

**USE OF ADDITIVELY MANUFACTURED ELEMENTS
THROUGH PLASTIC FOR GEOTECHNICAL APPLICATIONS**

BY

AQEEL UR REHMAN

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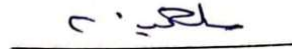
DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by **Aqeel Ur Rehman** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN CIVIL ENGINEERING**.



Dr. Shamsad Ahmad
Department Chairman

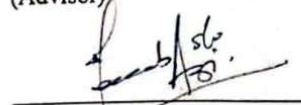


Dr. Suliman Al-Homidan
Dean of Graduate Studies

Date



Dr. Syed Umair Ali
(Advisor)



Dr. Mubashir Aziz
(Co Advisor)



Dr. Omar Al Amoudi
(Member)



Dr. Ammar Al-Shammari
(Member)



Dr. Usman Ali
(Member)



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2024

Dedicated to My Mother and Father

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ABSTRACT

Full Name : Aqeel Ur Rehman

Thesis Title : Use of Additively Manufactured Elements through Plastic for Geotechnical Applications

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The environmental concerns related to the increasing plastic waste generation in Saudi Arabia have led researchers to utilize it in the geotechnical field, including soil improvement. Despite numerous research studies on plastic waste for ground improvement, the use of discrete hollow particles from recycled plastic through an advanced manufacturing technique has not yet been explored. This study investigates the efficacy of Additive Manufacturing (AM), an advanced technique in geotechnics, by integrating 3D-printed hollow geometric elements into marl soil to enhance its performance. Marl soil, a sedimentary material commonly found in arid regions, is characterized by low strength and water sensitivity. Various AM geometric configurations and proportions were analyzed through geotechnical tests, including compaction, unconfined compressive strength (UCS), direct shear, triaxial, and permeability tests. AM elements were manufactured in three different shapes, i.e., triangular, circular, and square, with three different sizes for each shape. The MDD and OMC were reduced with an increasing percentage of AM elements. UCS strength increased to an optimum percentage of 1.5%. Additionally, UCS strength was more significantly affected by the size of AM elements as compared to the shape. The shear strength increased about 25% when AM is mixed to the soil. Confining stress improves soil's stress-strain behavior, and the soil's permeability is also increased when AM particles are mixed with the soil. Finally, regression

models for Unconfined Compressive Strength (UCS) were proposed, identifying UCS as a primary performance indicator of shear strength in AM-reinforced marl soil.

Keywords: Additive Manufacturing, Plastic waste, Soil improvement, Shear strength, Sustainability, Marl soil

ملخص الرسالة

الاسم الكامل: عقيل الرحمن

عنوان الرسالة: استخدام العناصر المصنعة بالطباعة الإضافية من البلاستيك للتطبيقات الجيوتقنية.

التخصص: الهندسة المدنية

تاريخ الدرجة العلمية: ديسمبر 2024

المخاوف البيئية المتعلقة بزيادة النفايات البلاستيكية في المملكة العربية السعودية دفعت الباحثين إلى استغلالها في المجال الجيوتكنيكي، بما في ذلك تحسين التربة. على الرغم من وجود العديد من الدراسات حول استخدام النفايات البلاستيكية لتحسين التربة، إلا أن استخدام الجسيمات المجوفة المنفصلة المصنوعة من البلاستيك المعاد تدويره من خلال تقنية التصنيع المتقدمة لم يتم استكشافه بعد. تبحث هذه الدراسة في فعالية التصنيع الإضافي (AM)، وهي تقنية متقدمة في الجيوتكنيك، من خلال دمج عناصر هندسية ثلاثية الأبعاد مجوفة مطبوعة بتقنية AM في تربة المارل لتحسين أدائها. تربة المارل، وهي مادة رسوبية توجد عادةً في المناطق القاحلة، تتميز بانخفاض قوتها وحساسيتها العالية للماء. تم تحليل تكوينات هندسية مختلفة ونسب متنوعة من عناصر التصنيع الإضافي من خلال اختبارات جيوتكنيكية شملت اختبارات الدمك، وقوة الضغط غير المحصورة (UCS)، واختبارات القص المباشر، والاختبارات ثلاثية المحاور، واختبارات النفاذية. تم تصنيع عناصر التصنيع الإضافي بثلاثة أشكال مختلفة: مثلثية، ودائرية، ومربعة، وبثلاثة أحجام لكل شكل.

أظهرت النتائج انخفاضاً في الكثافة الجافة القصوى (MDD) والمحتوى المائي الأمثل (OMC) مع زيادة نسبة عناصر التصنيع الإضافي. زادت قوة UCS حتى نسبة مثلى بلغت 1.5%، ثم لوحظ اتجاه تناقصي. أعلى قوة UCS لوحظت للعناصر المثلثية الصغيرة الحجم. بالإضافة إلى ذلك، تأثرت قوة UCS بشكل أكبر بحجم عناصر التصنيع الإضافي مقارنة بشكلها. لوحظ أن قوة القص زادت بنسبة حوالي 25% عند خلط عناصر

التصنيع الإضافي مع التربة .عمل الإجهاد الحابس على تحسين سلوك الإجهاد والانفعال للتربة، كما زادت نفاذية التربة عند خلط الجسيمات الإضافية مع التربة. وأخيرًا، تم اقتراح نماذج انحدار لقوة الضغط غير المحصورة (UCS) ، حيث تم تحديد UCS كمؤشر أساسي لأداء قوة القص في التربة المعززة بعناصر التصنيع الإضافي.

CHAPTER 1

INTRODUCTION

1.1.General

Weak soils, characterized by low shear strength, poor bearing capacity, and high moisture retention, are particularly vulnerable to settlement and volume changes, risking structural stability. Addressing such issues involves options like relocating the project, soil replacement, or improving soil properties. Due to increasing urbanization and land scarcity, enhancing the engineering properties of existing soils has become essential, positioning ground improvement as a focal area in geotechnical engineering. Soil stabilization techniques aim to improve soil properties such as compressibility, strength, density, and hydraulic conductivity. Traditional methods, including mechanical stabilization and vibratory techniques, chemical stabilization, geosynthetics, biomaterials.

In Saudi Arabia, common types of soil are sabkha, calcareous (marl) soils, dune sands, collapsible and expansive soils. Sabkha soils are significantly found in Saudi Arabia and problematic in nature due to high compressibility, low bearing capacity and highly saline. Dune sand is an aeolian sand with low cohesion and permeability and exposed to wind erosion. Collapsible and expansive soils are highly sensitive to water and show significant volume change upon wetting and drying. Calcareous soils are susceptible to dissolution, leading to karst formations and cavities. Collapsible soils require careful consideration of settlement and moisture control.

The generation of plastic waste in Saudi Arabia is steadily rising, posing significant environmental challenges. The rate of plastic waste production far exceeds recycling efforts, which is a growing concern, particularly in the Kingdom of Saudi Arabia (KSA). The primary contributors to plastic waste include water bottles, plastic bags, food packaging, and single-use items predominantly originating from the food industry, retail sector, and tourism, including pilgrimage activities. Furthermore, modern sources of plastic waste now encompass discarded electronics, automotive components, plastic toys, household appliances, and industrial manufacturing scraps.

Utilizing this plastic waste in geotechnical applications, such as soil improvement, offers a promising solution to mitigate its environmental impact. This approach not only provides an effective means of recycling but also helps reduce the volume of waste directed to landfills, thereby increasing recycling rates and promoting sustainable resource management.

Furthermore, various techniques can be implemented to incorporate plastic waste into soil improvement. While raw or product forms of waste, such as plastic bottles and bags, can be directly mixed into the soil, this approach limits the scope of waste utilization. To maximize its potential, the integration of advanced additive manufacturing techniques alongside recycling processes is essential. By converting recycled plastic waste into filaments, additive manufacturing can produce innovative geomaterials of any desired shape and size. These customized materials can be effectively applied to address problematic soils, offering a sustainable and efficient solution for soil improvement.

1.2. Marl Soil in Saudi Arabia

The Marl soil is an abundantly available marginal soil in the Gulf region specifically in Saudi Arabia (Figure 1), which is naturally calcareous and majorly composed of calcium carbonate and clay minerals.

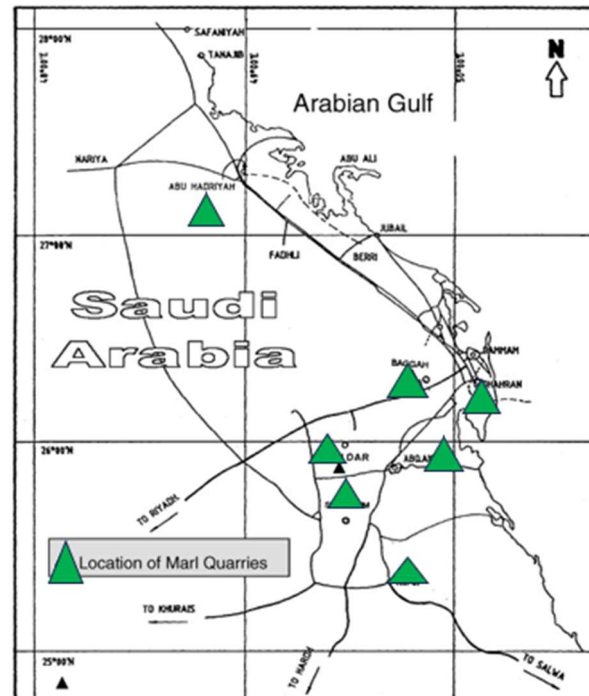


Figure 1. Marl soil deposits in Saudi Arabia region

Marl soil is problematic for infrastructure due to low dry density and higher water sensitivity. Marl soil is commonly found throughout the Kingdom of Saudi Arabia, specifically in the Eastern Province, where it is majorly used as a backfill material due to its low price and easy availability [1]. Its abundance and marginal geotechnical properties make it suitable soil for the subject research. Thermogravimetric analysis (TGA) is one of the techniques to characterize the marl soil (Figure 2) in which the weight loss of a soil is plotted against the increasing temperature.

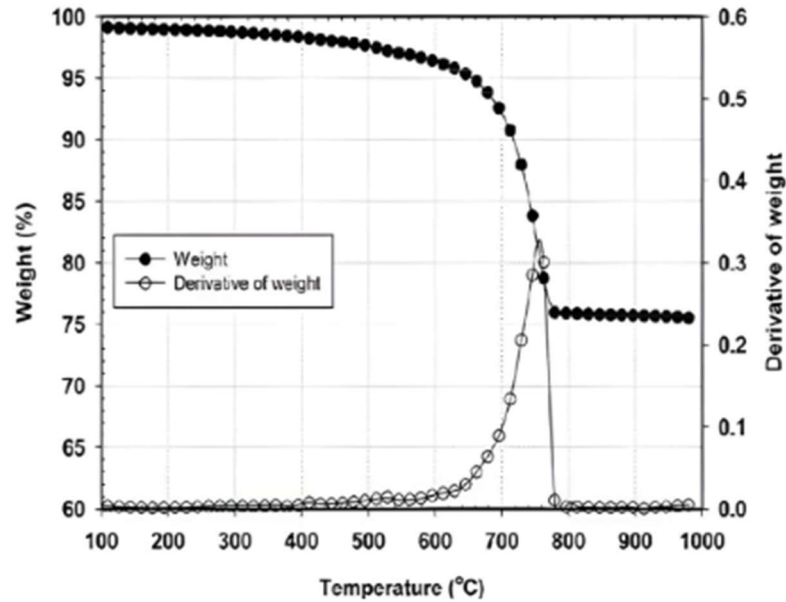


Figure 2. Marl soil identification using TGA curve

1.3.Additive Manufacturing (AM)

Additive manufacturing (AM) offers a promising avenue for repurposing plastic waste, converting it into functional materials for construction and ground improvement. AM, which uses 3D model data to create complex geometries, enables rapid, efficient, and sustainable solutions. Additive manufacturing is the process of designing materials with complex shapes and geometry. In recent decades, this technique has received more attention (Figure 3) in the construction industry as well as in other industries [2], [3]. Additive manufacturing is further dividing different techniques based on the source energy which include, material jetting, binder jetting, stereolithography, fused deposition modelling, contour crafting. The most common materials used in additive manufacturing are resin, metals, ceramics, polymers, plastic, glass etc. The use of plastic waste in AM also extends to ground improvement applications, where recycled materials help enhance soil properties such as shear strength, stiffness, and permeability. The dual benefit of addressing plastic waste pollution and improving soil performance is achieved by integrating recycled plastics into stabilization processes, aligning with global sustainability goals. The

chemical interaction of the AM particles with the soil can be evaluated using Fourier Transform Infrared Analysis (FTIR).

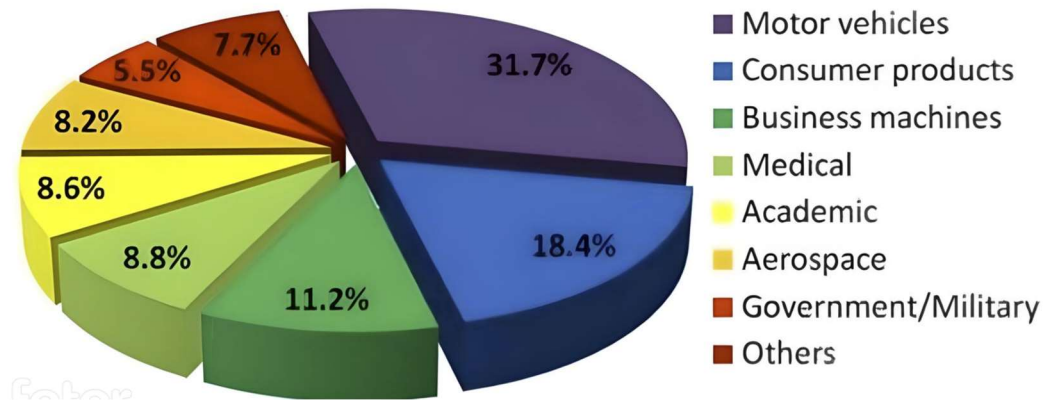


Figure 3. Additive manufacturing in different industries [3]

1.3.1 Additive Manufacturing (AM) techniques

Additive manufacturing techniques vary significantly based on the energy source used, including laser, electron beam, thermal, UV light, plasma arc, and mechanical energy. In laser beam techniques, high-powered laser beams are introduced to selectively melt or sinter powdered materials or resins layer by layer to build the desired object. Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Stereolithography (SLA) are some of the common techniques which use laser beams. Stereolithography (SLA) uses a laser to cure liquid photopolymer resins. They are mostly applied to aerospace, automotive, medical implants, and detailed prototypes.

In electron-based beam techniques, focused electron beams are used, instead of laser beams, to melt or fuse metal powders in a vacuum environment, reducing contamination and oxidation. They are mostly applied to orthopedic implants, and high-performance metallic structures.

Fused Deposition Modeling (FDM) and material extrusion are some of the techniques which use thermal energy generated by heating elements or extrusion mechanisms. Materials such as

thermoplastics or composites are heated and extruded through a nozzle to create layers. They are applicable in prototyping, consumer goods, and soil stabilization studies.

Ultrasonic Additive Manufacturing (UAM) and Photopolymerization are the techniques which employed mechanical and chemical energy respectively, for curing processes. Plasma arcs are used to fuse metallic materials, particularly in Directed Energy Deposition (DED) processes. Plasma Arc DED melts metal feedstock (wire or powder) and deposits it in layers to form a component. Mostly used in repairing damaged metal parts, creating large metallic components.

Selecting the appropriate technique depends on the material, precision, and application requirements. For sustainable solutions, integrating thermal-based methods like FDM using recycled plastic waste filaments offers a promising pathway for producing geomaterials for soil improvement applications.

1.3.2 Additive Manufacturing (AM) materials

Different materials can be used for additive manufacturing including metals, ceramics, polymers, plastic, alloys, composites, concrete, biomaterials and glass. The selection of a material depends on the method used and intended application. For instance, metals and alloys are compatible with selective laser techniques, electron beam melting and directed energy deposition as they are requiring strength, durability, and precision for automotives and aerospace components.

