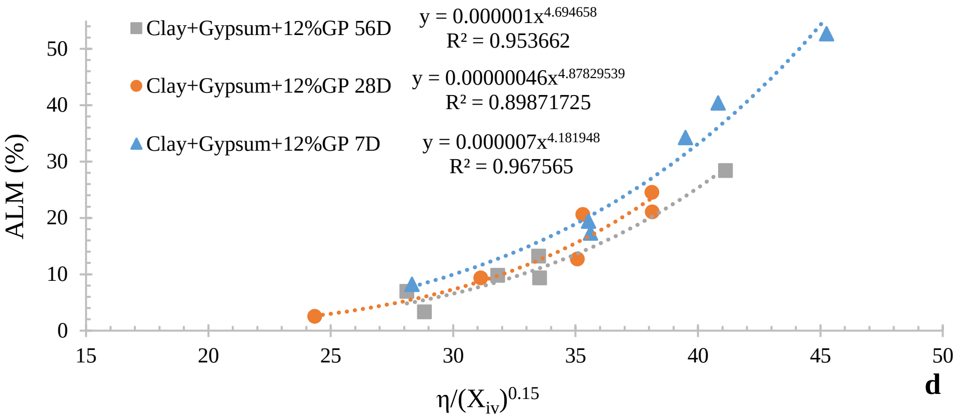
Conversely, similar to the formulas in the physical properties part, a formula has been generated to predict the ALM by various combinations of additives. Equation 11, with a strong regression coefficient (R^2 = 0.867), expresses an accurate prediction tool for the ALM assessment in further investigations.

$$ALM = \mathrm{ALM}_{(\eta/X_{iv}{}^{0.15}=29)} \times (0.00000069)\left(\eta / X_{iv}{}^{0.15}\right) x^{(4.21)} \qquad (11)$$

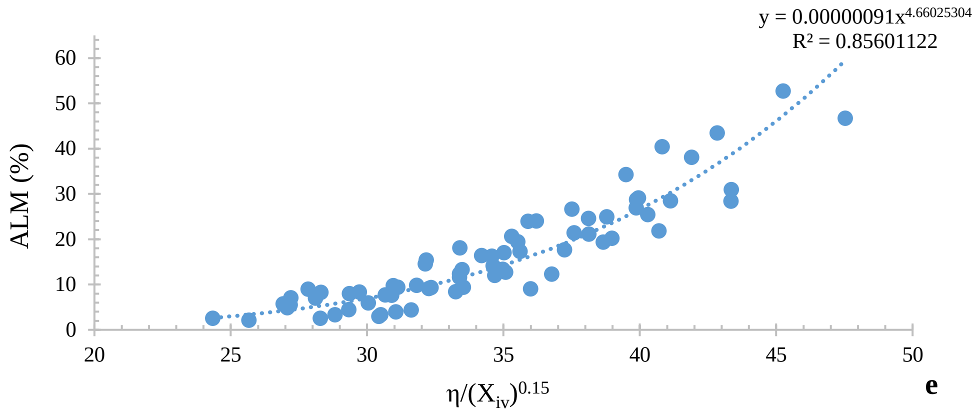
Figure 29

The Associations Between the ALM and the Modified P/B Index for All Curing Durations and Different Amounts of Sintered Gypsum with (a) 0% GP, (b) 4% GP, (c) 8% GP, (d) 12% GP, (e) All GP-Improved Samples in One Chart, and (f) All Normalized ALM for GP-Improved Samples with Additives in One Chart for Both Samples' Dry Densities

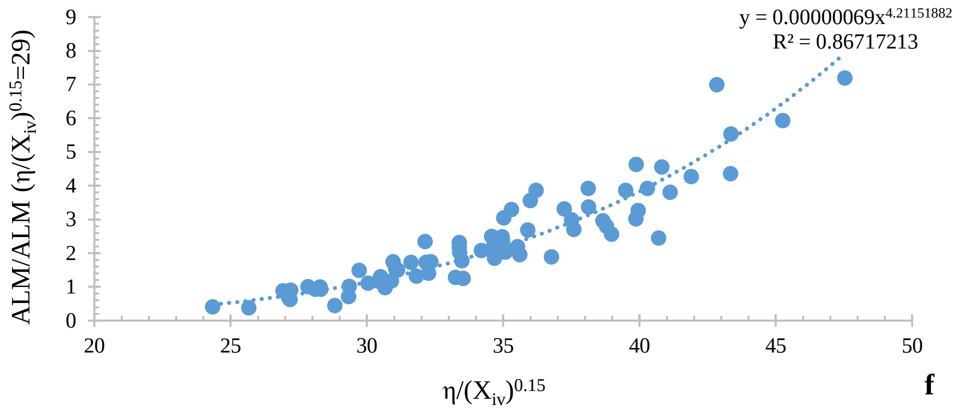




d



e



f

Microstructural Analysis

Additionally, some microstructural assessments were performed using X-ray diffraction (XRD) and scanning electron microscopy (SEM). Figure 30 presents the results of the XRD investigation, which contains 12 sample types. These samples differed in two GP levels (0% and 8%) as well as two levels of interest gypsum (5% and 15%) and were evaluated at curing times of 7, 28, and 56 days whilst the density was constant at 1700 kg/m^3. Among the identified phases, quartz (Q) and calcite (C) are present in dominant levels, while silicon (Si) and alumina (Al) are available in lower amounts. The X-ray powder diffraction spectra presented the surviving and consistent sodium montmorillonite or smectite, illite, and the probable presence of a chlorite-kaolinite group among the phyllosilicates, indicating a broad and different mineral in the material.

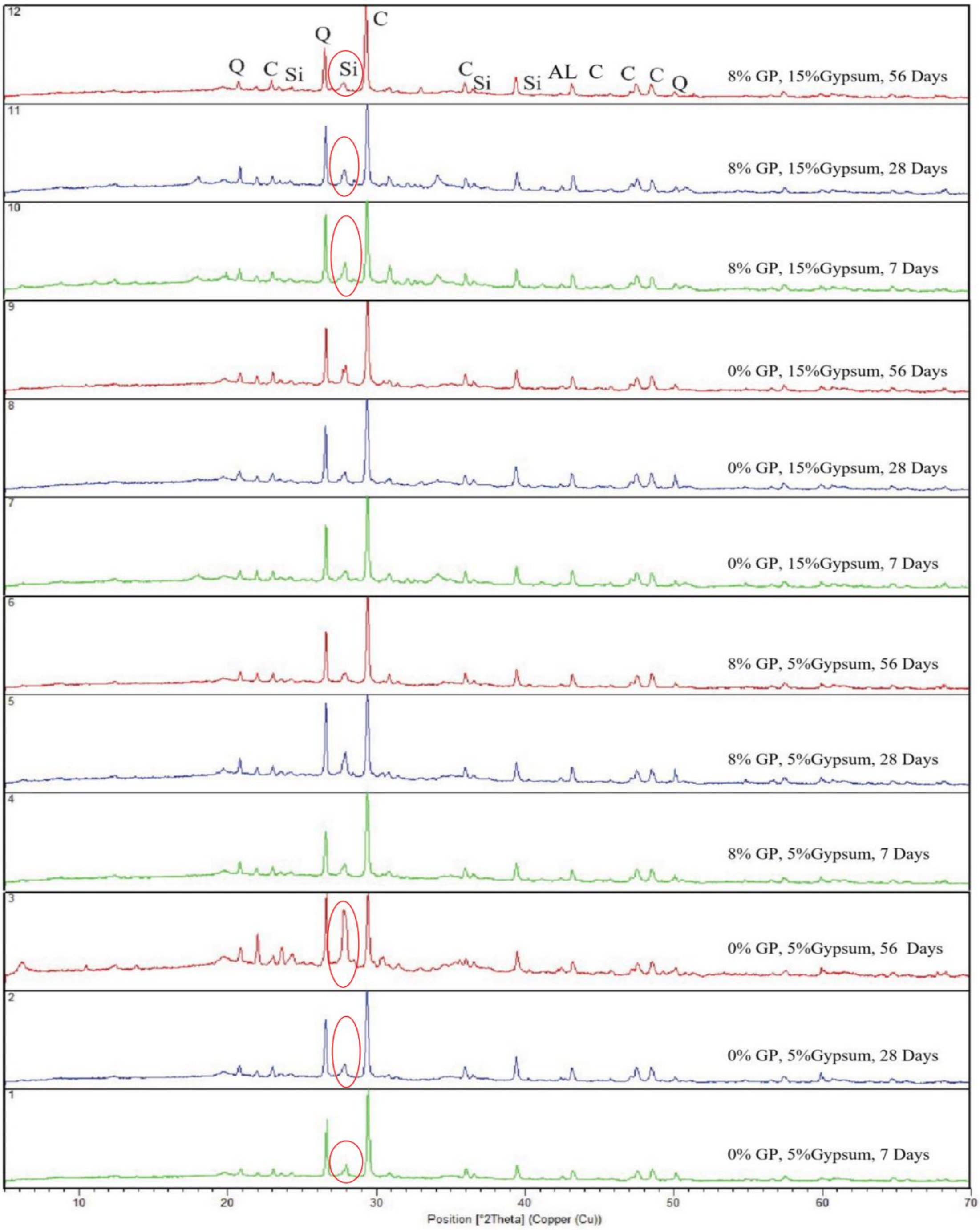
The XRD patterns exhibited an interesting feature of having an additional peak associated with silicon, which was positioned between quartz and calcite peaks. This intermediate silicon peak is shown to increase from sample 1 to sample 3, as highlighted with a red oval in Figure 30. This trend pertains to the GP-free samples, and it is observed to amplify with the increase in curing time of 7 to 56 days. This suggests that with the increase in curing time, the reaction between silicon and other phases becomes more enhanced in the absence of GP.

On the contrary, the opposite trend is evident in samples including GP (sample numbers 10 to 12) curing, where the intensity of the silicon peak decreases with the increase in curing time. The main reason for such a difference between both groups of samples is the higher amount of silicon that is present in the GP component. Hence, as the curing time increases, the pozzolanic reactions of silica and calcium become strong, especially for GP samples; the consumption of free silicon contributes to the declining intensity of the silicon peak in the XRD patterns.

Even in the GP-containing samples with increased GP content during the curing period of 7 to 56 days, the pozzolanic activity of the GP-containing samples (especially those with higher GP content) is enhanced. Consequently, there is a high and rapid consumption of silicon, which explains the trends observed in the XRD patterns. The higher the GP content, the higher the extent of conversion of silicon into reaction products, which accounts for the unique behaviors of the peaks in X-RD patterns. These findings illustrate the critical role of GP in modifying the mineralogical and microstructural evolution of the blend, particularly through improved pozzolanic activity that accelerates hydration processes and strengthens the material matrix.

Figure 30

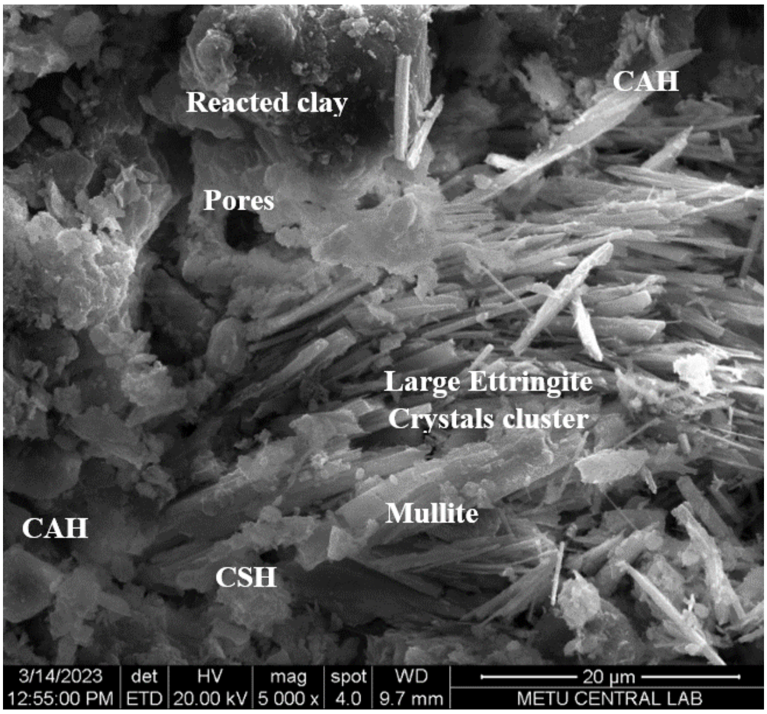
XRD Results for Tested Samples' GP Content of 0 And 8 Percent and Gypsum Content of 5 and 15 Percent at Different Curing Days, at a Density of 1700 kg/m³



The SEM microphotograph presented in Figure 31 illustrates a sample with 15% gypsum content, which was cured for a period of 28 days and did not contain GP. Such features are crucial in determining the strength properties of clay soil. Needle-like structures, representing ettringite, are observed alongside distinct aluminum phases, mullite, and hydrated silicate identified as C-A-H and C-S-H, respectively (Wu, 2016). These compounds, formed through chemical reactions with stabilizing agents, significantly enhance the engineering properties of clay soil. Including these topological compounds helps out the structure-soil composites. Ettringite contributes positively to soil blends by producing a rigid network that bonds decade soil particles, flooring the soil's ability to withstand erosion, endure stress, and become stiffer. Such a network aids in lessening the plasticity of the clay of soils, helps in increasing the density of the soils, and determines whether the structure will still hold after a period. Mullite is characterized by its elongated crystal structure, formed through high-temperature reactions between alumina and silica. This structure enhances the material's thermal stability and mechanical strength. Unlike pure clay, C-S-H worked as a filler material and significantly improved thick water-conducting gels with high mechanical strength-based organic polymers. In addition, C-A-H is an important axial binding property of the soil chain, which also enhances further pozzolanic reactions to make more cementing materials. Frustrations posed by encounters with such environments begin with an easy response to arrangements because solving risky situations requires proper early dumplings of pozzolanic or filler agents.

Figure 31

SEM Micrograph of Treated Sample, which Includes Major Structures



The microphotographs, as shown in Figures 32 a-c, provide the opportunity to systematically evaluate the effect of different curing durations on the resulting alteration in the structural components of the specific blend. Within these microphotographs, one also notes the gradual increase in the amount of hydration products such as C-S-H, C-A-H, and ettringite as the curing days increase. This gradual development particularly emphasizes the need for longer periods of curing to improve the development of the microstructural characteristics of the material. More specifically, Figure 32c compares the volume fraction of porous structures that were trapped at the end of the hydration and crystallization processes. These mechanisms result in the creation of a structure that is dense and more packed together, giving rise to a well-connected orientation of calcite particles, which has consistently been a key phase in the X-ray diffraction (XRD) number of samples analyzed.

Particularly, regarding the sample with 8% (GP) (Figure 32c), there are also quite pronounced differences in the ettringite and C-S-H gel formation texture when compared to the studies without or with very low GP content samples. The gel appears to be not comparable in structure and has fewer porous areas relative to the space visible in Figure 32d. The absence of GP in Figure 32d, on the other hand, brings out the high voids, which are prominent features as a result of there being no filler materials present that would have enhanced the packing of the matrix. Unreacted clay particles are also present in Figure 32d, indicating some inefficient reactions and clearly showing the need for factors such as GP for much better hydration and void filling.

Moreover, the results of this experiment reveal the interaction between sintered gypsum, glass powder, clay, and stress conditions as they pertain to the strengthening properties. With the advancement of curing times, the ability to withstand compressive loads is improved due to the formation of C-S-H as well as ettringite under load-bearing conditions. This is quite noticeable, especially in the samples that were amended with GP, where the GP acts like a micro-filler, filling up the spaces that better fried against the stresses applied. This induced compaction of the soil matrix also hastens the pozzolanic reaction, especially in high GP samples, leading toward a more dense and tough soil matrix.

Figure 32

SEM Microphotographs of Samples With 8% GP and 15% Gypsum Content at (a) 7 Curing Days, (b) 28 Curing Days, (c) 56 Curing Days, and (d) Samples with 0% GP and 15% Gypsum Content at 56 Curing Days 15% Gypsum Content at 56 Curing Days