Suitable technique for concrete material is extrusion based technique as they are applicable to Building structures, bridges, and modular housing. Similarly, polymers and plastic filaments are widely used in fused deposition modelling (FDM) and digital light processing. Most commonly used polymers Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS). For geotechnical applications, ABS is preferred over PLA because ABS is non-biodegradable, durable

and impact resistant. PLA has lower impact resistance, ductility, and toughness compared to ABS. It is brittle and more prone to breaking under load or impact. ABS offers better chemical resistance and can withstand exposure to oils, greases, and many solvents, making it suitable for harsh environments.

1.4. Problem statement

Each year, millions of tons of plastic are released into the environment by households and companies. About 11% of Saudi Arabia's municipal solid trash is plastic waste. Therefore, it would be wise to consider using plastic waste more effectively. Numerous researchers have investigated the use of raw plastic (fibers, granules, or powder) for soil stabilization. However, the utilization of the additive manufactured particles using recycled plastic in the soil remains unexplored. Addressing this gap can enhance the soil properties as well as a waste, thought to be harmful and dangerous to the environment, could be converted to a valuable resource. Earlier research concentrated on the full replacement of AM particles with natural soil. Research on employing AM particles as a partial soil substitute, especially in weak or widely accessible soils, hasn't been done yet. Additionally, what makes this approach unique is the use of individual, discrete particle shapes rather than continuous 3D-printed layers or sheets.

1.5. Thesis Objectives

The principal objective of this research is to explore the feasibility of Additive Manufacturing (AM) techniques in soil improvement. These specific goals included:

- The utilization of the AM technique to produce elements of varying shapes and sizes using recycled and virgin ABS plastic.
- Characterization of soil and AM elements.

- To investigate the strength of Marl soil blended with varying AM shapes and sizes and to determine the optimal percentage of AM elements.
- Investigating the effect of AM elements on the permeability of the marl soil.
- To explore the confinement effect on soil strength mixed with AM elements.

1.6. Thesis Outline

The methodology defines the steps that will be taken to complete the various tasks for this research. The first phase involves the production of materials needed in this study, which are soil and 3D AM elements, and then conducting the required physical tests. The second phase will evaluate the effect of AM elements on UCS strength and stiffness of soil and optimize the percentage of AM elements. The third phase includes the shear strength and permeability analysis.

Chapter 1 introduces the concept of soil improvement for marl. It also discusses additive manufacturing and its applications and how this can be used to utilize geotechnical perspectives. This chapter concludes with a summary of the objectives of the thesis.

Chapter 2 reviews the literature on conventional improvement techniques like mechanical and chemical stabilization. This chapter also summarizes the previous studies related to the concept of additive manufacturing in geotechnical engineering.

Chapter 3 talks about the process of constructing the experimental setup. Along with the case studies and experimentally examined parameters, this chapter also discusses the measurement apparatus and their specification.

Chapter 4 presents and discusses the experimental study's findings. Individual graphs representing parametric studies and the findings of other case studies are displayed.

Chapter 5 provides a detailed discussion of the experimental study's findings. Experimental setting up shortcomings and suggestions for further research were made.

CHAPTER 2

LITERATURE REVIEW

Major challenges faced by the Geotechnical engineers related to soil properties are mostly in the regions with high plasticity or poor strength strata. The most significant issues are low shear strength, differential settlement, high compressibility, volume changes, that is, expansion and contraction, and soil heaving. This leads to issues that compromise the stability of construction projects and infrastructure [4]. Traditional, advanced, and non-traditional techniques have been widely adopted to improve soil strength and overcome the above-mentioned problems. The traditional and oldest method developed was mechanical stabilization, such as compaction, vibration, and the use of stone columns. Compaction, vibration methods, blast densification [5], preloading [6] and stone columns, particularly in soft clay soils [7] are mechanical methods that are used widely in ground improvement. Despite their success, these traditional methods have limitations due to the specific land use, urbanized area, excessive noise, and space restriction [8]. Moreover, insufficient lateral confinement in soft soils results in a bulging and failure of Stone columns [9].

Non-traditional additives, including polymers and other materials, are also considered to overcome these limitations. Additive binders, including the use of cement, calcium-based additives, and chlorides, lime, fly ash [10], [11], and other ashes [12], [13], [14], have also proven effective in stabilizing expansive soils [10], [11]. However, cement produces carbon dioxide emissions that demand immediate attention [15]. Traditional additives (lime and fly ash) can cause brittleness or other unwanted effects when applied excessively, while other ashes possess biodegradable characteristics [16], [17]. Promising results were observed using advanced techniques involving nanomaterials; however, they are unsuitable for large-scale projects due to high costs [18]. This

has led to the search for more flexible and environmentally friendly solutions, which brings additive manufacturing (AM) techniques into the spotlight. Additive manufacturing uses different materials, including plastic, to create the final product. Previous researchers also utilized plastic in a different way for ground improvement.

2.1. Plastic and its utilization in the geotechnical field

In 1950, plastic production was 2 million tons globally, which rose to 459.75 Mt in 2019, and the main source is packaging [19]. It is expected to cross 13.2 billion tons by 2050 [20]. In Saudi Arabia, 15.3 million tons of solid waste is generated annually, approximately 1.4 kg/capita/day [21]. The generation of municipal solid waste per year for KSA is shown in Figure 4. Two major contributing wastes in KSA are organic wastes (Food, paper, yard waste) and plastic wastes (polystyrene, polyethylene PET) [22]. The composition of organic waste is 45.5%, and plastic waste is 11%. 85% of solid waste is disposed of in landfills, and only 15% is recycled (World Bank 2024). By 2035, a new plan was put into place in Saudi Arabia that calls for 42% of garbage to be recycled, 35% to be composted, 19% to be burned for energy recovery, and 4% to be handled in other ways [23]. So, the utilization of plastic in a better way for geotechnical purposes should be taken into account.

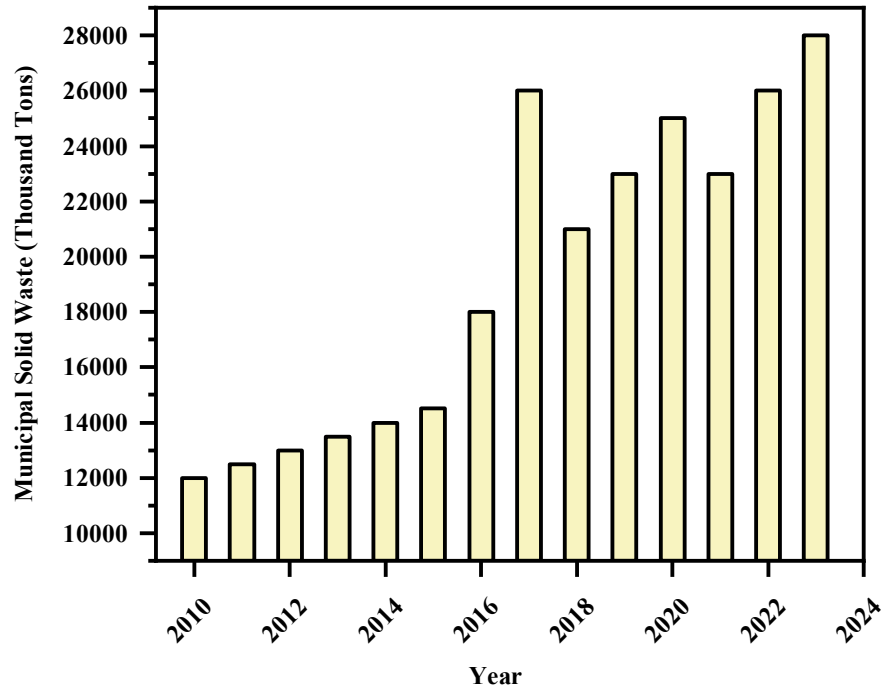


Figure 4. Generation of MSW in Saudi Arabia [23]

Lucarelli et al. [24] studied the reinforcing capability of Polyethylene Terephthalate (PET) and polypropylene to reduce the environmental effects. The results indicated that including plastic fibers decreased the maximum dry unit weight and optimum moisture content compared to natural soil. Moreover, shear strength is improved, and the dilation behavior is suppressed. Gangwar and Tiwari [25] also studied the use of plastic bottles in soil improvement. Many other researchers [26], [27], [28] also explored plastic waste as a soil stabilizer in terms of compaction tests, direct shear tests, and CBR tests. It reduced the maximum dry density and improved the UCS strength and CBR up to the optimum plastic dosage. Omine et al. [29] developed new geomaterials from plastic waste and performed different experiment tests. The author concludes that the shear and compressive strength is improved when plastic waste is mixed with the soil.

However, a notable limitation in the existing literature is that plastic waste, such as sheets, fibers, granules, or powder, is predominantly used in its raw form. The potential of transforming plastic

waste into new materials or discrete structural elements still needs to be explored. The possibility of transforming plastic waste into entirely new materials or manufacturing discrete hollow particles, which could offer enhanced mechanical properties and broader applications, remains underexplored. By focusing on such advanced processing techniques, there is significant scope to address environmental concerns and improve material efficiency in engineering applications.

One key advantage of utilizing plastic to create new geomaterials for geotechnical applications is its long-term stability in the ground, lasting several decades (Figure 5). In contrast, conventional recycled products often degrade in quality within a few years and require repeated recycling [29].

Furthermore, one of the existing uses of plastics in geotechnical engineering is the utilization of geogrids, geotextiles, geocells, and polyester fibers, which is being studied by researchers for soil improvement [30], [31], [32], [33], [34], [35], [36]. Geocells and geogrids are interconnected cells that provide confinement effects to the soil and improve the soil's mechanical properties. However, the influence of hollow discrete cells has yet to be studied before.

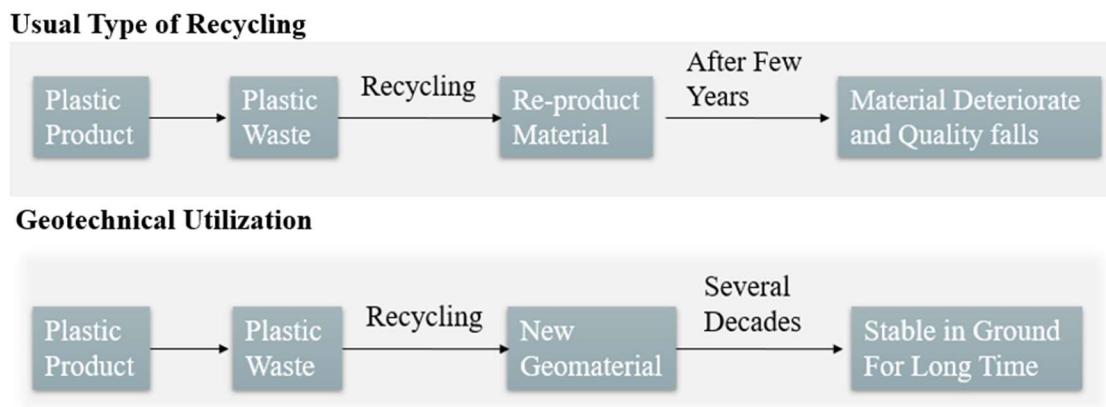


Figure 5. Life Cycle of plastic waste in usual recycling and geotechnical utilization [29]

2.2. Additive Manufacturing (AM)

AM processing allows the creation of custom structures and components by building up materials layer by layer from digital models [37]. AM technique offers rapid, efficient, accurate, and sustainable manufacturing [38]. AM techniques that are commonly used are Fused deposition modeling, contour crafting, Stereolithography (SLA), Selective Laser Sintering (SLS), Binder jetting, powder bed printing [39], [40], [41] and these techniques are classified based on the material used and the process followed [37]. Common materials that are used for different techniques are metals, resins, photopolymers, alloys, ceramics, paper, synthetic materials, nylon, polymers, and plastic [42], [43], [44], [45].

The workflow of additive manufacturing is shown in Figure 6. Additive manufacturing follows five major steps to produce a final model: (i) Creating and designing a 3D model, (ii) Converting a CAD file to an STL file, (iii) Generating a G-code file to assign parameters to each layer of the model known as slicing (iv) Final Printing and (v) Post-processing. Post-processing plays an essential role in the mechanical and aesthetic characteristics of a final model as it is affecting the surface roughness, scratch resistance, and wetting behavior [46], [47].

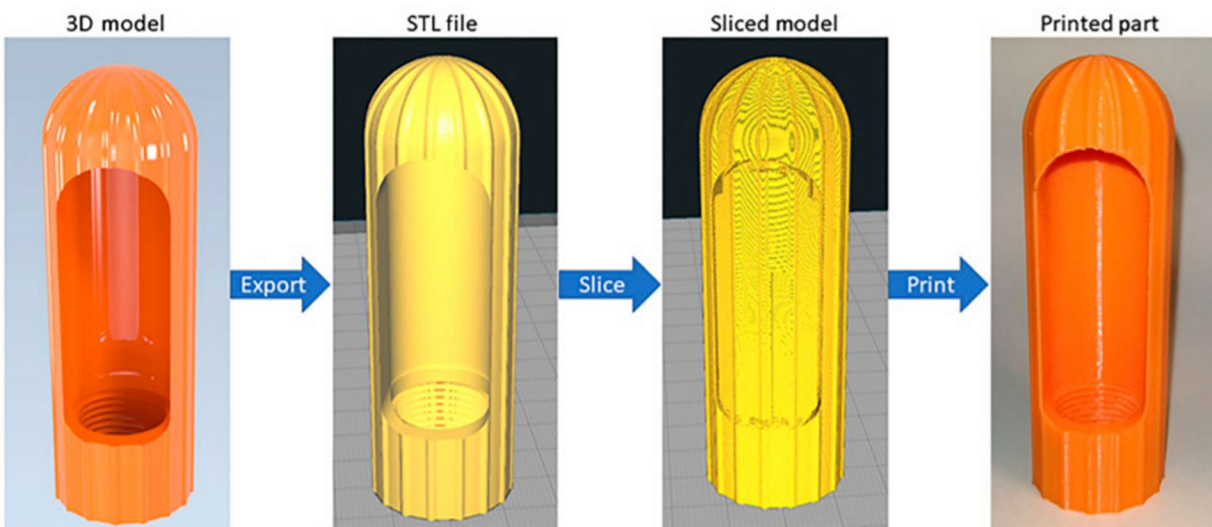


Figure 6. Additive Manufacturing workflow [44]

AM also supports innovative multi-material systems, which provide flexibility in designing materials with specific properties for different parts of a structure. This ability to customize materials for specific purposes improves both their performance and sustainability [48].

2.3. Additive Manufacturing (AM) in different fields

In 1983, Charles W. Hull used additive manufacturing to successfully print a 3D teacup, and the 3D-printed kidney was first manufactured using a bioprinter in the late 1990s [44]. Additive manufacturing is now used in every industry such as aerospace [49], [50], medical [51], [52], food [53], electronics [46], automobiles [54], [55], and construction industry. In recent decades, AM techniques have received more attention in the construction industry and powder technology [56]. AM is considered a third revolution in the construction industry [41]. In 1997, Pegna was the first person to use AM to increase the bonding between cement and sand utilizing steam [57]. After that, different techniques were adopted to utilize AM in the construction sector, such as the construction of 3D printed concrete [62], wall [63], slab [64], and building [58], some researchers also reviewed different techniques and advancements of AM in architecture and construction industry, different applications and new construction materials [45], [59], [60]. Carcassi and Ben-Alon [61] summarize the construction of different materials, such as soil, ceramics, cement, and concrete, through additive manufacturing. China created a basic house structure in just one day using additive manufacturing and a two-story villa in 45 days, while the US built a three-story building in just one day using the Extrusion-based technique [41]. Figure 7 shows the concrete manufactured using the material extrusion technique at Eindhoven University. Unlike traditional methods, additive-manufactured plastic elements allow for waste reduction by using recycled materials, and their modular nature enables easy customization for specific geotechnical

challenges. Introducing 3D additive manufacturing with plastic materials presents a more sustainable solution [29].