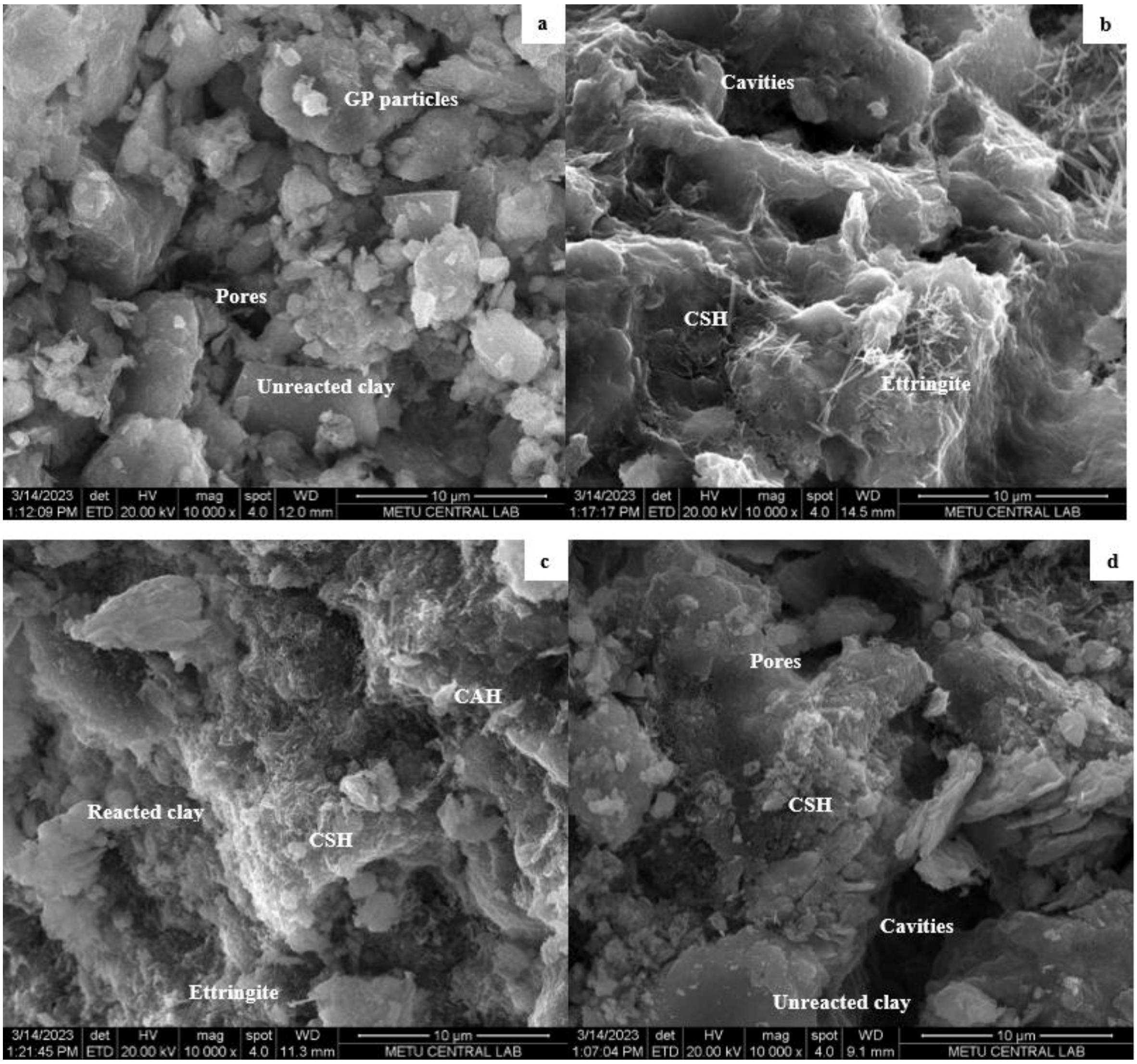


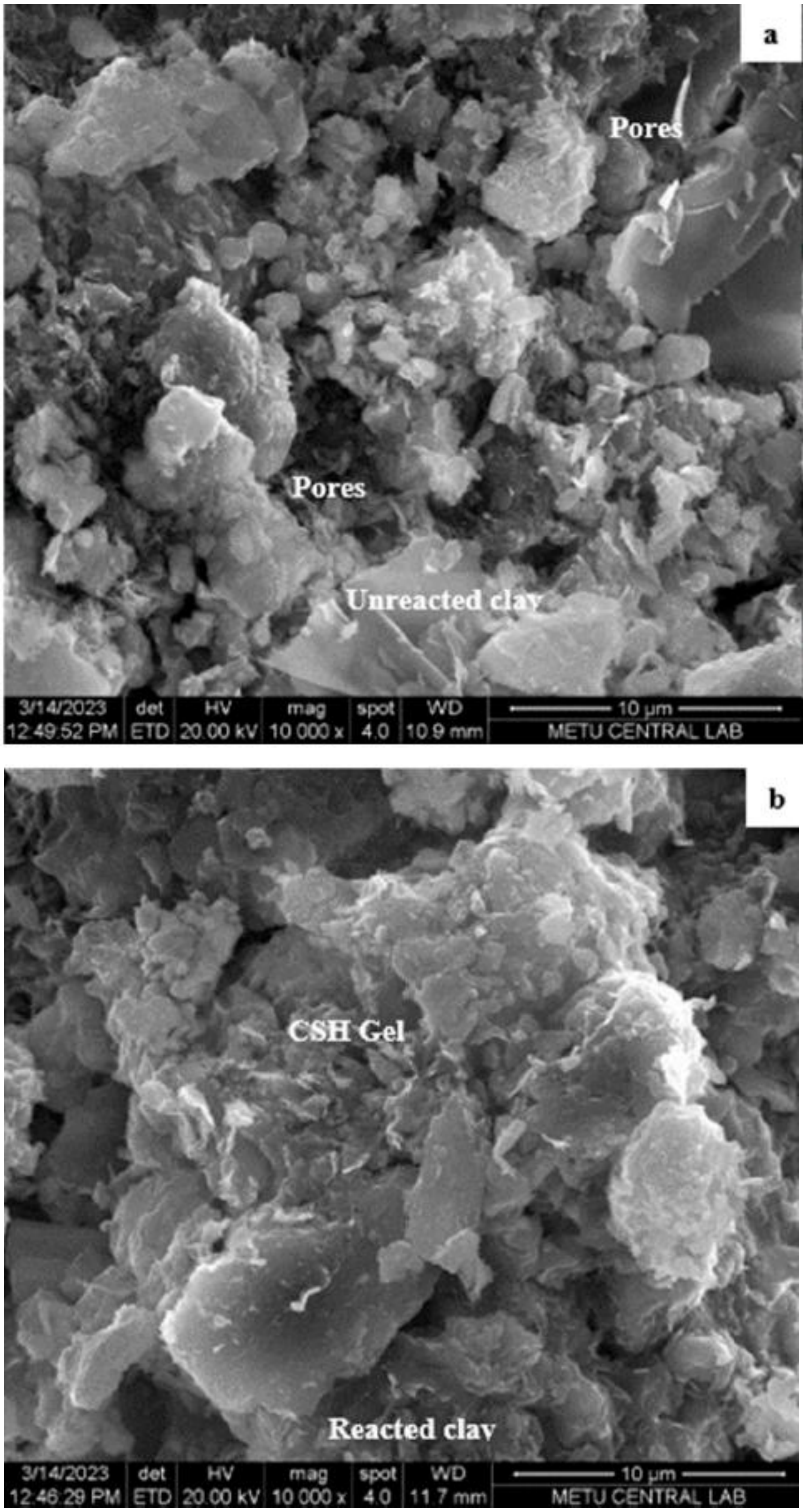
Figure 33a illustrates a significant difference between the sample cured for 56 days and the one cured for only 28 days, as shown in Figure 33b. The key distinction lies in the microstructural characteristics, where the sample in Figure 33a exhibits a greater number of pores and more evident particle separation. This observation is consistent with the behaviors observed in Figures 18c, 19c, and 20c, reinforcing the role of curing duration in influencing the material's properties. The increased porosity and clearer particle boundaries in Figure 33a, despite their presence, contribute to an enhanced structural organization that leads to improved mechanical strength and performance. This is particularly noteworthy when compared to the sample in Figure 33b, where a denser and less porous structure may suggest a different phase in the curing process.

The distinct soil structures observed in Figure 33a are directly related to the progressive strengthening of the material, with more defined particle arrangement and matrix consolidation. These structural characteristics have a more pronounced impact on the strength and stiffness of the material as compared to the sample in Figure 33b. The enhanced particle separation and porosity in Figure 33a allow for better load distribution and contribute to improved stiffness and deformation resistance.

These variations in the characteristics of the soil matrix are attributed to differences in the period of curing for the various blends, and these are quite relevant as far as the strength and mechanical behavior of the material is concerned. It is also observed that with the increase in the curing age, the occurrence of the evolution of the microstructure becomes more apparent, but long curing times do not always yield more stable textures. This shows the bond that exists between curing time and soil microstructure.

Figure 33

SEM Microphotographs for Tested Samples with 8% GP and 5% Gypsum Content at (a) 56 Curing Days and (b) 28 Curing Days



Life Cycle Assessment (LCA)

The chart in Figure 34 describes the response of six environmental impact factors for every blend composition, which additionally shows that both dry bulk densities increase with the addition of sintered Gypsum and Glass powder. This increase is due to the large amount of energy that is utilized in preparation of these additives and their mixture (Kumar et al. 2023).

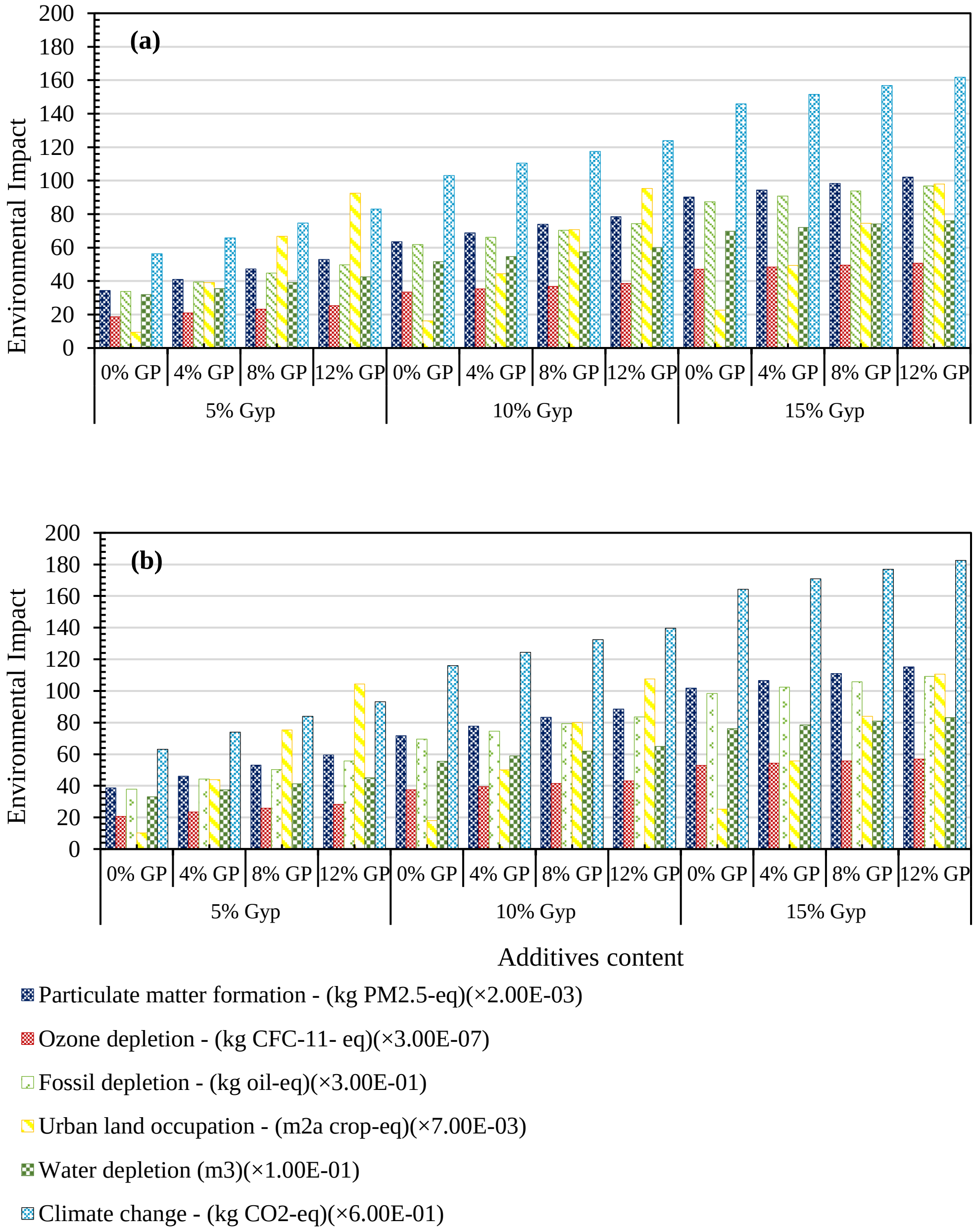
The figure points out that such increases in density would also lead to greater impacts because of the amount of the additives that are incorporated in denser samples. However, most of the impact categories follow the same trends except for urban land occupation, which is rather devoid of this trend. This is specifically so because, at 12% glass powder content, the environmental impacts show a dramatic increase and even more when gypsum is incorporated.

Of all the environmental factors, climate change potential sees the most dramatic increase, indicating that these additives are particularly impactful in this area. On the other hand, ozone depletion shows only a minimal increase, staying relatively steady for a given amount of gypsum, which suggests it is more influenced by the glass powder content.

Urban land occupation impacts exhibit a distinct behavior. As shown in Figure 33, the most significant increase in urban land occupation occurs with the addition of glass powder, although a slight increase is observed with the addition of gypsum. This divergence suggests that glass powder has a more pronounced effect on urban land occupation compared to gypsum (Deschamps et al., 2018).

Figure 34

Six Environmental Impact Correlations Versus Blends with Different Additive Combinations for Two Densities: (a) 1500 kg/m³ and (b) 1700 kg/m³



Environmental Impact Normalization

In this investigation, mechanical properties (UCS, G_0) as well as ALM were used to account for environmental impacts and measure the influence that the composition of each blend possesses in normalizing the mechanical properties and ALM. The ALM value is multiplied by the impact amount to normalize environmental impacts by ALM, while the normalization of impacts by UCS and G_0 is achieved through division. This approach is important given the inverse characteristics of the ALM, where lower amounts of ALM are beneficial. With the aid of radar graphs, it's possible to illustrate better how each blend behaves in relation to other blends rather than all. Normalization is also important to demonstrate the relationship between density and environmental impacts. Higher density samples lead to lower environmental impacts, and therefore, lower density samples are expected to have greater environmental impacts. Compared with the previous part, this different pattern is due to the normalization, which shows that considering the mechanical properties provides a better understanding of environmental impacts.

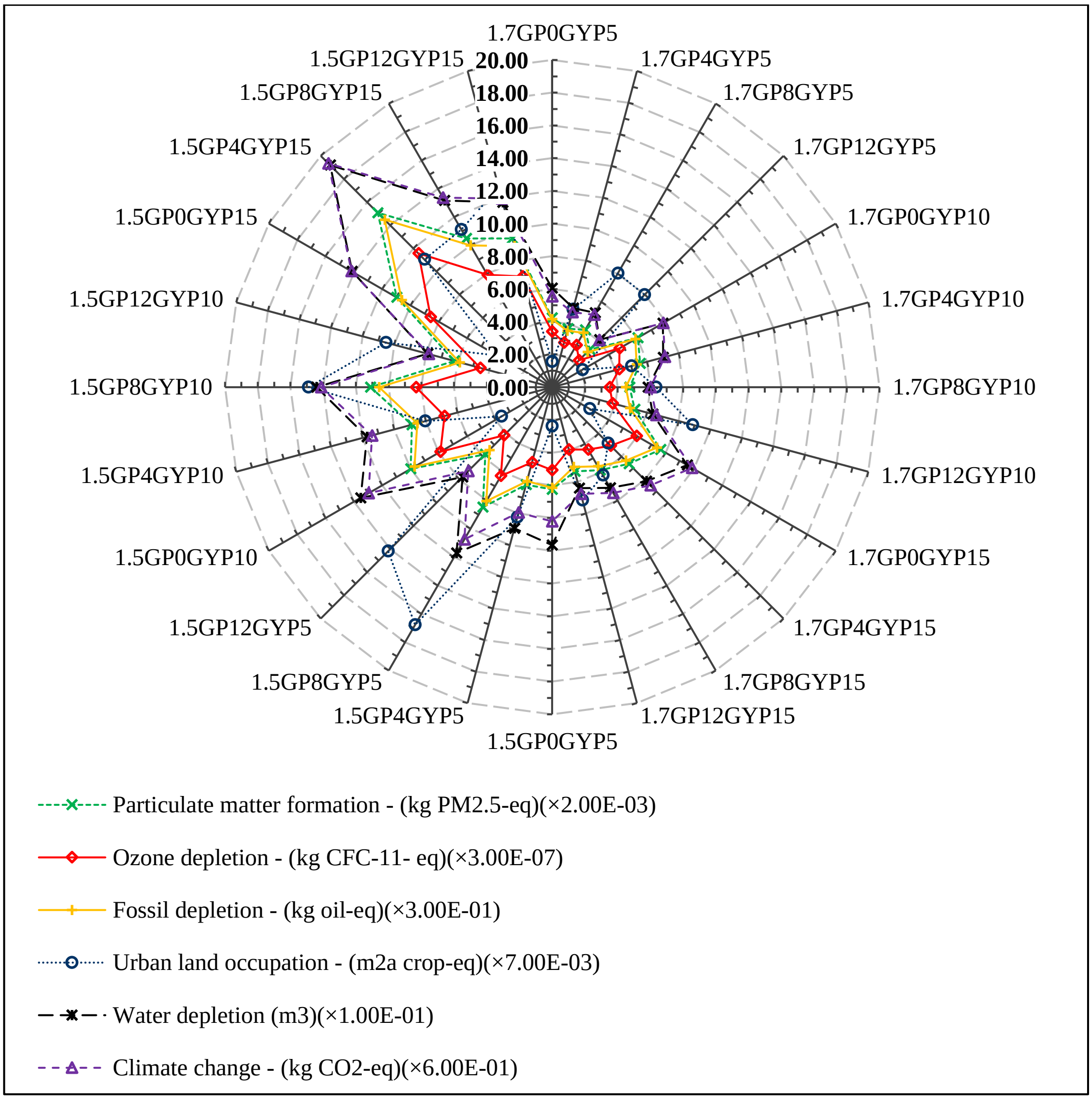
Figure 35 shows that in terms of behavior, all of the environmental impact factors are related, with the exception of one, which is the impact of urban land occupation, which has been discussed earlier. The figures show that the thickest sample, which contains 12% glass powder and 5% gypsum, is the best due to its environmental benefits. However, the urban land occupation impact for this sample is still the highest among other impacts, which shows that this type of behavior is unique.

Conversely, the sample with the most detrimental environmental impact is the loose sample with 4% glass powder and 15% gypsum. This composition is neither environmentally sustainable nor rational from a strength perspective, making it the least desirable option. Low-impact development methods usage patterns are established and demonstrated in Figure 35, and it can be concluded that the behavior of all environmental impact factors except for urban land occupation impact that has been discussed above is nearly the same. From the figure, it is clear that the sample that is least harmful to the environment is the dense sample of high pozzolan content comprising 12% glass powder and 5% gypsum. However, the occupation of urban land impacts for this sample remains high when compared with other impacts so far discussed, which pans this sample into a different category.

On the other hand, the worst in terms of environmental impact is the loose sample with 4 % glass powder and 15 % gypsum. This particular composition is environmentally and strengthwise not rational and is thus the most disadvantageous.

Figure 35

Correlation of Normalized Six Environmental Impacts by UCS Versus Blends with Different Additive Combinations for Two Densities of 1500 kg/m³ and 1700 kg/m³



The environmental impact patterns in Figure 35 mirror the patterns in Figure 36, which is not surprising considering the comparison made between UCS and G_0 bar charts. It can clearly be seen in Figures 35 and 36 that the most undesirable samples in the denser region are those having a high amount of sintered gypsum percentage with low glass powder filling. This point clarifies the clear dependency of these additives on their function.

Figure 36

Correlation of Normalized Six Environmental Impacts by G_0 Versus Blends with Different Additive Combinations for Two Densities of 1500 kg/m^3 and 1700 kg/m^3

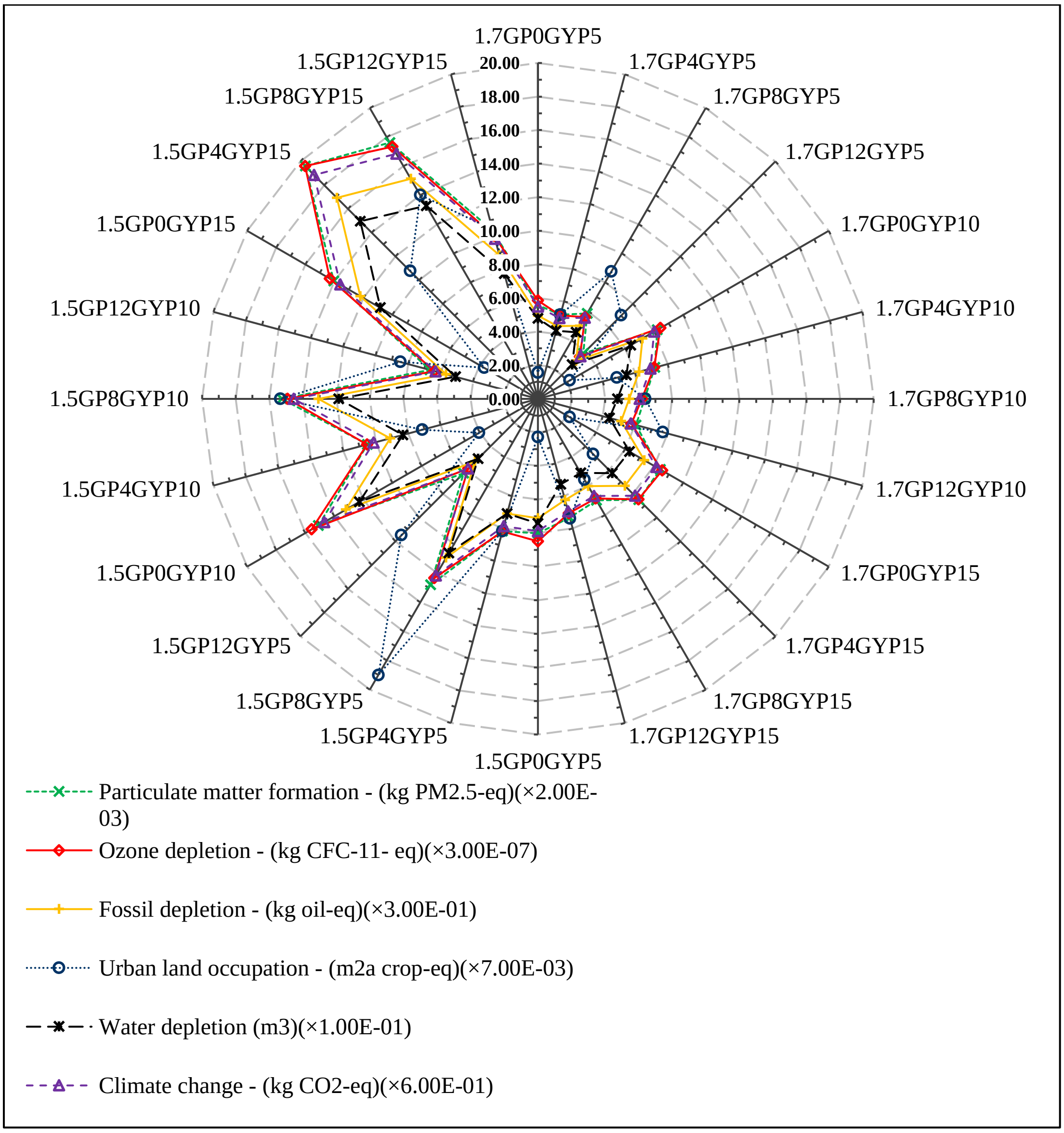
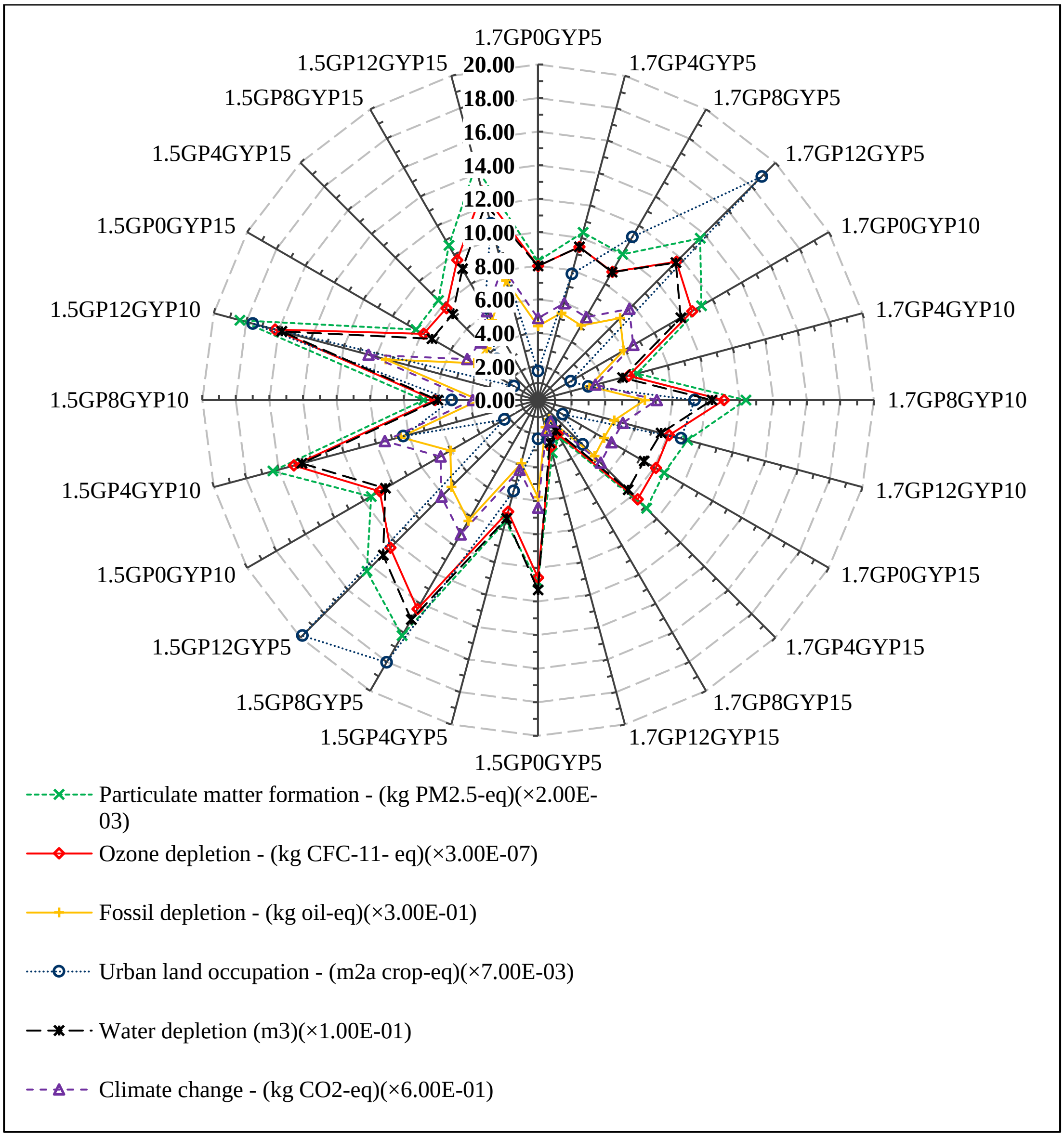