Figure 7. Concrete printing at the university [45]

Extensive literature is available on the use of additive manufacturing in every industry, including the electronics, mechanical, and construction industries. So, why not utilize this technique in geotechnical engineering applications and challenges? The literature lacks on how additive manufacturing techniques can address geotechnical challenges like soil stabilization, reinforcement, or modification of in-situ soil properties. Furthermore, while it mentions using recycled plastic materials, integrating such techniques into ground improvement strategies, such as creating geomaterials for soil stabilization or addressing site-specific geotechnical constraints, is not elaborated.

2.4. Additive Manufacturing (AM) in geotechnical engineering

Additive manufacturing (AM) has increasingly found applications in geotechnical engineering, with various studies exploring its potential for transforming traditional research practices. In geotechnical engineering, additive manufacturing was initially limited to studying rock mechanics. Hasiuk first prepared an AM reservoir rock model [62] for the students to visualize the porosity and its geometry. Following this, Hasiuk along with his student Ishutov and colleagues, produced 3D-printed models of sandstone (Figure 8) using fused deposition modeling technique to study the pores interconnectivity, fluid flow, grain matrix, and other properties of the rocks [63]. The authors recommended utilizing AM models for further exploration as they are low-cost and easy to use in laboratories. Furthermore, 3D printing models of rocks were used to study microstructures, crack propagation, stress distribution, and hydraulic conductivity within the rocks [64], [65], [66], [67], [68], [69], [70], [71].

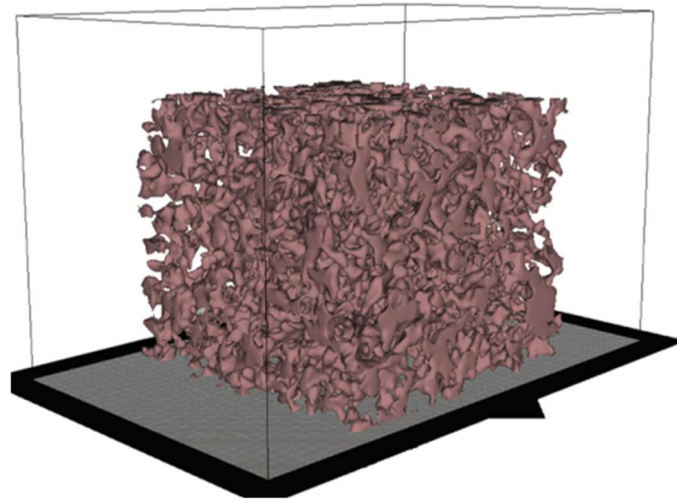


Figure 8. Additively manufactured model of sandstone [63]

Xia et al. [72] demonstrated how 3D printing could significantly improve the mechanical testing of rock masses, allowing for the repetitive preparation of samples and the study of complex structural behaviors under different conditions. This technique helps reconstruct rock structures

and precisely capture their mechanical and failure characteristics, advancing subsurface construction research.

Similarly, researchers have explored 3D printing for the development of tunnel models (Figure 9). These models, printed from materials like gypsum and PLA, were able to replicate the mechanical responses of tunnels with faults and support structures, showing that 3D printing can advance the study of tunnel stability and the performance of geotechnical infrastructure [73]. The results suggested that the failure characteristics of the tunnel model were similar to those of the case studies, experimental results, and numerical simulations (Figure 10). It was recommended that the 3D printing technique be used over conventional tunnel preparation to reduce tunnel damage, artificial errors, and time consumption. In the geotechnical field, fused deposition modeling is extensively utilized for the investigation of rock mechanics [74], [75].

Recent literature highlights the growing potential of additive manufacturing (AM) in the soil mechanics branch of geotechnical engineering. The applications of additive manufacturing in geotechnical engineering include soil improvement using geogrids, geotextiles, and geomembranes [2], [75], [76]. Other applications include small retaining structures [77], replication of rock-joints [74] and soil behavior and interaction [73], [78], [79].

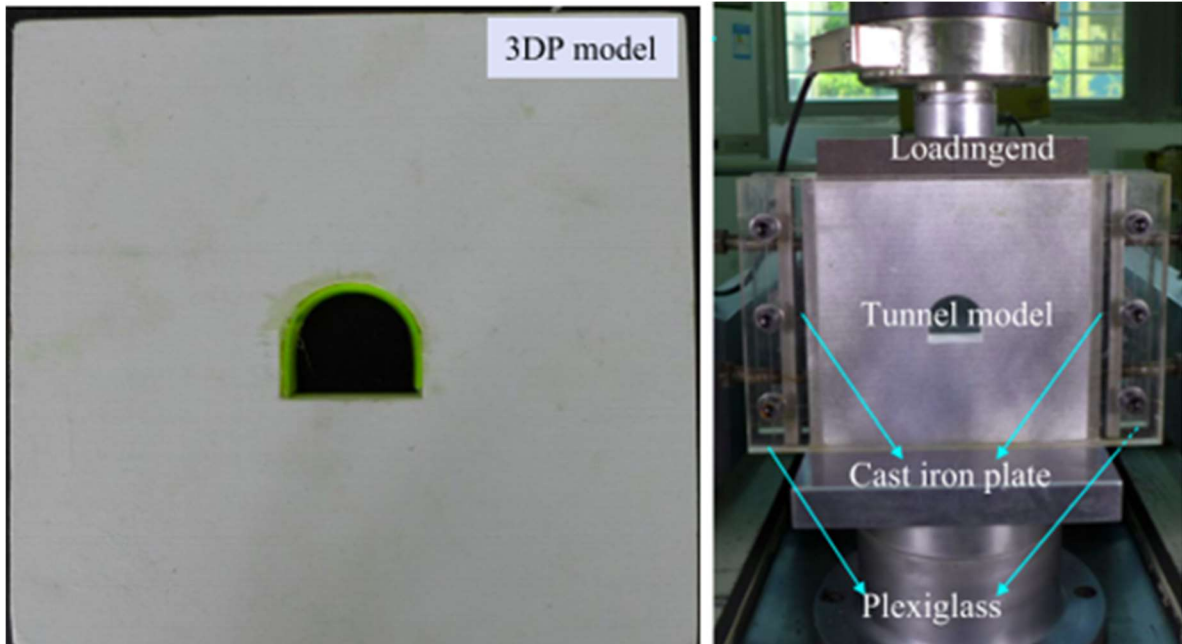


Figure 9. 3D printed tunnel model and compression loading [73]

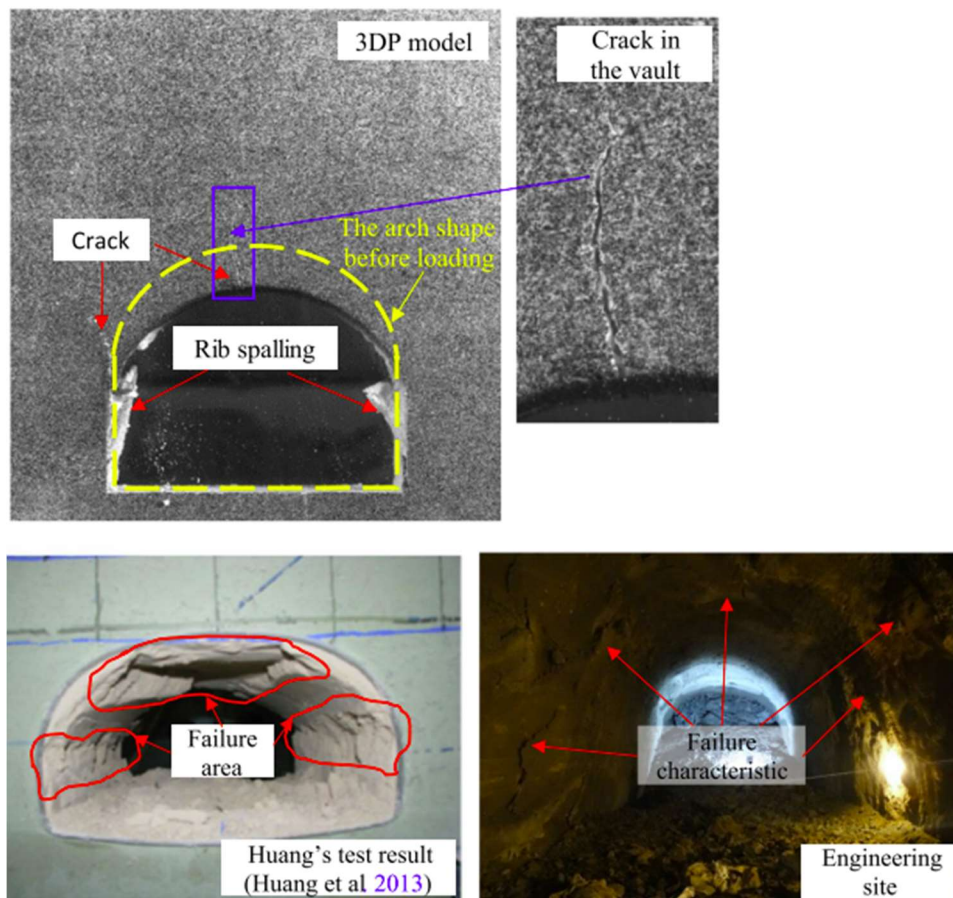


Figure 10. Comparison of AM model with experimental and site data [73]

AM elements/materials are mostly used to improve the shear strength, stiffness, and permeability of soil. Miskin and Jaeger [80] studied the packing characteristics of granular material under compression using AM geomaterial. Compact particle shapes resulted in stiffer packings, and rod-like shapes created softer, more flexible packings (Figure 11). Hanaor et al. [81] discussed three different techniques to generate AM grains with realistic morphology successfully (

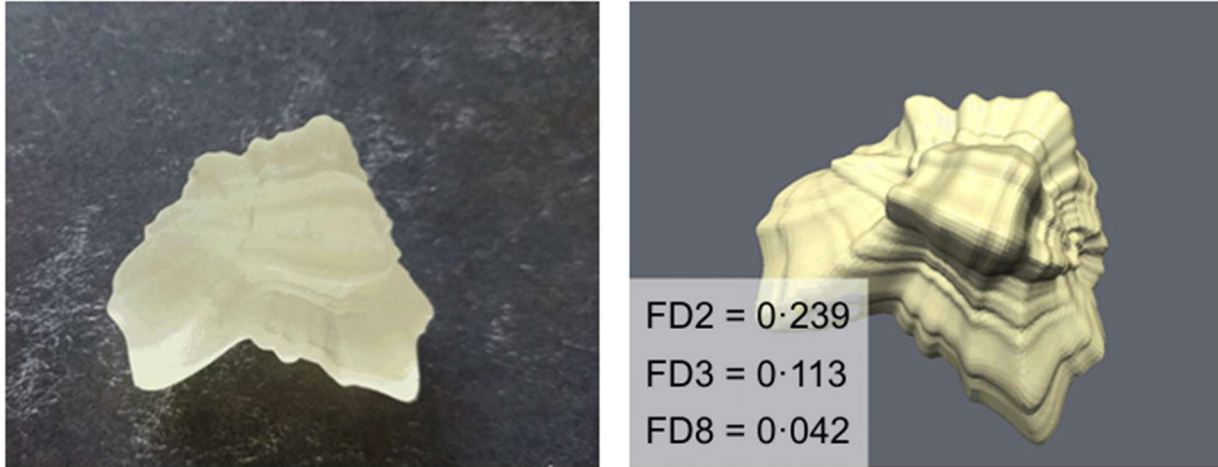


Figure 12). These techniques include fractal surface overlay (FSO), contour rotation interpolation (CRI), and directed polyhedral aggregation (DPA) to define morphology. Later on, triaxial tests were performed, which gave a response similar to the natural soil.

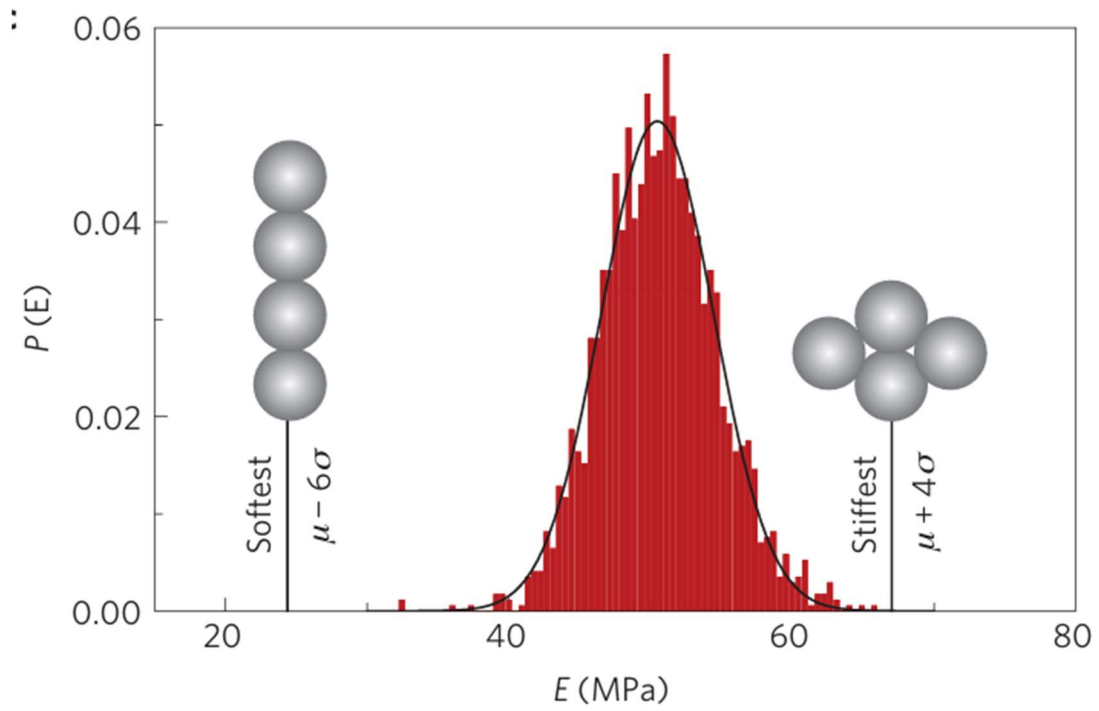


Figure 11. Elastic modulus histogram for the AM particles [80]

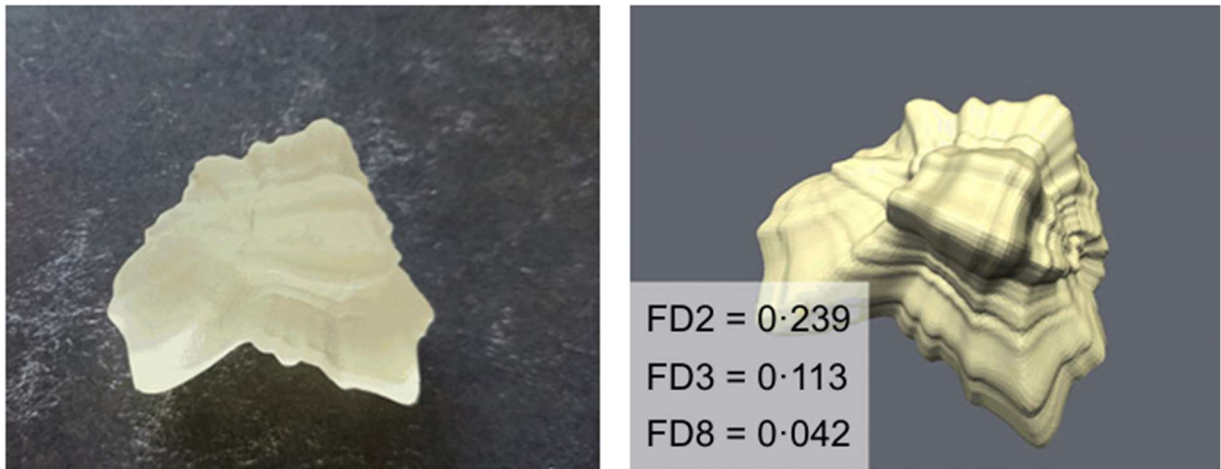


Figure 12. Printed and Simulated grains [81]

Landauer et al. [82] used a selective laser sintering technique to manufacture granular particles of different shapes including cube, Tetrahedron, Octahedron, Tetrapod, and Quadropod to investigate the particle packing characteristics and angle of repose using static and dynamic methods. The

author commented that the densities of additive material showed no significant difference. However, the angle of repose showed variations. Therefore, the suggested technique of employing additive-manufactured particles is a significant experimental addition to simulating research utilizing comparable particle morphologies.

Similarly, Ahmed & Martinez [83] studied the behavior of coarse-grained soil using AM particles formed by additively manufactured methods (Figure 13). The study examined and contrasted AM particles' shear wave transmission behaviors, oedometer compression, and uniaxial inter-particle compression behaviors with those of glass and steel spheres and naturally occurring angular and rounded sand particles. The outcomes showed that AM is capable of accurately replicating the form of coarse sand particles.

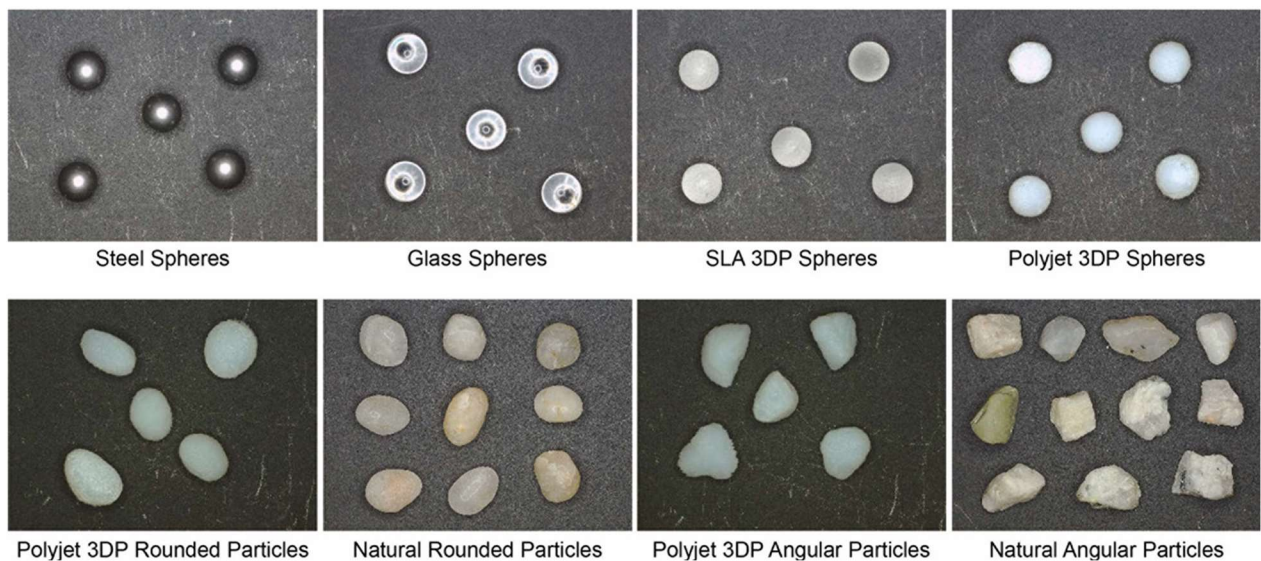


Figure 13. Comparison of AM particles with the natural soil [83]

Li et al. [84] developed a transparent granular soil (Figure 14) using a viable additive manufacturing technique (SLA). Transparent sand prepared from previous techniques had some discrepancies in terms of the particle shape. So, AM technique was utilized and performed different laboratory tests including direct shear, compression and triaxial compression tests to compare it

with the natural soil. To define the morphology of a particle, the CRI method was adopted as discussed by Hanaor [81].

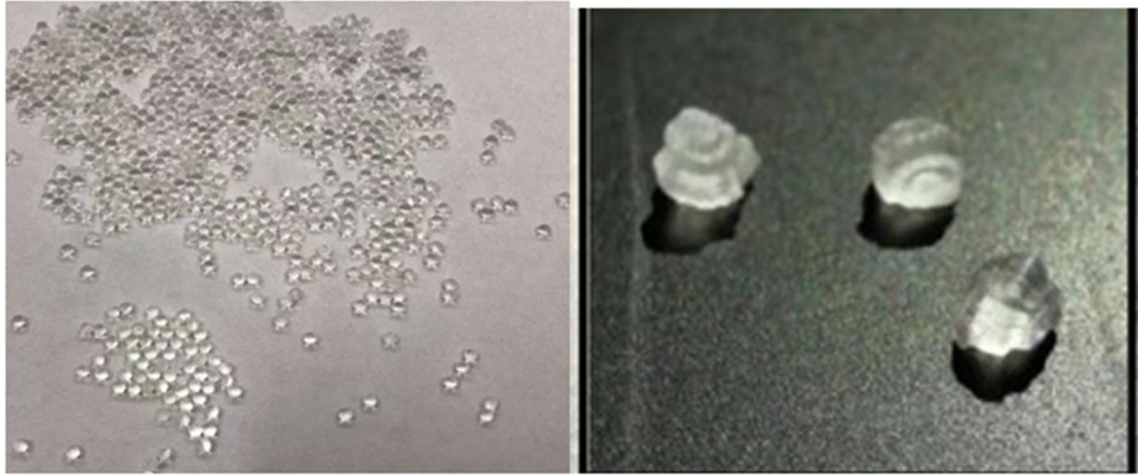


Figure 14. Spherical and non-spherical AM particles [84]

The results indicated that the printed particle behavior under compression resembles silica and calcareous sand for low vertical stresses. However, for higher stress the behavior deviates due to low stiffness (Figure 15). Also, the results of triaxial tests is in line with the natural soil (Figure 16) because dilation is decreased with the higher stresses and the peak strength occurs when the dilation starts. Also, the friction angle from direct shear test for spherical particles is lower than the non-spherical due to roughness of the surface. This confirms the usefulness of the proposed 3D printed transparent soil technique.

Lei et al. [85] conduct a parametric study to explore the shear behavior of additively manufactured particles (Figure 17). The influence of particle shape, initial condition and shape parameter was studied in detail. Particle geometry was characterized by the holistic geometry parameter (S_h) which includes the volume, surface area and size. Higher S_h showed negative relation with packing densities but positive relations with the shear strength and dilation angle, according to test data.

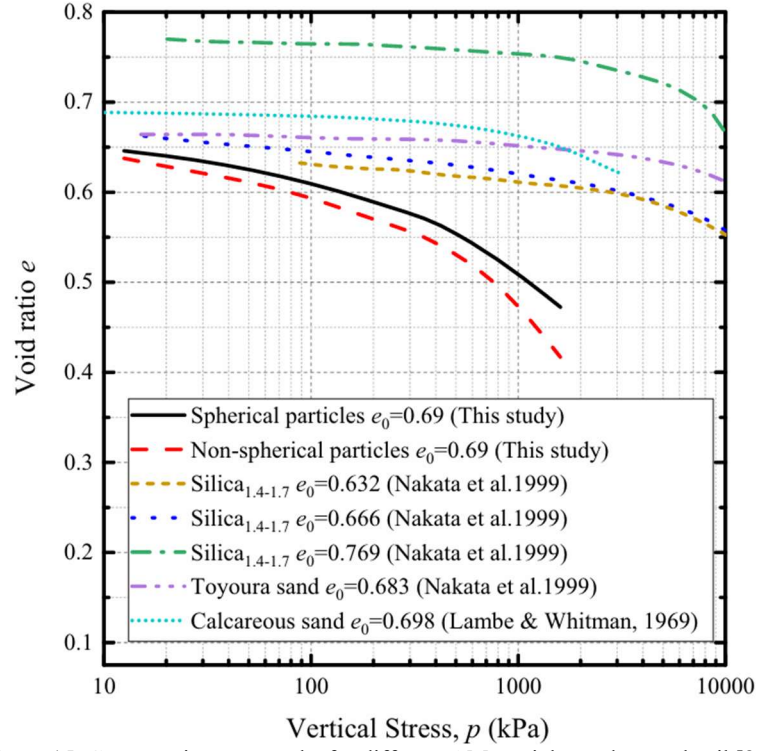


Figure 15. Compression test results for different AM particles and natural soil [84]

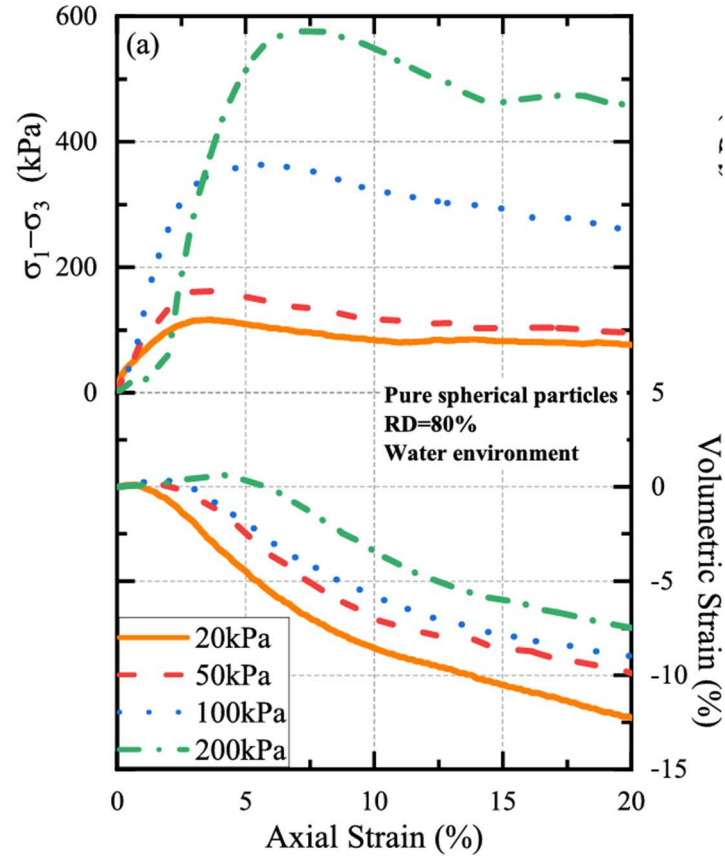


Figure 16. Triaxial CD test under different normal stresses [84]

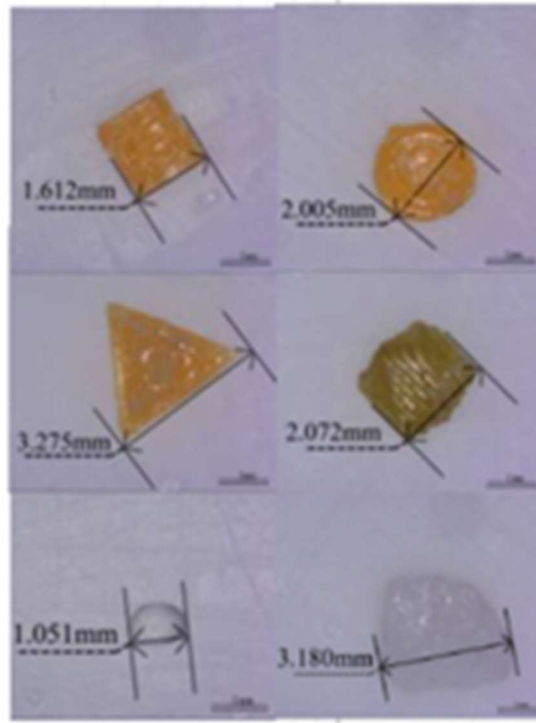


Figure 17. AM particles of different shape [86]

Natural soils, such as volcanic soils, are porous and irregularly shaped so it cannot be replicated experimentally. Matsumura et al. [87] developed porous AM particles to examine the mechanical properties of these particles using crushing and triaxial compression tests and compare it to natural volcanic soils. The study used three different particles of solid spheres (3DPs), porous particles with voids (3DPv), non-porous particles with filled inner voids (3DPf). Natural volcanic soil (VS) was included for comparison. Porous 3DPv particles had significantly lower strength than non-porous 3DPf and 3DPs particles. Porous particles (3DPv) exhibited stress-hardening and contractive behavior, similar to volcanic soils. Volcanic soil showed behaviors matching porous 3DPv particles, but with higher variability due to its natural heterogeneity. This research highlights the potential of 3D printing for creating controllable synthetic soil particles.

The articles mentioned earlier focused on using 3D-printed solid particles as a complete replacement for natural soil. However, there hasn't been any research on using additively

manufactured elements as a partial replacement for soil, particularly in weak or commonly available soils. This study explores the possibility of utilizing additively manufactured hollow elements made from plastic wastes for improving the marginal soils for geotechnical applications, providing an efficient and eco-friendly technique that reduces the carbon footprint through waste reduction. Additionally, what makes the approach in this work unique is the use of individual, discrete particle shapes rather than continuous 3D-printed layers or sheets.

CHAPTER 3

METHODOLOGY

3.1. Soil

Soil samples were collected from Al Dawhah Al-Janubiyah Dhahran, in Eastern Province, Saudi Arabia, at $26^{\circ}18'41''$ N latitude and $50^{\circ}10'06''$ E longitude (Figure 18). Undisturbed samples were assembled in core cutters and UCS test samplers to investigate the in-situ characteristics of the soil. In addition, a number of bags containing disturbed samples (Figure 19) were gathered and brought to the laboratory in order to examine their engineering and physical characteristics as well as the behavior of soft soil when AM elements are mixed. Many laboratory studies were conducted to evaluate the physical properties, index properties, and engineering parameters from compaction tests, unconfined compressive strength tests, shear strength tests, and triaxial tests in order to define the soil. The tests were carried out in compliance with ASTM Standards. The gradation curve and soil properties are shown in Figure 20 and Table 1 respectively.