Figure 37 shows that the most undesirable sample is found to be the loose sample containing 12% GP and 10% sintered gypsum. On the contrary, the same combination of the additives in the denser sample is found to be environmentally friendly which underscores the importance of compaction in soil environmental impact analysis.

However, in this case, the most beneficial sample contains 12% and 15% of the glass powder and sintered gypsum, respectively. This shows the advantage of high additive contents for dense conditions.

Figure 37

Correlation of Normalized Six Environmental Impacts by ALM Versus Blends with Different Additive Combinations for Two Densities of 1500 kg/m^3 and 1700 kg/m^3



CHAPTER V

Discussion

The findings of the experiment underscore and explain the interaction between the mechanical, microstructural, and environmental properties of clay soil stabilized with glass powder (GP) and sintered gypsum. It looks into the benefits of strengthening materials by changing the percentages of GP and sintered gypsum, which were examined over different curing periods with respect to the strength, stiffness, durability, and environmental effects

Results Discussion

Mechanical and Microstructural Properties

The unconfined compressive strength (UCS) and initial shear modulus (G_0) results, as presented in Figures 18 and 19, describe a perfect correlation where, with an increase in curing time, there is an improvement in the stiffness and strength of the samples and even the 8% GP content that behaved differently. The stiffness of samples with 12% GP always recorded the highest regression coefficient which indicates that higher content of GP has a positive influence on the resistance of the soil to stress. Nevertheless, the variations in the 8% GP sample may perhaps be accounted for by the poor interfacial bonding of the clay particles with the additives at the specific percent. Such a type of secondary bond-forming at these states could, therefore, be more or less investigated since these observed results are atypical of those established by other GP contents.

The findings of this study confirm the critical role of curing time in enhancing the stiffness and strength of stabilized clay soil, as demonstrated by the UCS and initial shear modulus (G_0) results (Figures 18 and 19). This aligns with the results of Salih et al. (2023), who reported a significant increase in strength and stiffness with extended curing in clay soils treated with pozzolanic additives. However, the observed atypical behavior of the 8% GP sample, possibly due to poor interfacial bonding, requires further investigation. Such variations have also been noted by Canakci et al. (2016), who emphasized the influence of additive distribution on soil strength, particularly at lower percentages.

Correlations and Predictive Models. It comes out clearly from the findings of this work that mechanical properties are well related to their predictive abilities. Specific clay-additive combinations are shown to have UCS, G_0, and elastic modulus (E) that can be modeled with equations 6, 7, and 8. These regression models, with R^2 values ranging from 0.76 to 0.89, suggest that the mechanical properties of the soil can be accurately estimated based on the modified porosity-to-binder index ($\eta/X_{iv}^{0.15}$). This finding corroborates the work of Consoli et al. (2007), who demonstrated the efficacy of porosity/binder indexes in modeling the mechanical properties of stabilized soils. This is of great importance, especially in geotechnical engineering, since it enables soil stabilization and the prediction of the performance of treated soils under different situations in combination with soil stabilization, which leads to improved and more efficient techniques of soil treatment.

Besides, where ALM is correlated against the porosity index, as described in Figures 29(e, f), it is beneficial for soil to have internal structural improvement in order to increase its strength. This resonates with the observations of Al-Subari and Ekinci (2022), who highlighted similar structural enhancements in cement-treated soils. It goes without saying that the formulation of Equation 11 will enable the prediction of ALM for various combinations of the additives and achieve proper regression of R^2 = 0.867. This is an important design for soil blends, which not only enhance mechanical properties but also maintain durability under environmental aggravation.

Durability Analysis

Durability, assessed by accumulated loss of mass (ALM), showed an inverse relationship with GP content (Figure 25). As GP content increased, ALM increased, indicating that GP’s cohesionless nature negatively affects the durability of the blend. Similar observations were made by Canakci et al. (2016), who noted that non-cohesive additives like GP often compromise durability despite improving strength. In contrast, sintered gypsum, due to its cementitious properties, significantly improved the soil’s durability by enhancing pozzolanic reactions. Notably, samples containing 15%

gypsum and 1700 kg/m³ density exhibited the highest durability, further reinforcing the critical role of gypsum in long-term soil stabilization.

ALM results, additionally, showed that curing time is another effective factor for durability performance enhancement, as extended curing times resulted in a lower ALM (Figures 26, 27, 28). This is in agreement with the microstructural actions, as the progressive formation of C-S-H, C-A-H, mullite and ettringite was seen over the period. The extended curing period enables these pozzolanic compounds to further ‘set’ and bond the mass, making it more cyclic wet/dry than it would otherwise be, which usually tends to weaken the performance of soil.

However, it is important to note that the addition of GP to the mixture aggravates the durability factor, particularly at lower percentages of 4%, which exhibited the worst performance in terms of ALM. This suggests that while GP contributes positively to mechanical strength, its impact on durability should be carefully balanced, possibly requiring higher percentages of sintered gypsum to mitigate the brittleness GP induces.

Microstructural Analysis

Moreover, the effect of adding sintered gypsum is evident during pozzolanic reactions with the clay texture during the process. The SEM analysis (Figures 31, 32, and 33) highlighted the development of important products such as ettringite, mullite, and C-S-H as well as C-A-H, which play a crucial role in upgrading the strength, stiffness, and erosion resistance of the soil. The formation of needle-like ettringite, contributing to the matrix’s densification, mirrors the findings of Wu et al. (2022), who described similar mechanisms in gypsum-treated clay. The presence of needle-like ettringite adds to the structure in the form of a matrix that holds the soil grains together, making the soil dense while decreasing its plasticity. This is important as it helps explain the role of sintered gypsum in enhancing the engineering characteristics of the soil with respect to strength and durability.

On the other hand, the alteration of microstructure by GP proved to be more interesting. The XRD, in particular (Figure 30), showed that a gradual decline of silicon intensity was observed in samples containing GP, implying that the pozzolanic interactions between the GP and calcium became ever more active with the curing time and utilized up the free silicon present. This pinpoints that GP in itself acts as a reactive filler, which improves the nature of the soil matrix by densifying it, allowing for hydration product formation. The SEM pictures (Figure 32c) also provided confirmation that the GP is able to aid in void filling as well as the densification of the matrix, which would further enhance the mechanical properties of the stabilized clay soil. Void filling and matrix densification due to GP addition, as confirmed by SEM images, were also noted by Bilgen (2022) in his study of waste glass in soil stabilization. Such improvements in mechanical properties through microstructural densification are key to achieving sustainable soil stabilization.

Environmental Impact Assessment

The environmental impact assessment of this study underscores the role of GP and sintered gypsum additives in influencing the overall environmental footprint (Figure 34). As anticipated, the increasing addition of GP and gypsum amplified the environmental effects due to the energy-intensive processes required for their preparation. Among the assessed environmental parameters, the climate change potential exhibited the most significant increase, while the depletion of ozone potential remained largely unaffected. Interestingly, urban land occupation diverged from the trends observed in other impact categories, with higher percentages of GP, especially, contributing more prominently to this parameter than sintered gypsum. This suggests that waste materials like GP influence land use differently, raising concerns about potential unintended environmental consequences when recycled materials are integrated into construction.

This observation aligns with a study by Al-Subari et al. (2023) on rubber tire (TRP), bottom ash (BA), and marble dust (MD). For instance, while TRP and BA replacements demonstrated improved mechanical properties and lower environmental impacts per unit strength, MD exhibited the opposite, highlighting the variability in waste material performance. Similarly, in this study, the addition of higher GP content (e.g., 12% GP and 5% gypsum) yielded the most environmentally favorable outcomes, emphasizing the critical role of compaction in reducing environmental burdens. In contrast, loose samples with high gypsum and low GP contents exhibited suboptimal environmental and mechanical performance.

A key takeaway is the interplay between additive content, density, and mechanical performance in determining environmental impacts. Just as the normalization of environmental impacts per unit strength, stiffness, and mass loss (UCS, G_0, ALM) in the referenced study provided insights into optimizing material performance, this research highlights that compaction density and the appropriate mix of GP and gypsum are vital for achieving sustainable soil improvement. Notably, while higher densities often reduce environmental impacts per unit strength, excessive additive content or imbalanced compositions, as seen in samples with high gypsum content, can negate these benefits.

The comparison further reinforces the need for a holistic design approach in soil stabilization projects that integrates safety, performance, and sustainability. As shown in both studies, the inclusion of waste materials such as GP and sintered gypsum has the potential to provide substantial environmental benefits when impact ratios are considered. However, the distinct characteristics of different waste materials necessitate careful evaluation, as not all recycled additives perform uniformly across mechanical and environmental parameters.

Finally, the methodological approach of normalizing environmental impacts to target mechanical properties, as demonstrated in the second study, offers valuable guidance for future research. Applying such frameworks to GP and gypsum mixes can enable better quantification of environmental trade-offs and facilitate the design of more sustainable geotechnical applications.

Practical Implications and Future Research

The outcomes of this research are relevant to the area of geotechnical engineering, especially when addressing the challenge of stabilizing soils in an environmentally friendly manner. Non-destructive tests such as G_0 help to predict mechanical properties and quantitative performance and, therefore, can evaluate soil mixes in an economically viable way. In addition, analysis of environmental impacts demonstrates that it is necessary to think about the lifecycle of the additives, particularly when GP needs to be procured from a more sustainable option.

CHAPTER VI

Conclusion and Recommendations

The study concentrated on evaluating the changes in the physical, mechanical, and microstructure due to changes in the GP proportions (0%, 4%, 8%, and 12%) and the sintered gypsum (0%, 5%, 10% and 15%) at varying curing periods of 7, 28 and 56 days and dry densities of 1500 and 1700 kg/m^3. The development of the experimental program included a number of tests: UCS, wetting–drying cycles, UPV tests, and micro-structure analysis, including SEM and XRD.

Conclusion

- The results showed strong relationships between the test variables and the samples' strength and stiffness. The mechanical properties of the clay specimens progressively increased as the density and gypsum content increased, which was notable. In contrast, the effect of glass-powder content showed a typical non-linear behavior, as a detrimental amount of 12% GP was evidenced, emerging a change in the trend towards better strength and stiffness properties than those of lower GP percentage.
- The investigation also established a close association between the P/B index and mechanical properties. Normalizing the data, these attributes attain greater degrees of predictability, granting useful equations for calculating q_u, $G_{0,}$ and E for defined clay mixtures and enhancing a proper design and evaluation process. On top of that, the durability assessment indicated that the low content of GP increased the brittleness factor of the specimens. Among others, the worst GP content for durability was 4%, while an increase to 12% GP led to a marginal reduction in porosity and increased durability. The produced equation for ALM was confirmed as a good predictor of the ALM for different proportions of the additive.
- Microscopic Studies employing SEM and XRD provided important observations of the pozzolanic reactions induced by GP and sintered gypsum. SEM micrograph shows ettringite formation and C-A-H or C-S-H Structures, which contributed immensely to the increase in strength, stiffness, and durability of the treated samples. Furthermore, microstructural analyses highlighted the curing duration as an extremely crucial variable to the soil structure and, therefore, the mechanical behavior.

- The environmental impacts of soil stabilization procedures get worsened by the use of sintered gypsum and GP due to their high energy consumption. Certainly, the use of higher additive content results in higher densities and higher environmental impacts.
- The presence of glass powder modifies the environmental impact in a different manner than that of gypsum. When GP content increases by up to 12%, environmental impacts become worse as well. There is also a noticeable jump in the environmental impact with the addition of sintered gypsum, which is a significant increase.
- Climate change potential is the most sensitive to any of the additives among all environmental impacts. The impact on ozone depletion tends to stay the same regarding the gypsum content level but increases when more GP is added. The environmental impact concerning urban land occupation occurs mainly due to the introduction of GP and only minor increases with the addition of gypsum.
- Trying to approximate the environmental impacts in regards to mechanical properties (UCS and G_0) and the amount of mass lost normally through accumulated loss of mass (ALM) enhances the comprehension of the environmental aspects. It follows that high-density samples tend to have lower normalized environmental impacts and these correlate well with UCS which emphasizes the role of mechanical properties.

In conclusion, it follows that this comprehensive research evaluation greatly illustrated the role that GP and sintered gypsum could play in modifying the geotechnical behavior of clay soils. The research outcomes offer significant points in understanding how the test variables, strength and stiffness features, microstructure changes, and environmental impacts, hence making it possible to design and use materials in geotechnical applications, which include green strategies. The correlations obtained and the predictive equations developed are useful instruments for the optimization of the additive proportions as well as for the evaluation of the mechanical performance of the clay matrix composites for various building applications. As such, this study provides an improvement to current generation practices by encouraging the repurposing of waste materials, especially EoL PV panels, and innovating new ways of doing geotechnical engineering.

Recommendations

Taking into account the results from this research work, it is possible to suggest some recommendations for the use and further investigation of waste EoL solar PV panels, specifically glass powder, in future construction activities:

Optimized Proportions for Soil Improvement

The study indicates that soil strength and stiffness improved with the addition of gypsum, with optimal improvement at 15% gypsum content. In the case of glass powder, optimum content appears to be about 12%, beyond which a positive influence on soil properties begins. Therefore, it is recommended that these proportions be used for practical applications in soil stabilization projects.

Further Exploration of Glass Powder Integration

While Soil strength reduction occurs regarding the addition of GP, its benefits become evident at higher contents (12%). Further research should investigate the long-term effects of glass powder on soil properties and its potential for other types of soil stabilization projects.

Non-Destructive Testing Correlations

The formulas have been generated in this study to predict unconfined compressive strength (q_u), initial shear modulus (G_0), and modulus of elasticity (E) using non-destructive testing methods should be further validated and standardized. This approach can smooth the assessment process in field applications, providing quick and reliable estimates of soil properties.

Environmental Impact Considerations

Looking at the potential environmental consequences of the product using the LCA approach, for example, the sintered gypsum has certain drawbacks in relation to its environmental sustainability because of high energy input, it is advisable to look for other more sustainable ways to prevent such impacts. One measure is to enhance the conditions of the sintering or adopt alternative materials to gypsum that are eco-friendly.

Durability Improvements

From durability test results, mass loss increased as the content of glass powder was elevated, while sintered gypsum reduced this effect. For this reason, optimal proportions of gypsum and glass powder have to be used for enhancement of mechanical and durability properties in the stabilization of soils.

Field Implementation and Long-Term Monitoring

Field evaluation is a critical component that needs to be done to confirm the results of the laboratory analysis under open conditions. Assembled data from these field applications for a longer term would enable the authors to get information on the performance and durability of the treated soils over time.

Policy and Regulatory Frameworks

The recognition of these changes should be integrated by regulatory patterns that will also aid in the incorporation and responsible practices of EoL PV panels in geotechnical engineering. Incentives for using recycled materials and guidelines for their safe and effective application can drive the adoption of these innovative solutions.

Utilization of the Electrical Parts of End-of-Life Solar Panel Materials

In addition to glass powder, dissociation applications should also include other materials returned from the end-of-life solar panels, such as metals, e.g. aluminum, silver or polymers, into their practical applications. By utilizing the blue part of the solar cells as reinforcement fibers for the accelerated soil recovery process, geotechnical enhancement may be improved while efficiently trapping heavy metals in the clay soil. The method provides a more environmentally friendly way of disposing of the waste compared to the ordinary disposal of the panels in the ground.

Behavior of Treated Soils in Diverse Climatic Conditions

The strength of soils treated with gypsum and glass powder application needs to be tested following a temperature cycle, including extreme heat, freeze-thaw, and moist-hydra cycles. It will be important to appreciate how these climatic conditions and factors impact the quality and physical stability of these soils after treatment so that such techniques can be utilized in regions and environments that may be more stringent.

Integration of Geotechnical Simulation Tools

Investigating the possibilities of employing computer-aided geotechnical engineering tools, such as software for geotechnical simulation, should be included in the design and analysis of soil stabilization projects. Such programs can predict timely and accurate soil behavior under various loads and/or environmental conditions, thus increasing the performance of design parameters. In addition, incorporating simulation tools in the design process would also uncover potential problems earlier and offer more effective stabilization measures.

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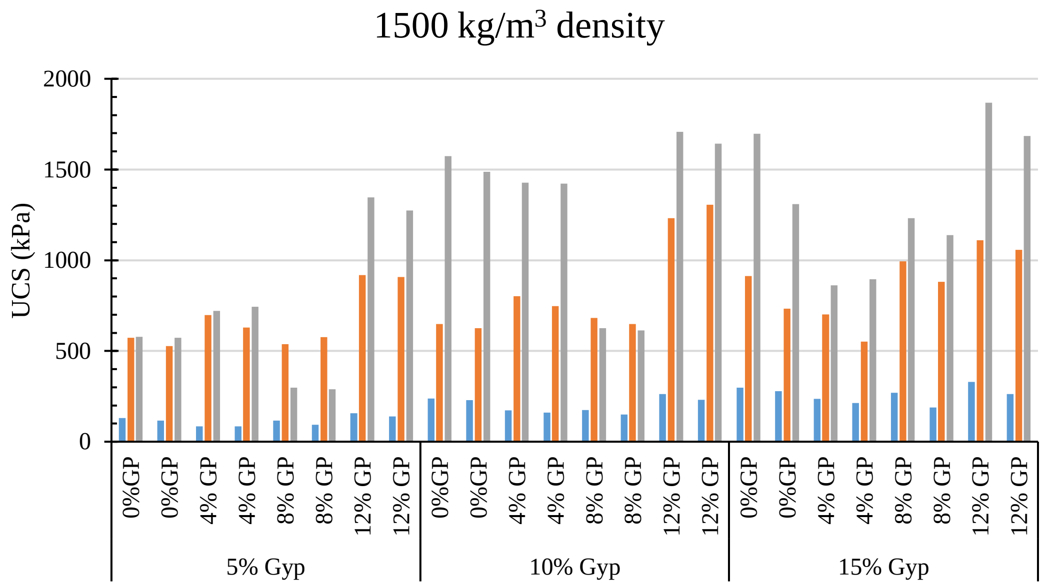
Appendices

Appendix A

Figure A-1.

Correlation Between Different Additive Combinations and UCS Amounts for Two Densities (Each Combination Has Two Samples).