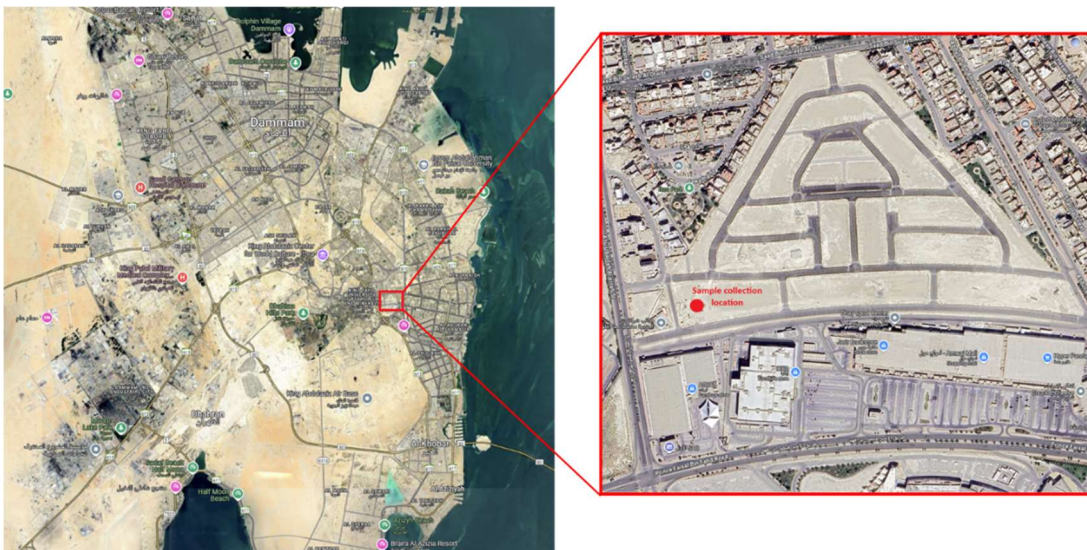


Figure 18. Location of marl soil in Dhahran

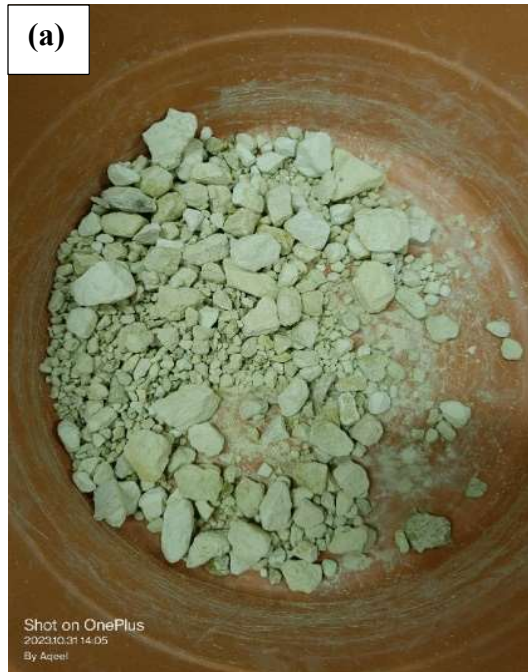


Figure 19. (b) Marl soil lumps (b) Grinded to powder

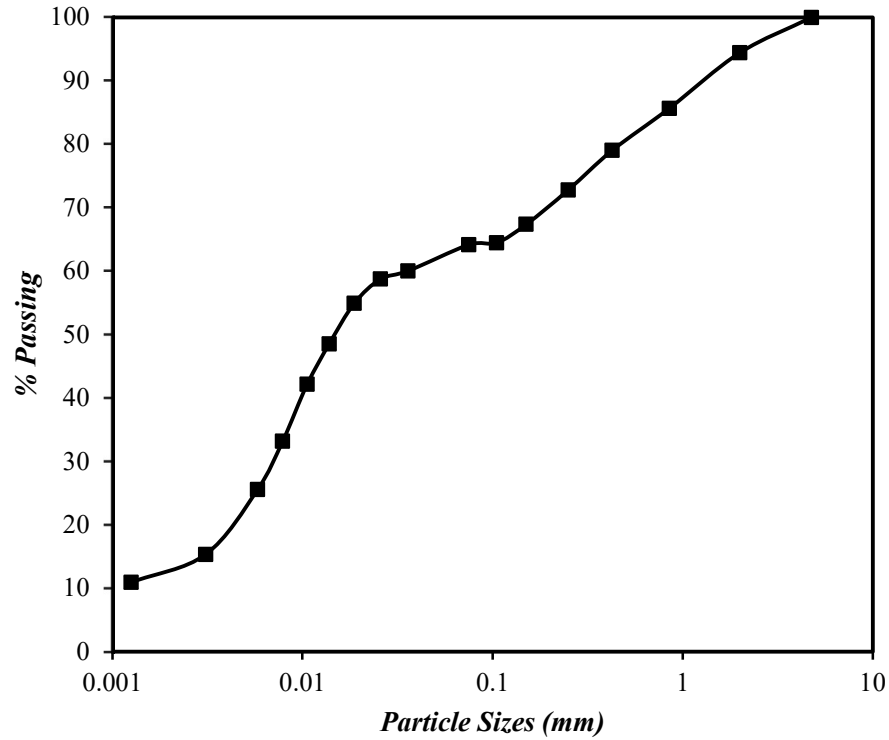


Figure 20. Gradation curve of marl soil (wet sieve analysis)

Table 1. Basic engineering properties of marl soil

Properties	Value	ASTM
Average Diameter, D_{50} (mm)	0.015	
Sand (%)	35.52	D1140-17
Silt (%)	41.60	
Clay (%)	22.60	
Liquid limit (%)	41.35	D4318
Plasticity index (%)	16.50	
Soil classification (USCS)	Sandy Lean Clay	D2487-17
Maximum dry density (kN/m^3)	19.8	D1557
Maximum void ratio, $e_{\max}$	0.85	D4254
Minimum void ratio, $e_{\min}$	0.35	
Specific gravity	2.73	D854

XRD analysis was performed using a monochromatic Cu K α 1 radiation at 40 kV and 40 mA with a diffractometer. The 2θ range was from 5° to 90° with an increment of 0.04°. XRD samples were prepared by sieving the soil through a 75 μ m sieve in accordance with the specifications of the laboratory equipment. The given XRD pattern (Figure 21) shows the presence of several key clay and non-clay minerals in the marl soil. The prominent clay minerals are illite and kaolinite, with peaks of approx. 10° and 12.5° 2θ respectively. Also, the non-clay minerals are quartz, calcite, and dolomite. The quartz shows four peaks corresponding to 2θ at 38°, 45°, 52° and 68°. Dolomite is a carbonate mineral like calcite but contains magnesium in addition to calcium.

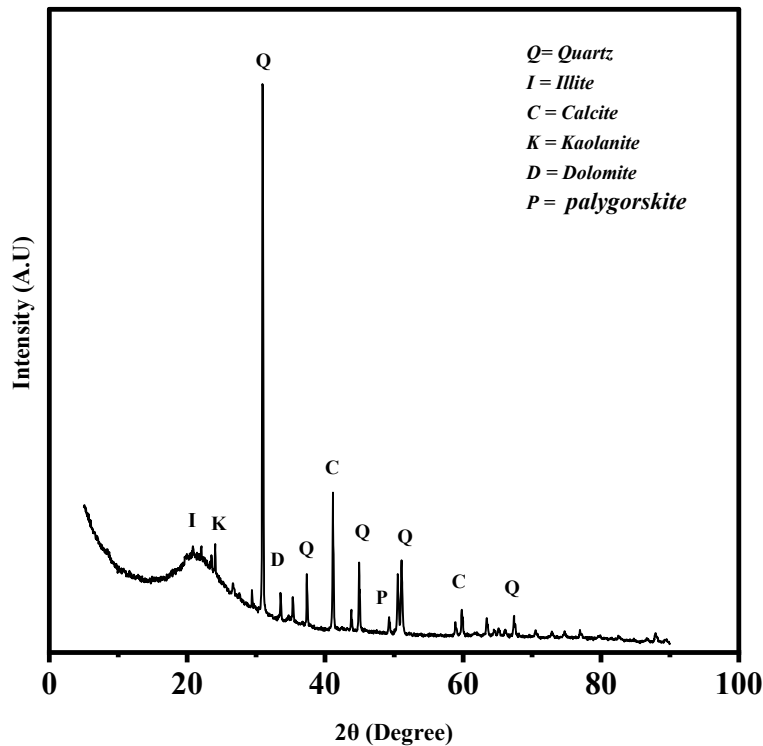


Figure 21. XRD Pattern for a marl soil

To ascertain a greater understanding, the microstructure study for particle shape and texture was done using a scanning electron microscope (SEM). SEM was selected for microstructure analysis because of its simplicity in sample preparation. Microstructure images for both the shape and

texture of the marl samples are presented in Figure 22. SEM images showed quartz with rounded particles, and white particles represented calcite and clay sheets.

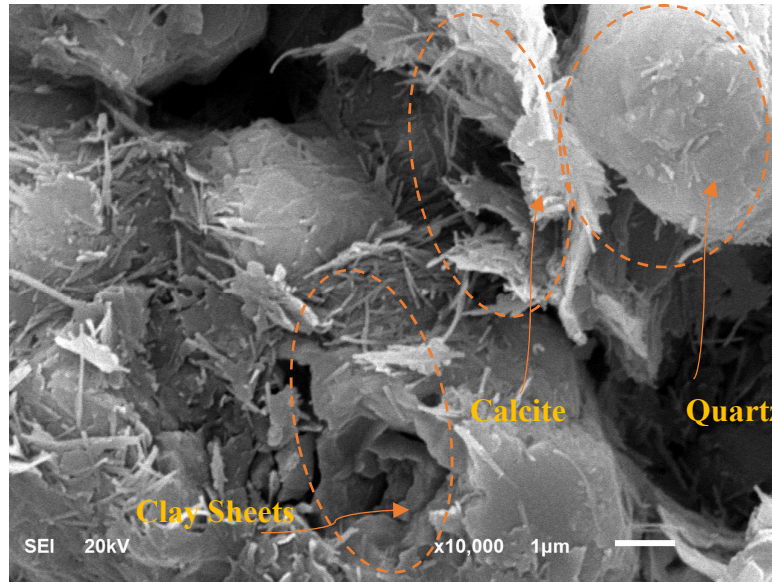


Figure 22. SEM images of a marl soil

3.2. Additive Manufactured Elements

This study uses the additive manufacturing technique, Fused Deposition Modelling, to print the 3D elements, which are manufactured from the Acrylonitrile Butadiene Styrene, or ABS plastic, amorphous in nature. Typically, the filament is heated to a molten condition and then forced into the device's nozzle (Figure 23). In accordance with the G-code instructions, the nozzle head can move in three degrees of freedom (DOF) to place the extruded polymer on the build plate [88]. In this study, three different shapes, i.e., square, triangle, and rectangle, were used (Figure 24).

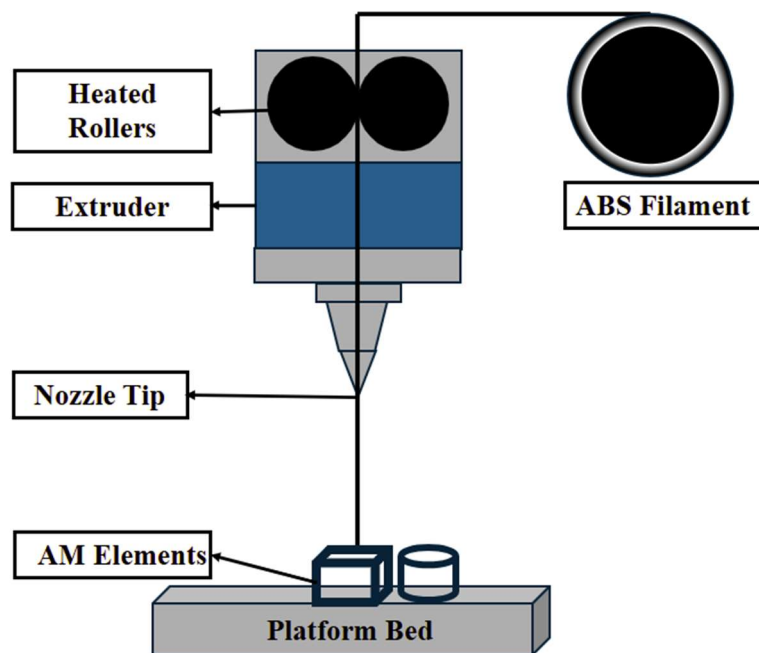
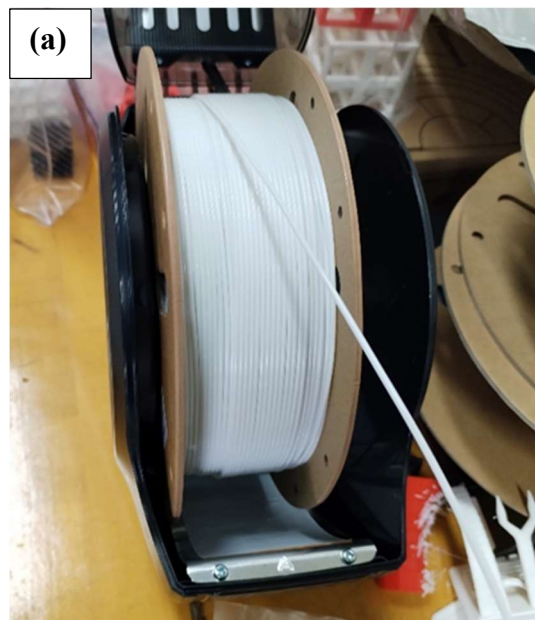


Figure 23. Flow chart for AM processing (Fused deposition modelling)



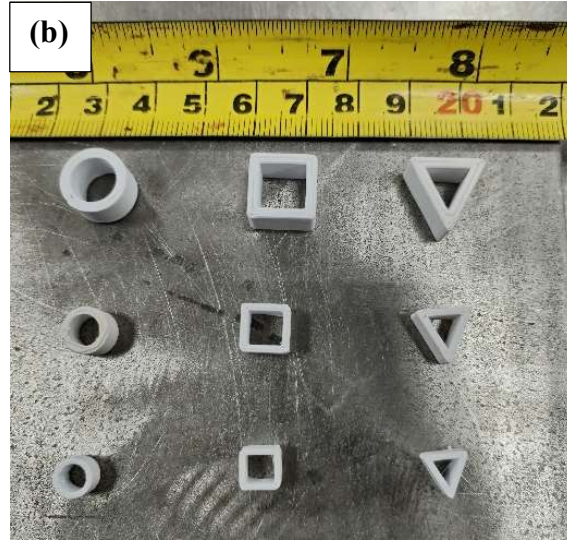


Figure 24. (a) ABS Filament (b) post-process 3D Printed Elements

Three different sizes of each shape (Table 2) were manufactured to determine the effect of elements' size on soil properties such as strength and permeability. The 3D-printed elements are hollow with some thickness. Some of the properties of ABS are given in Table 3. ABS (Acrylonitrile Butadiene Styrene) and PLA (Polylactic Acid) are the most used polymers in additive manufacturing. In this study, ABS is preferred as it is frequently used via FDM. In addition, ABS is more durable (higher chemical and stress resistance) and rigid as compared to biodegradable PLA [89]. Therefore, ABS is suitable for long-term applications.

Table 2. Dimensions of AM elements (All in mm)

	Circular Elements	Triangular Elements	Square Elements
Small	$D_o = 6.20$	$B = 7.35$ $H = 7.20$	$L = 6.30$
Medium	$D_o = 8.05$	$B = 10.40$ $H = 10.30$	$L = 8.15$
Large	$D_o = 12.40$	$B = 14.35$ $H = 15.10$	$L = 12.45$

Do = Outer Diameter, L = Length, B, H = Base and Height of Triangle

Table 3. Basic engineering properties of AM elements

Properties	Value
Thermoplastic Type	Amorphous
Melting temperature (°C)	220
Density (g/cm ³)	1.1
Melt-mass flow rate * (g /10 min)	41
Tensile strength (MPa)	35
Modulus of Elasticity (GPa)	2.1
Compression Strength (MPa)	51
Coefficient of friction	0.35
Flash Ignition (°C)	349

3.3. Sample Preparations

Marl soil is mixed with AM elements in different proportions, specifically 1%, 1.5%, 2%, 2.5%, and 3% of the total soil mass. In the case of AM element additions, there were two approaches i.e., random mixing of AM elements with soil or layer by layer placement of AM elements after each soil layer. Both cases were initially evaluated. In random mixing, the AM elements were mixed randomly with the soil in the mixer and then it was compacted in five layers to get the required density. However, in this case the AM particles were exposed to the sample surface which results in creating the weak failure zones (Figure 25) and underestimating the sample strength (Figure 26).

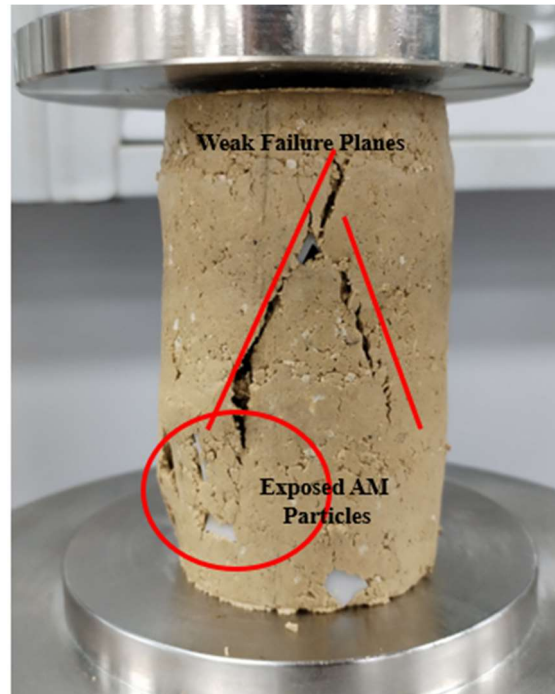


Figure 25. Sample tested for random AM-soil mixing

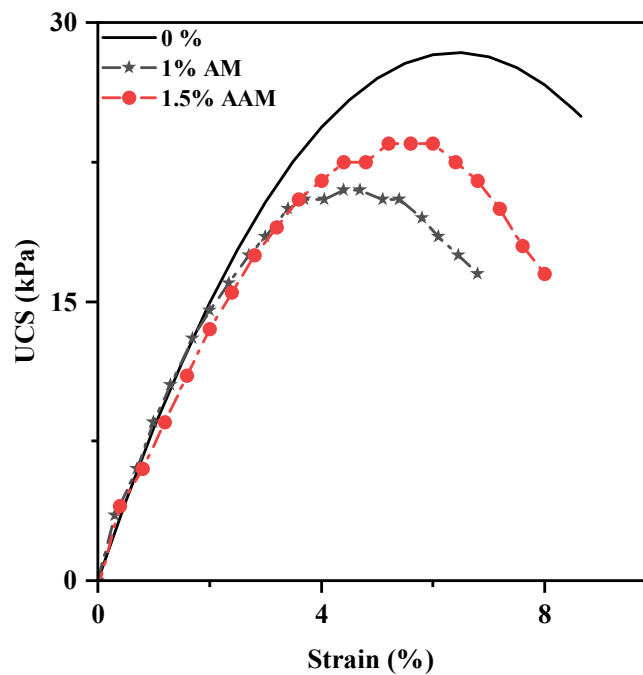


Figure 26. UCS results for the AM-soil random mixed samples

In the second case, AM elements were placed after each soil layer with their hollow faces oriented upside down (Figure 27) and maintaining the cover layer around the AM elements which results

in no exposed AM elements on the sample surface (Figure 27b). The following combinations (Table 4) of soil material and AM elements have been prepared for various tests to study the effect of AM elements on the Marl soil. Detailed results discussion for the second case is given in section 4.3.

Table 4. Percentage proportion of AM elements in AM-mixed soil samples

S.No.	Treatment	Dosage (%)
1	Untreated	0
		1.0
		1.5
2	AM Elements	2.0
		2.5
		3.0





Figure 27. UCS sample preparation (a) AM elements layer (b) UCS cylindrical sample

3.4. Experimental Setup

Figure 28 represents the outline of the experimental program for the study. The experimental Program includes different phases: Material collection, Material Characterization using micro and macro laboratory tests, and detailed laboratory tests, including compaction tests, unconfined compression tests, direct shear tests, triaxial tests, and permeability tests. UCS tests were performed to define the optimum percentage for AM elements and to determine the shape and size effect of AM elements on UCS strength. A direct shear test was mainly performed to ascertain the effect of normal stresses on soil behavior with and without AM elements and to determine the shear strength parameters. The triaxial test was conducted to determine the confining influence on AM elements.

3.4.1 Microstructural Characterization

Fourier Transfer Infra-red (FTIR) spectroscopy uses a Nicolet iS50 Analytical FTIR Spectrometer (Figure 29a) under an Automated Beam splitter Exchanger arrangement. The absorbance spectral range is selected from 2500-400 cm^{-1} for all the soil samples and AAM materials.

Thermal stability analysis (TGA analysis) of AM100 (100% ABS) and AM50 (50% Soil and 50% ABS) mixture is carried out using an SDT650 machine (Figure 29b) with a 10°C/min heating rate for a mass sample of about 8-10mg up to 600°C under a nitrogen-rich atmosphere. TGA/DTG curves of AAM-soil samples are analyzed by plotting mass loss at different elevated temperatures. Testing conditions and summary for TGA and FTIR are given in Table 5.

Table 5. Testing conditions for FTIR and TGA

Test	Conditions	Machine	Soil and AM Ratio	Symbol
TGA	10°C/min heating rate 8-10mg up to 600°C	SDT650 machine	100% AM	AM100
			50% Soil and 50% AM	AM50
FTIR	spectral range from 2500-400 cm^{-1}	FTIR Spectrometer	Marl Soil	Marl Soil
			75% Soil and 25% AM	AM25
			50% Soil and 50% AM	AM50

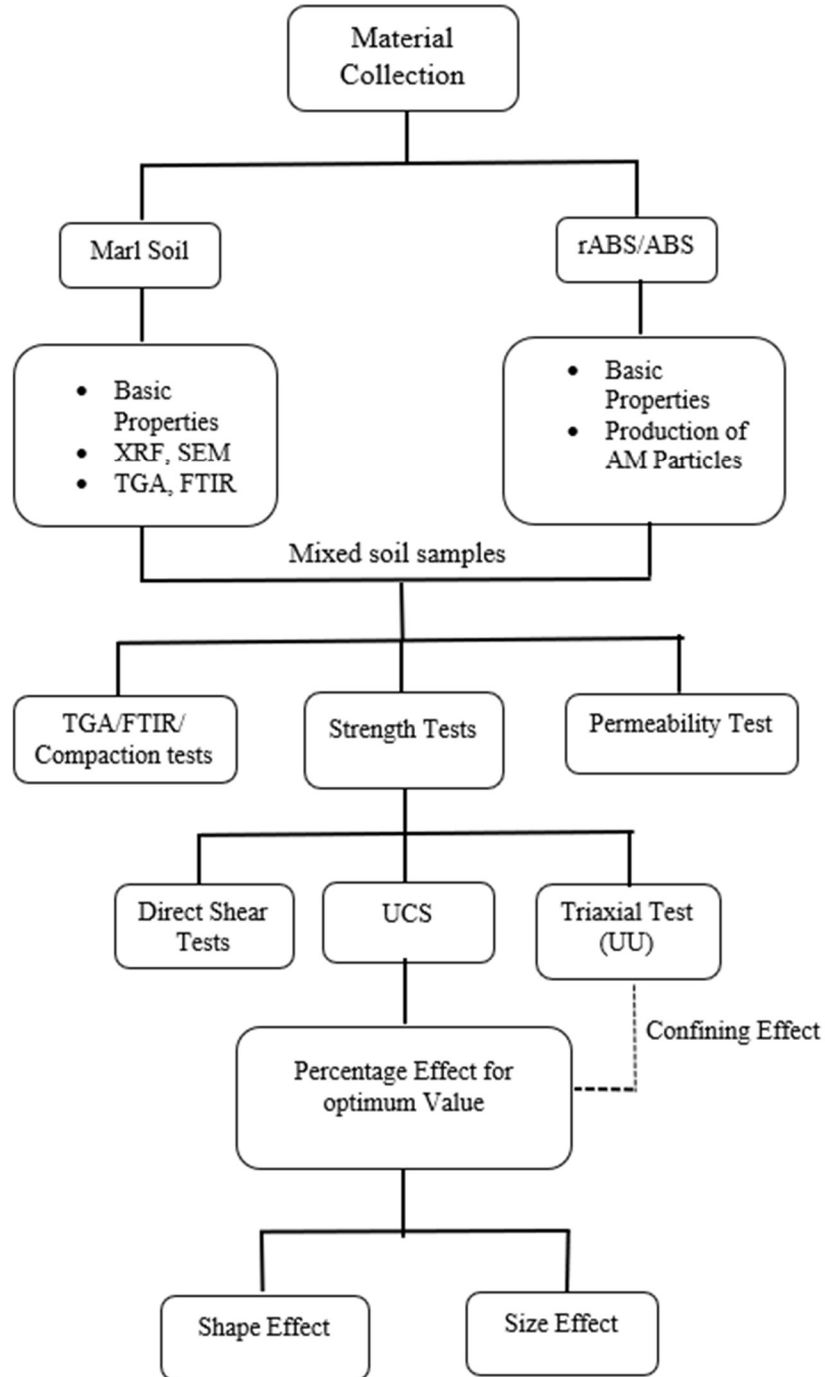


Figure 28. Flow chart for the experimental program



Figure 29. (a) FTIR spectrometer (b) Thermogravimetric machine

3.4.2 Geotechnical Characterization

Compaction tests were performed on the natural soil and for each percentage of AM elements (ranging from 1% to 3.5%). The tests followed the Modified Proctor procedure as per ASTM D1557. A 4-inch mold was filled with five layers for sample preparation, each compacted by 25 blows. Testing conditions for the tested samples of proctor test are summarized in Table 6.

Table 6. Compaction tests summary for medium-sized mixed shape elements

Test	Conditions	Parameters Studied	AM Elements (%)
Modified Proctor Tests	ASTM D1557	MDD and OMC	0
			1.0
			1.5
			2.0
			2.5
			3.0
			3.5

Unconfined compressive strength (UCS) was conducted in a MATEST UCS Machine (Figure 30) accordance with ASTM D2160. UCS specimens were prepared using a 2-inch Dia (50 mm) mold, filled in five layers, and compacted to 95% of the maximum dry density ($0.95\gamma_{dmax}$) at the optimum moisture content. The UCS tests were performed on specimens under strain-controlled conditions at a constant loading rate of 1.25 mm/min. The capacity of the load and LVDT was 50 kN and 25 mm, respectively. Testing conditions and summary for the tested samples of UCS is given in Table 7.

Table 7. Unconfined compression tests summary

Test	Conditions	Parameter Studied	AM Elements		
			Percentage	Size	Shape
Unconfined Compressive Strength (UCS) Tests	50.8 mm Sample Diameter 1.25 mm/min Strain Rate	Percentage Effect	0	Medium	Mixed
			1.0		
			1.5		
			2.0		
			2.5		
			3.0		
		Shape and Size Effect	Optimum	Large	Circular
					Square
					Triangular
				Medium	Circular
					Square
					Triangular
				Small	Circular
					Square
					Triangular



Figure 30. MATEST machine used for unconfined compressive strength tests

The Direct shear test (DST) was conducted using a VJ Tech DST machine (Figure 31) under drained conditions, following ASTM D3080-04 guidelines. A soil sample was prepared in a sampler cutter (Figure 32) by maintaining the relative compaction of 95%. For the DST, a slow strain rate of 0.1 mm/min was applied to prevent the development of excess porewater pressure. The direct shear test was performed alone on small-sized triangular AM elements to meet the sample size ratio requirements. The capacity for both shear load and vertical load cells was 10 kN. The limit for the horizontal and vertical LVDT was 50 mm and 25 mm, respectively. Testing conditions for the tested samples of the direct shear test are summarized in Table 8.



Figure 31. VJ Tech Direct shear test machine



Figure 32. Sampler for direct shear test sample preparation

Table 8. Direct Shear tests summary

Test	Conditions	Parameters Studied	AM Elements			Samples Tested
			Percentage	Size	Shape	
Direct Shear Test (DST)	100 x 100 mm Sample Size 0.1 mm/min Shear Rate	Shear Strength Parameters	Optimum	Small	Triangular	21

Unconsolidated Undrained (UU) triaxial tests were performed using a cylindrical sample of diameter 50 mm and height 100 mm, filled in five layers, and compacted to 95% of the maximum dry density ($0.95\gamma_{dmax}$) at the optimum moisture content. A cylindrical soil sample was encased in a thin rubber membrane and placed within a triaxial cell. The soil sample was not allowed to consolidate under the applied confining pressure (200 kPa). This ensures that the soil's initial

structure and pore water pressure are unchanged, simulating undrained field conditions. A confining pressure (σ_3) was applied to the sample to simulate lateral earth pressure. An axial load was then applied until the sample failed. This produced shear stress, and the sample deforms while the pore pressure remains constant. Testing conditions for the tested samples of the triaxial test are summarized in Table 9.

Table 9. Triaxial test summary for medium-sized mixed shape elements

Test	Conditions	Parameters Studied	AM Elements (%)
Triaxial Test	UU		0
	Condition	Percentage Effect and Confinement Effect	1.0
	200 kPa		1.5
	Cell		2.0
	Pressure		2.5
	50.8 mm		3.0
	Sample Diameter		3.5

Falling head permeability tests were also conducted (Figure 33) on a cylindrical sample with a diameter of 63.8 mm and a height of 120 mm. The sample is compacted to 95% relative compaction, and water is allowed to flow through it. To remove air bubbles, saturation of the sample is required. The initial and final height of the water is noted to calculate the permeability. Testing conditions for the tested samples of permeability test are summarized in

Table 10.



Figure 33. Falling head test apparatus and prepared soil sample

Table 10. Falling head permeability tests summary

Test	Conditions	Parameters Studied	AM Elements (%)
Permeability Test	Falling Head 63.8 mm Sample Diameter	Percentage Effect	0
			1.0
			1.5
			2.0
			2.5
			3.0
			4.0
			5.0
			6.0

CHAPTER 4

RESULTS AND DISCUSSION

4.1. Fourier Transform Infrared Test (FTIR)

Fourier Transfer Infra-red (FTIR) spectroscopy is conducted for soil samples mixed with the AM elements to observe the chemical interaction of the AM particles with the soil. FTIR analysis for marl soil, 25% AM elements mixed sample (AM25), and 50% AM elements mixed sample (AM50) was conducted (Figure 34). Untreated marl soil shows the bending vibration of $=CH_2$ group of carbonate peaks at around 1440 cm^{-1} , reflecting the dominance of calcite minerals, while a broad asymmetric vibration Si–O–Si stretching peak around 1030 cm^{-1} is indicative of silicate minerals like quartz. A notable spectrum change is observed in the AM-soil, with the peak absorbance intensity of $-CH_2$ carbonyl and Si–O–Si bond around 1400 cm^{-1} and 1000 cm^{-1} , respectively. These changes are attributed to the densification and enhanced particle alignment around the AM inclusions, which are mechanically integrated into the soil matrix. The hollow, geometrically complex AM elements redistribute stress within the soil and promote tighter packing of particles, thereby modifying the interaction forces among silicate and aluminate species.

The reduced intensity of carbonate-related peaks in this mix suggests that the calcite particles are less accessible for vibrational response due to improved interlocking and compaction around the AM elements. Moreover, at higher AM ($\geq 25\%$), content in the soil exhibited a strong O–H and Si–Al in-plane bending vibration at around 740 cm^{-1} region. These spectral variations are not indicative of chemical bonding but rather result from the mechanical reinforcement and structural modifications through AM elements, indirectly creating an interconnected framework within the soil matrix that enhances particle interactions and improves the soil's microstructural texture. This

mechanical integration mechanism, as evidenced by the FTIR spectrum, aligns with the observed improvements in geotechnical properties, including increased cohesion, stiffness, and shear strength, in AM-reinforced marl soil. Apart from that, Si-O-Al bending vibrations are identified with a wavenumber of nearly 540 cm^{-1} . Thus, with a chemical shift of roughly 20 cm^{-1} , the spectrum peaks from untreated soil and AM-treated soil reveal identical linkages.