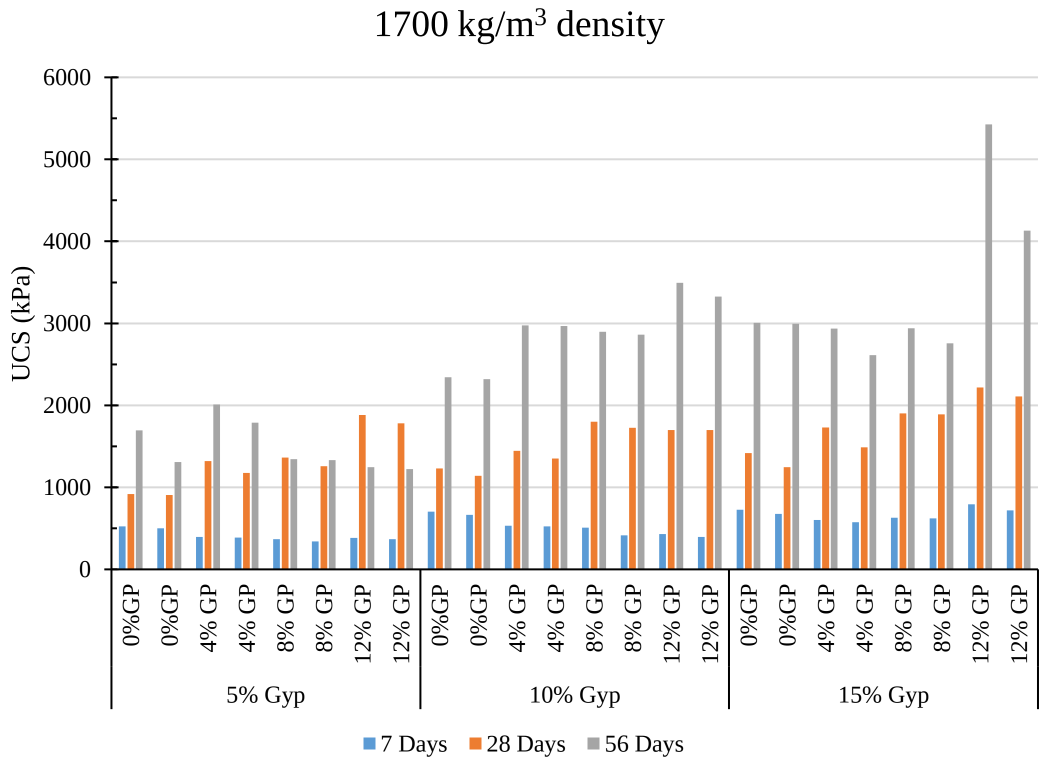


Figure A-2.

Correlation Between Different Additive Combinations and G_0 Amounts for Two Densities (Each Combination Has Two Samples).

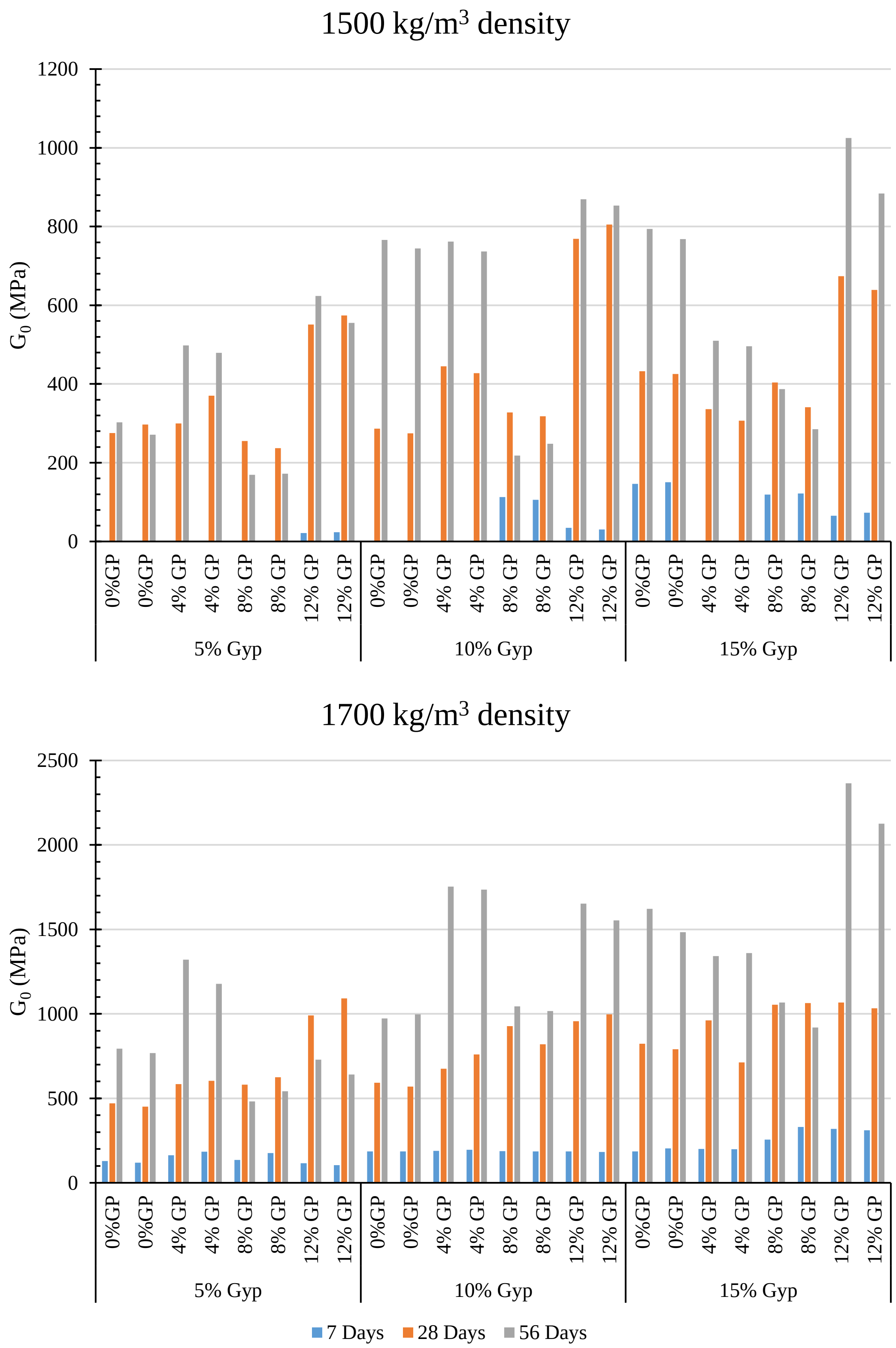
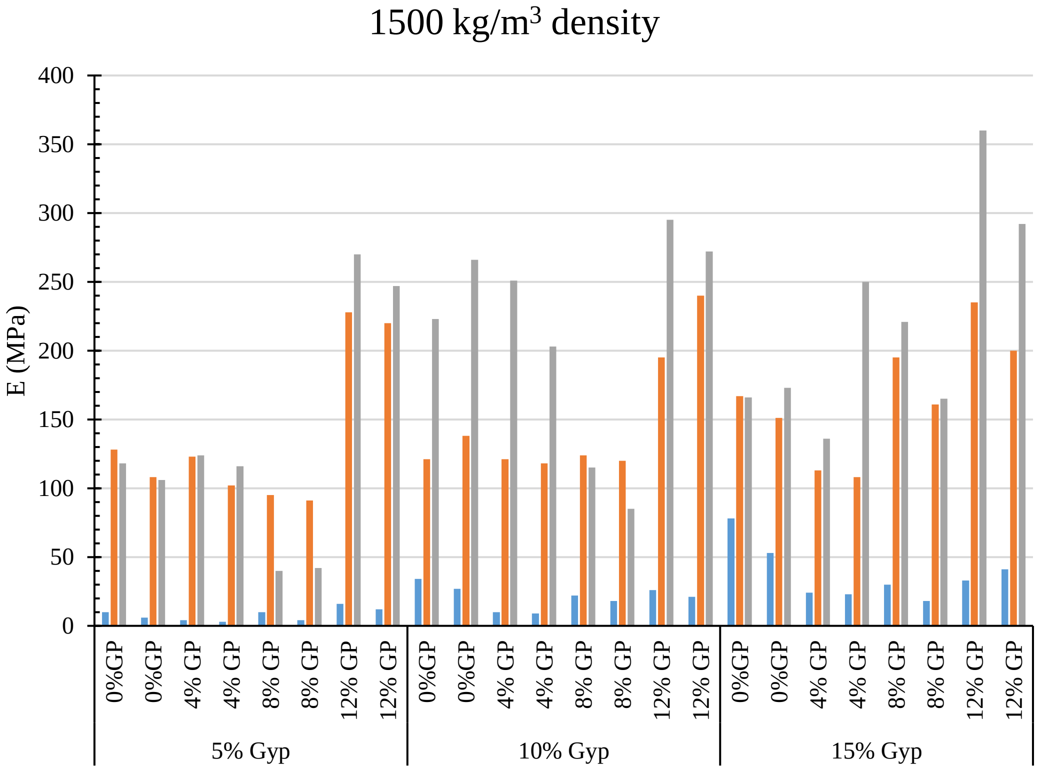


Figure A-3.

Correlation Between Different Additive Combinations and E Amounts for Two Densities (Each Combination Has Two Samples).



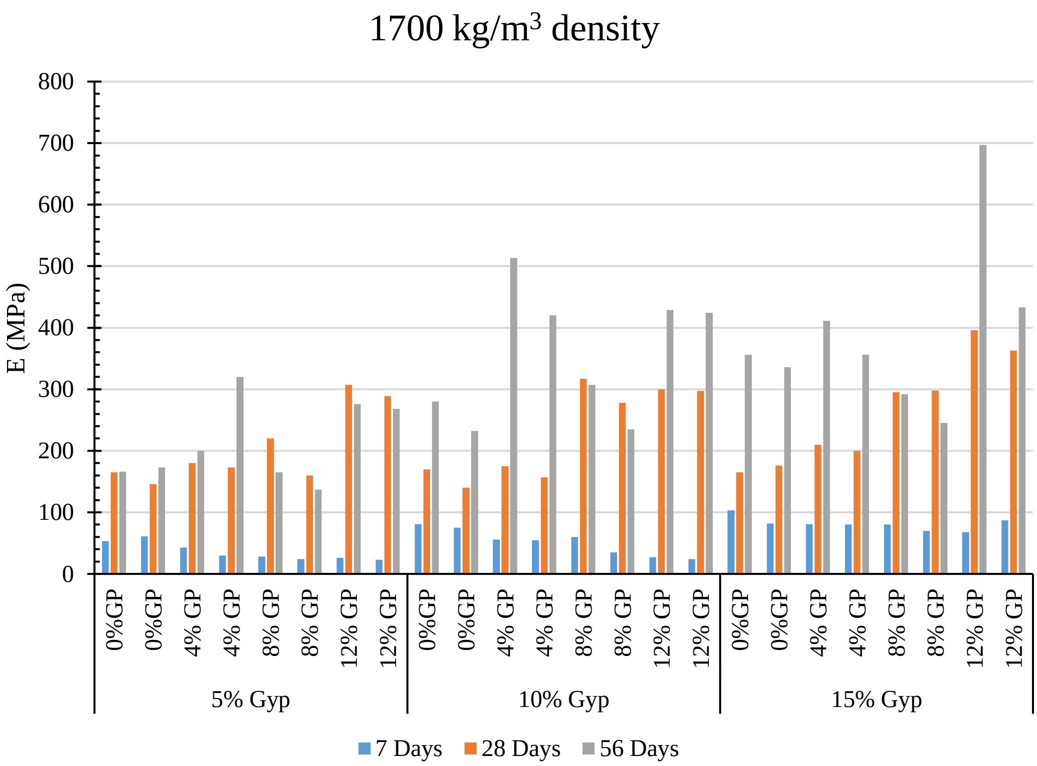


Figure B-1.