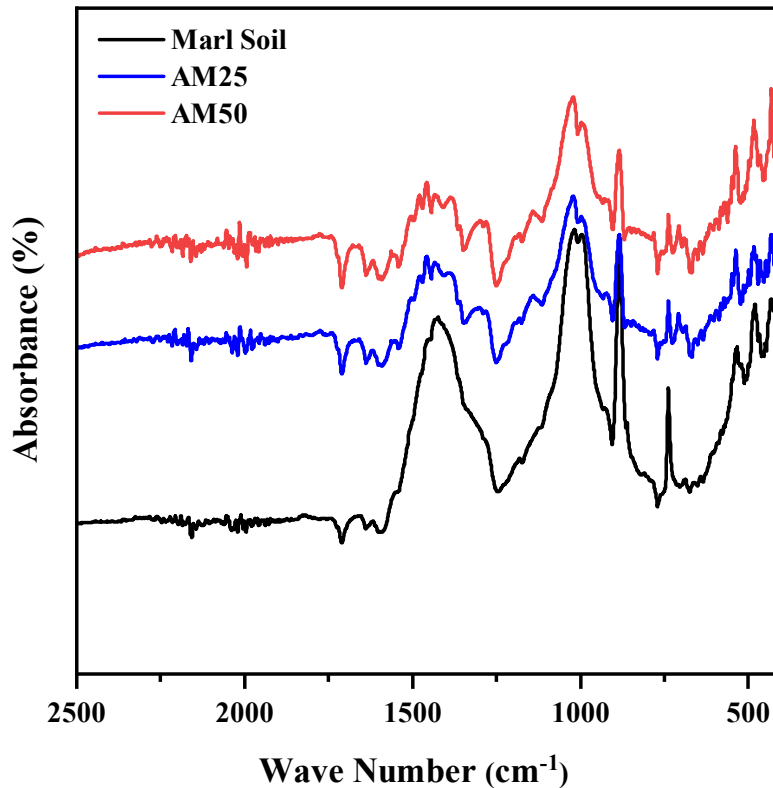


Figure 34. FTIR spectrum for reference sample and AM-mixed soil in two ratios

Thermogravimetric Analysis (TGA)

TGA was conducted to evaluate the performance and decomposition behavior of the AM elements with the increasing temperature, when mixed with the marl soil. The thermal stability and decomposition behavior of AM-Soil compositions were analyzed by using thermogravimetric analysis (TGA), and derivative thermogravimetric (DTG) analysis. Figure 35 shows the TGA/DTG curves of AM100 and AM50 samples in the form of mass loss and first derivative loss

upon temperature. Both samples exhibit a minor mass loss around 100-1200C at the initial stage. This reduction is due to free moisture removal and volatile matter evaporation. Moreover, a higher mass loss is noted in AM-soil samples (AM 50) than in pure AM material (AM100). The second mass loss is connected with organic binder compounds around 350-450°C due to the decomposition of the styrene and acrylonitrile components. The presence of marl soil contributes to additional weight loss due to the active degradation of organic matter and possible clay minerals within the soil. The DTG peaks correspond to the maximum rates of weight loss during these decomposition processes.

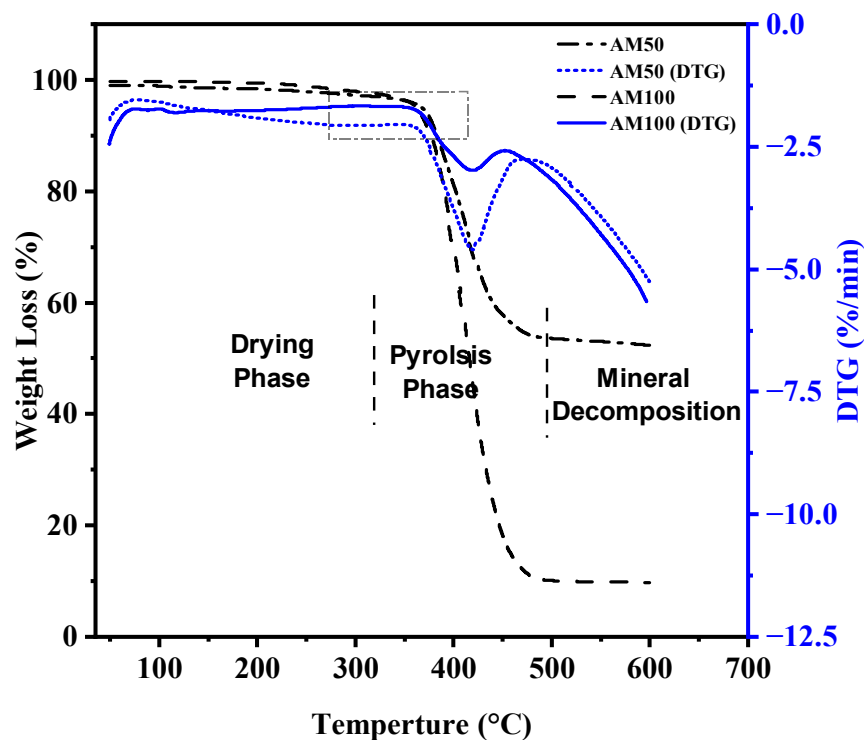


Figure 35. TGA curves of marl soil and AM-mixed marl soil

Further, it is also pointed out that the percentage of initial mass loss for AM 100 (10-12%) is relatively higher than for AM 50 (12-15%). At around 500°C, the reflective decomposition of the butadiene phase can relate to the AM compounds. Thus, the substantial reduction beyond 600°C

majorly follows the asymptotic behavior, which may be due to the early distraction of inorganic components and mineral phases. AM particles show a stable behavior up to a temperature of about 350°C, which implies their suitability to the field conditions as the maximum temperature obtained in extreme conditions might not reach the limit of 350 °C. Resultantly, AM elements are not anticipated to degrade under the field conditions.

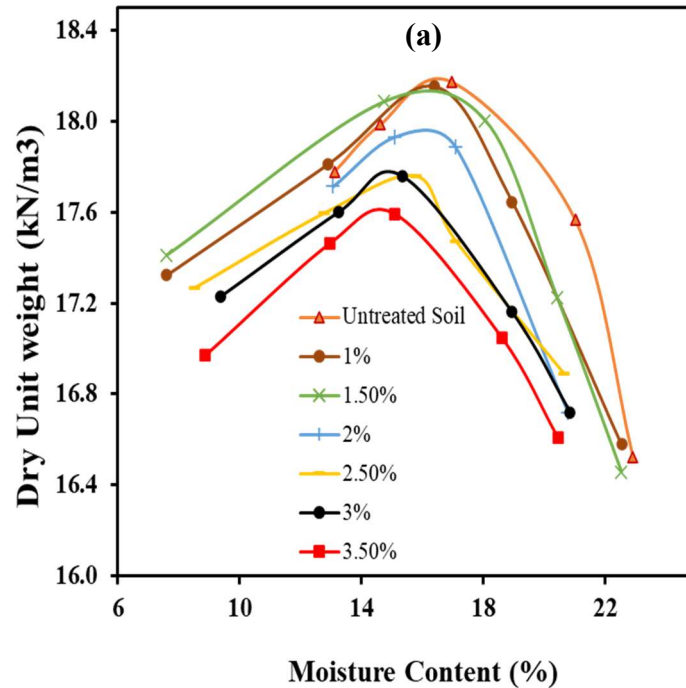
4.2. Compaction tests

Modified Proctor compaction tests were performed on various combinations of soil and additively manufactured (AM) materials using a MATEST compactor. The prepared samples were then carefully extracted using a sample extractor, as illustrated in Figure 36. The primary objective of these tests was to determine the maximum dry density (MDD) and optimum moisture content (OMC) for each mix proportion of AM elements and soil. These parameters are essential for achieving the desired density and strength of the AM-mixed soil under field and lab conditions.



Figure 36. Compacting machine for modified proctor test and sample extractor

Figure 37a shows compaction curves for different percentages of AM elements. It can be seen that with the increasing percentage of AM elements, the moisture content variation is decreasing along the curve. This is because of the lower absorption capacity of the AM elements which will help in the water sensitive behavior of the marl soil. Figure 37b summarizes the result of the compaction curves in a bar graph. The maximum dry unit weight of the soil is found to decrease when the AM components increase from 0% to 3.5%, going from 18.14 kN/m³ to 17.61 kN/m³. The maximum dry unit weight of treated soil may have decreased due to the low specific gravity of AM components. Similarly, from 16.5% to 14.5 %, the optimum moisture content was reduced as the content of AM components increased. The increment in optimum moisture content is due to the lower water absorption capacity of AM elements. This trend of decrease in MDD and OMC is in line with the results obtained by other investigators [90], [91].



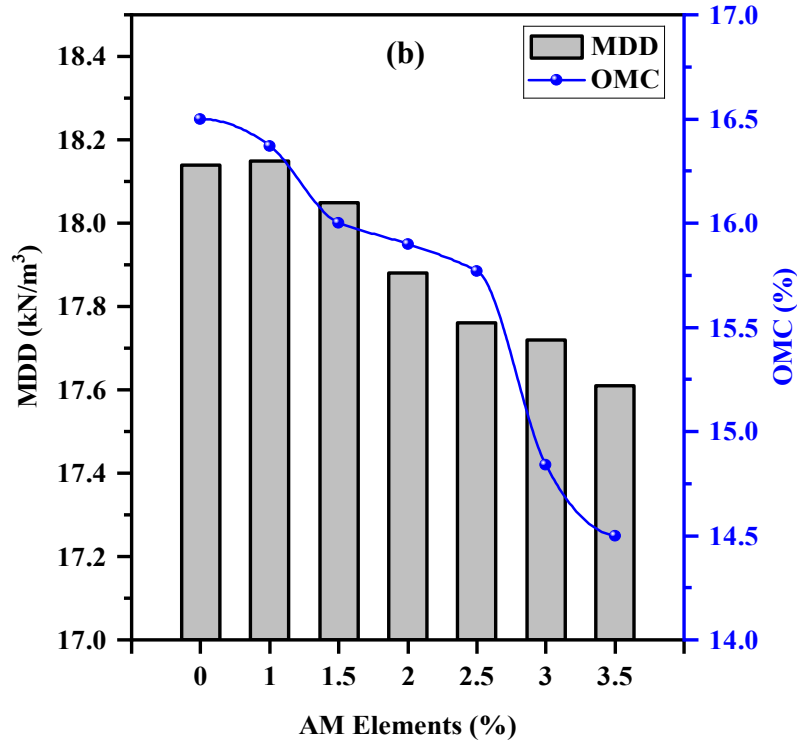


Figure 37. Modified Proctor test results (a) Compaction curves (b) Trends of MC and MDD vs AM elements percentage

4.3. Compressive Strength (UCS)

Figure 38 illustrates the influence of AM additives on the unconfined compressive strength (UCS) of Marl soil. The aim is to identify the optimal percentage of AM additives and assess additional parameters (shape and size) based on this optimum. Natural soil exhibits the lowest UCS, with a peak of around 20 kPa. All curves show a consistent increase in UCS as axial strain increases from 0% to 3%, regardless of the AM percentage. However, the natural soil shows pronounced strain-hardening behavior, while adding AM results in strain-softening. For all percentages of AM additives, UCS values exceed those of the natural soil, with a notable increase of 40% and 90%, corresponding to 1% and 1.5%, respectively. Beyond 1.5% AM content, the UCS begins to decline, as can be seen in Figure 38 (b).

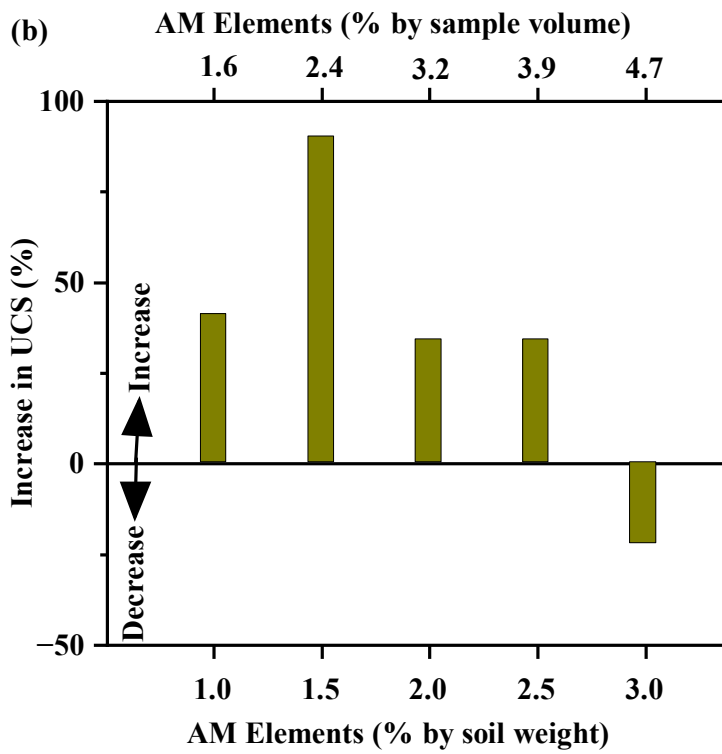
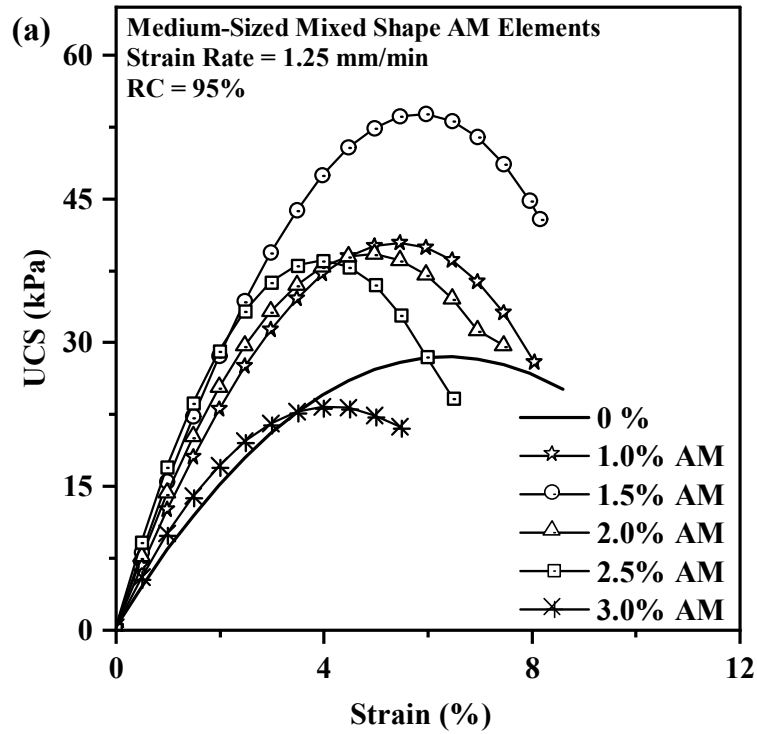


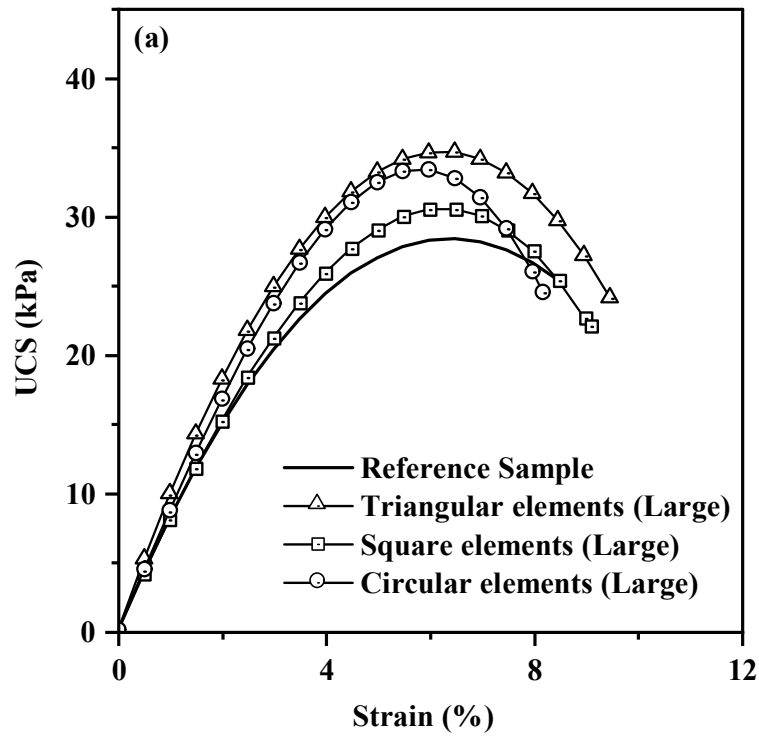
Figure 38. (a) Percentage Effect of AM-mixed samples (b) Percentage increased in UCS

Thus, the optimal percentage is determined to be 1.5%. Furthermore, most of the curves reach their maximum between 2% and 5% axial strain, with percentage increases ranging from 33% to 90%. The stiffness of the soil is also increased by adding AM elements.