Summary of Regression Models Evaluating the Relationship Between Normalized UCS, G_0, and E with $\eta/(X_{iv})^{0.15}$

Normalized UCS		Normalized G_0		Normalized E	
Model	R-Squared %	Model	R-Squared %	Model	R-Squared %
Power	86.66	Power	81.64	Power	75.53
Square root-Y reciprocal-X	86.61	Exponential	81.51	Square root-Y	75.43
Square root-Y logarithmic-X	86.6	Logarithmic-Y square root-X	79.8	Double square root	75.36
Exponential	86.58	Reciprocal-X	79.7	Square root-Y logarithmic-X	75.32
Double square root	86.5	Double square root	79.4	Square root-Y squared-X	75.29
Square root-Y	85.9	Square root-Y	79.4	Square root-Y reciprocal-X	75.27
Square root-Y squared-X	84.3	Square root-Y logarithmic-X	79.3	Exponential	75.25
Reciprocal-X	81.6	Square root-Y squared-X	79.2	Logarithmic-Y square root-X	75.22
Logarithmic-Y square root-X	81.3	Square root-Y reciprocal-X	78.8	Reciprocal-X	75.21
Logarithmic-X	79.4	Logarithmic-X	77.9	Logarithmic-X	75.2
Square root-X	78.2	Square root-X	76.8	Square root-X	74.6
Logarithmic-Y squared-X	77.5	Logarithmic-Y squared-X	76.6	Logarithmic-Y squared-X	74.3
Linear	76.8	Squared-X	73.2	Linear	73.8
Squared-X	74	Linear	72.5	Squared-X	72.2
Reciprocal-Y squared-X	68.1	Reciprocal-Y squared-X	71.5	Squared-Y reciprocal-X	61
Reciprocal-Y	64.9	Reciprocal-Y	70.5	Squared-Y logarithmic-X	58.4
Reciprocal-Y square root-X	63.3	Reciprocal-Y square root-X	69.9	Squared-Y square root-X	57
Reciprocal-Y logarithmic-X	61.6	Reciprocal-Y logarithmic-X	69.2	Squared-Y	55.6
Squared-Y reciprocal-X	60.1	Double reciprocal	67.5	Double squared	52.7
Double reciprocal	58.2	Squared-Y reciprocal-X	57.5	Reciprocal-Y squared-X	34.5
Squared-Y logarithmic-X	56.6	Squared-Y logarithmic-X	54.3	Reciprocal-Y	31.7
Squared-Y square root-X	54.9	Squared-Y square root-X	52.6	Reciprocal-Y square root-X	30.4
Squared-Y	53.1	Squared-Y	51	Reciprocal-Y logarithmic-X	29
Double squared	49.5	Double squared	47.7	Double reciprocal	26.5

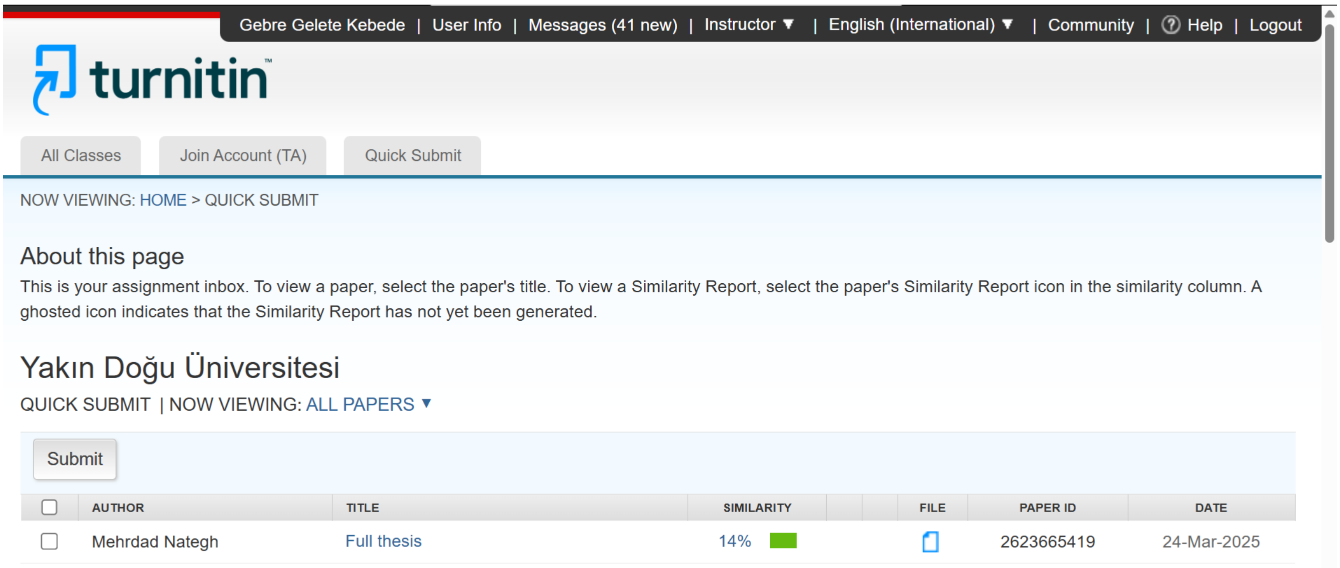
Table A-1.

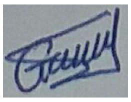
Atterberg limits and specific gravity of air-dried clay soil

Properties	**Clay**
Consistency Limits	
Plasticity index (%)	27.3
Liquid limit (%)	47
Specific gravity	2.66

Appendix C

Similarity Report





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Near East University, Lefkosa, Northern Cyprus
Geotechnical Engineering
Thesis Subject: **UTILIZATION OF END-OF-LIFE PV PANELS TO IMPROVE THE GEOTECHNICAL PROPERTIES OF THE CLAY SOIL**
GPA: 3.93 (Out of 4)

- **Master of Science** 2012 – 2014

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Civil Engineering with a minor in Soil mechanics
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University of Mazandaran, Babolsar, Iran
Physics with a minor in Solid State
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Areas of Interest

- Experimental Soil Mechanics
- Geotechnical Engineering
- Critical State Soil Mechanics
- Liquefaction Assessment
- Saturated Soils
- Unsaturated Soils
- Close Range Photogrammetry
- Soil Rehabilitation
- Clay Soil Improvement
- Waste Material Utilization in Geotechnical Engineering

List of publications

- Life Cycle Assessment of Soil Stabilization Using Gypsum and Recycled Glass Powder from End-of-Life Photovoltaic Panels (Under review)

- Nategh, Mehrdad, Abdullah Ekinci, Anoosheh Iravanian, and Murat Fahrioğlu. 2024. "Enhancing Clay Soil's Geotechnical Properties Utilizing Sintered Gypsum and Glass Powder" Applied Sciences 14, no. 12: 4961. https://doi.org/10.3390/app14124961

- Nategh, M., Iravanian, A., Ekinci, A. (2024). Close-Range Photogrammetry for Non-intrusive Prediction of Geohazards: Landslides. In: Cetin, K.O., Ekinci, A., Uygar, E., Langroudi, A.A. (eds) Proceedings of ISSMGE TC101—Advanced Laboratory Testing & Nature Inspired Solutions in Engineering (NISE) Joint Symposium. ISSMGE-TC101&NISE 2022. Springer Series in Geomechanics and Geoengineering. Springer, Cham. https://doi.org/10.1007/978-3-031-51951-2_9

- Kassem, Y., Gökçekuş, H., Iravanian, A., & Nategh, M. (2022). Implications of the FMEA Method in Evaluating Amirkabir Dam's Environmental Risk. Environmental and Climate Technologies, 26(1), 982-997. https://doi.org/10.2478/rtuect-2022-0074

- Nategh, M., Ekinci, A., Iravanian, A. and Salamatpoor, S., 2020. Determination of Initial-Shear-Stress Impact on Ramsar-Sand Liquefaction Susceptibility through Monotonic Triaxial Testing. Applied Sciences, 10(21), p.7772. https://doi.org/10.3390/app10217772

- Motaghedi, H., Salamatpoor, S., Nategh, M. (2015). Influence of shear parameter on liquefaction susceptibility of Ramsar sand. World Academy of Science, Engineering and Technology International Journal of Geotechnical and Geological Engineering Vol: 9, No: 1

Employment

- Enerchimi Engineering Company (Civil Engineer (Jul. 2020 – Aug. 2021))

- Persia Oil and Gas Industry Development Company (Civil/Geotechnical Engineer (Sep. 2017 – May. 2020))

- Kavosh Khak Azma Geotechnical Consulting Company (Technical Director (Sep. 2014 – Sep. 2016))

Professional Skills

- Field and lab experiments (Especially monotonic triaxial tests)
- Geo reports producer
- Road construction supervisor
- Scope of civil work producer
- Civil QC documents producer

Computer skills

- Semi-proficient in using AutoCAD
- Beginner programmer in Python.
- Proficient in using Microsoft Office including Word, Excel and Power-point.
- Semi-proficient in using IBM SPSS.

Languages

- Persian (Native)
- English (Advance)
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Ethical approval letter

Reference: Mehrdad Nategh- 20205017

I would like to inform you that the above candidate is one of our postgraduate students in Civil Engineering Department. He is taking thesis under my supervision and the thesis title is: **"UTILIZATION OF END-OF-LIFE PV PANELS TO IMPROVE THE GEOTECHNICAL PROPERTIES OF THE CLAY SOIL"** Since the researcher(s) did not collect primary data from humans, animals or plants, this project does not need to go through the ethics committee. Please do not hesitate to contact me if you have any further queries or questions.

Thank you very much indeed.

Best Regards.

Assist. Prof.Dr Gebre Gelete Kebede