Effect of Size and Shape of AM Elements

Once the optimum percentage of AM elements was determined, the shape and size effect was evaluated using UCS test. The shape and size of the AM elements can affect the unconfined compressive strength of soil, as shown in Figure 39. The UCS strength is improved for all sizes of AM elements as compared to the reference soil. Figure 39 (a) shows the UCS for large-sized AM elements, where triangular elements exhibit the highest UCS, followed by circular and square elements. The angularity of triangular shapes enhances particle interlocking and load distribution, resulting in an increased shear resistance and stress transfer efficiency within the soil matrix. Similarly, Figure 39 (b-c) represents a similar trend of shape effect for medium-sized and small-sized AM elements. Triangular AM elements outperform other shapes with the highest compressive strength. The increased compressive shear for small-sized triangular elements is due to their high angularity, which promotes particle interlock, better packing density, and confinement effects. The enhanced interface friction and load transfer capabilities lead to improved soil strength. Figure 40 quantifies the percentage increase in UCS for different sizes and shapes, highlighting that triangular elements yield the most significant strength improvements across all sizes, with increases ranging from 10% to 46%. Considering the size effect, the small-sized AM elements show the highest UCS strength, followed by the large and medium sizes. This increase is attributed to the size effect, as the small-sized AM elements have more surface area, increasing the energy absorption capacity and the confinement area. Thus, the triangular AM elements, irrespective of size, significantly improve the shear strength properties of soil by enhancing

particle interlock and confinement, providing a more robust and effective reinforcement material. Although there is a significant variation of strength with different shapes of AM elements compared to the control sample (approx. 53%), there is an insignificant difference between the samples with different shapes (between the triangular and circular = 5-10%; and between square and circular = 3-10%).



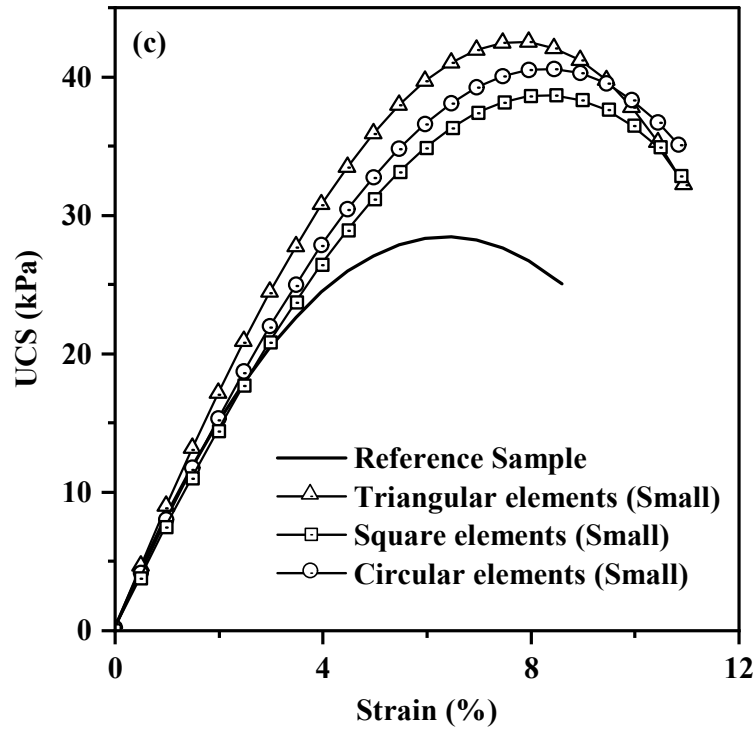
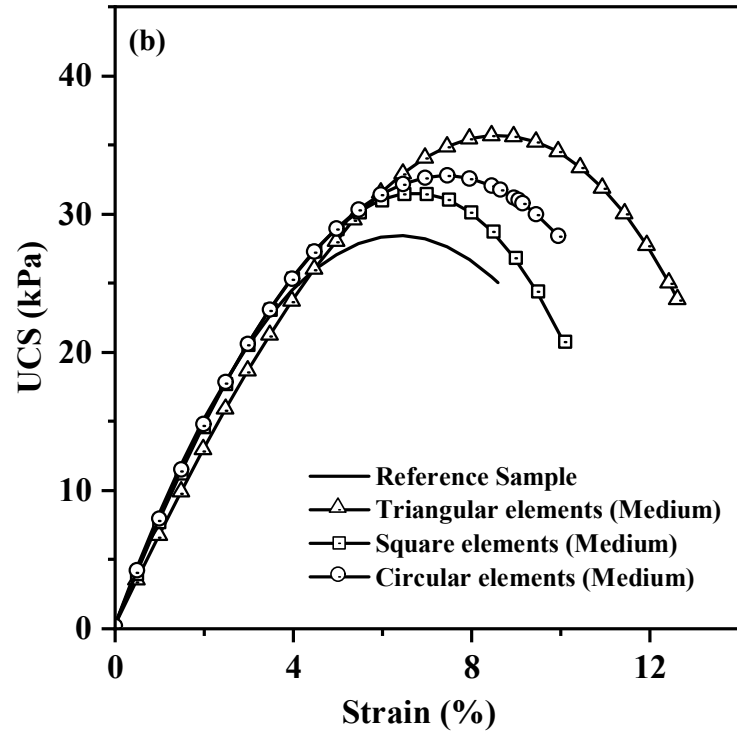


Figure 39. Size effect for (a) Large-sized (b) Medium-sized (c) Small-sized AM elements

One observation is clear that the biggest improvement was noticed for the triangular-shaped element as compared to circular and square-shaped elements, irrespective of the size. The increase in percentage for triangular elements varied from 10-46%. This increase may be due to the high angularity/irregularity of the triangle shape as compared to the other two. Moreover, the confinement effect is higher in triangular-shaped elements.

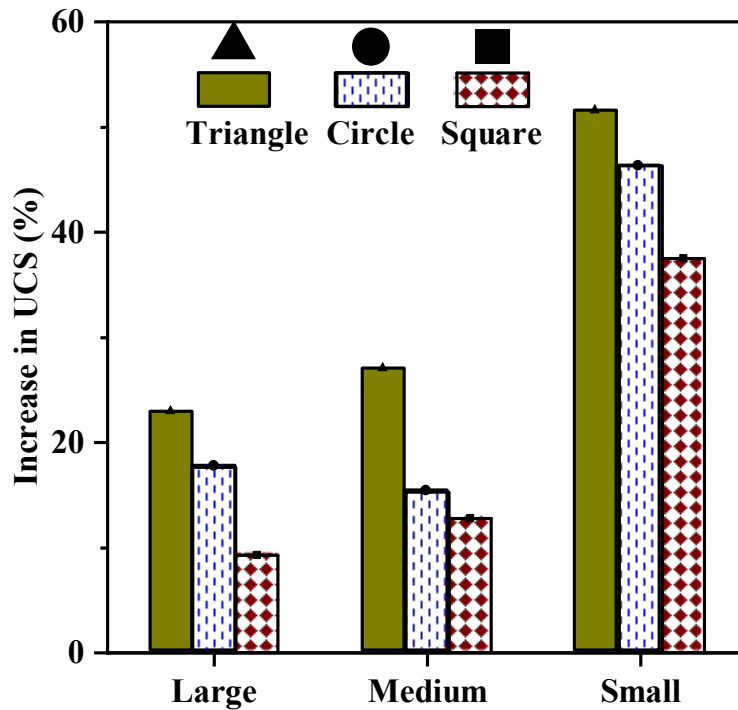
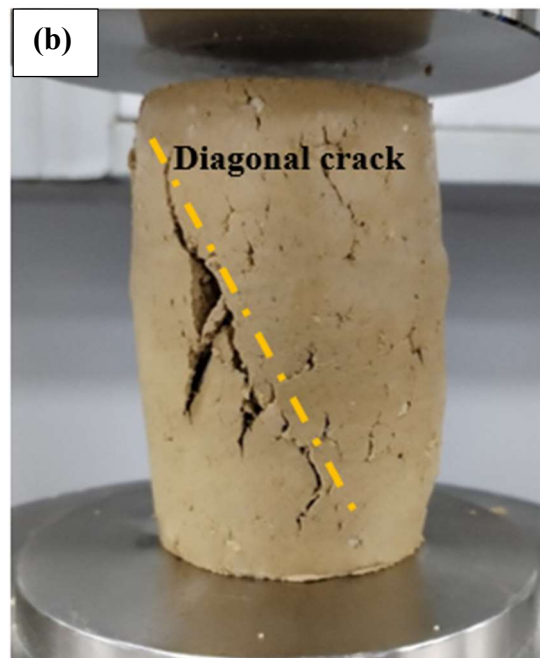
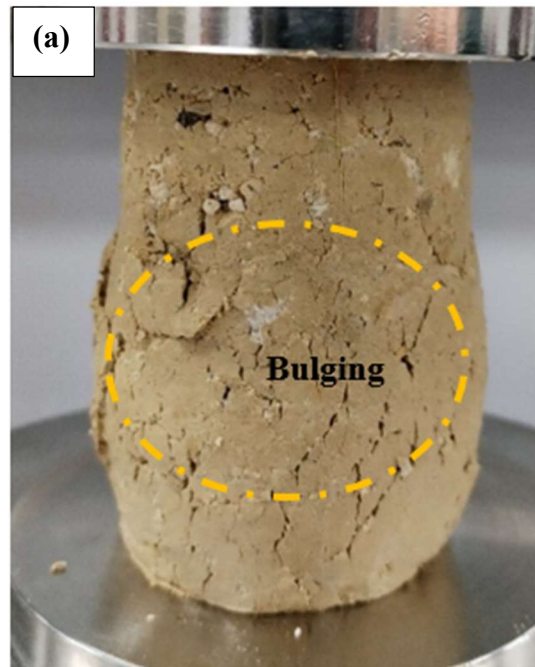


Figure 40. Percentage increase in UCS for different sizes and shapes

Failure patterns for different shapes of AM elements can be seen in Figure 41. The major change was observed as the failure pattern for the reference sample is prominently bulging while it was changed to shear and compression failure due to the addition of AM elements.

Vertical cracks along the body were observed for square-shaped AM elements. A well-defined 45° shear failure plane with respect to the horizontal axis is observed, as illustrated in Figure 41. More significant are wider vertical cracks and an undefined failure pattern in the case of circular shapes. On the other hand, triangular-shaped AM elements were preventing concentrated stress failure. A

V-shaped shearing failure pattern with a sharp peak was observed. This typically indicates ductile failure behavior. In this failure mode, the specimen undergoes significant plastic deformation before failure, resulting in a conical-shaped failure pattern.



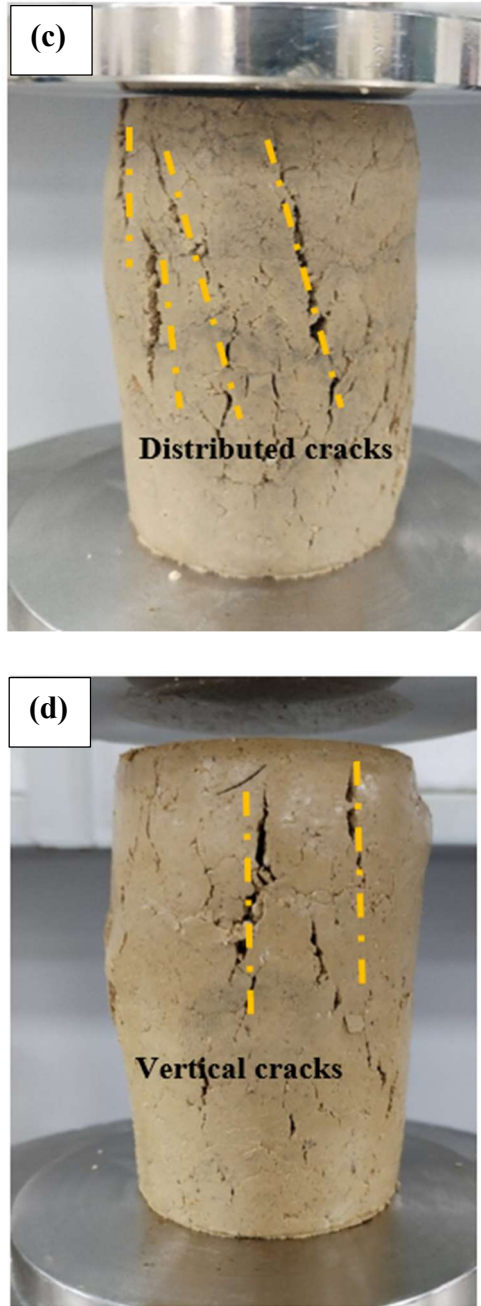


Figure 41. Failure Patterns from UCS tests (a) Reference Sample (b) Square-Shaped (c) Triangular-Shaped (d) Circular-Shaped AM Elements

Figure 42 represents the toughness values for different samples. The toughness of soil refers to the ability to absorb energy per unit volume under the axial loading until failure occurs. It is also known as the deformation energy or energy absorption capacity and is obtained by calculating the area under the stress-strain curve as defined by [92]. Small-sized AM elements exhibit the highest

toughness values across all shapes, indicating superior energy absorption and fracture resistance. This enhancement is attributed to the increased surface area for bonding and better stress distribution within the soil matrix. Triangular elements consistently outperform others due to their higher angularity, which promotes interlocking and efficient stress transfer. Moreover, the medium-sized AM elements show moderate toughness, while large-sized elements have the lowest values, likely due to less effective stress transfer and reduced interfacial bonding. Also, the circular elements exhibit the least improvement, highlighting the impact of shape angularity in enhancing the soil toughness behavior. The reference value shows that all AM shapes and sizes significantly improve the soil's toughness compared to the untreated soil.

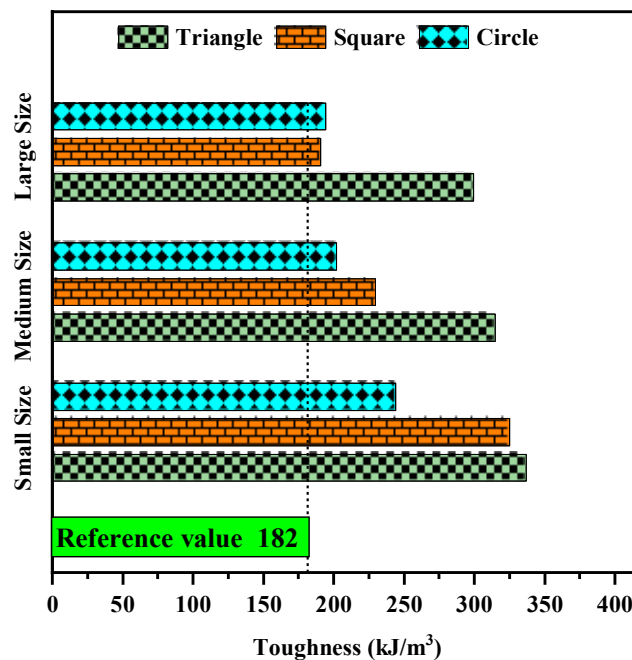


Figure 42. Toughness of different Samples

4.4. Direct Shear Test

Figure 43 illustrates the stress-strain curves and volumetric change under different normal stresses for the marl soil and AM elements-mixed soil. The stress-strain curves (Figure 16a) show that AM-mixed soils have significantly higher shear strength compared to the natural marl soil across

all normal stresses. For marl soil, the percentage difference between two normal stresses (50 and 150 kPa and 150 and 200 kPa) is 82% and 28%, respectively. Similarly, these values are approximately 125% and 17% for AM-mixed soil, respectively. The hallow reticulated shapes of the AM elements increase the resistance against shear forces, effectively transferring and distributing the applied loads more efficiently within the soil matrix. Additionally, the presence of AM elements restricts the movement of soil particles, thereby enhancing the soil's overall structural integrity and load-bearing capacity.

The volumetric change curves (Figure 43b) reveal that vertical displacement increases initially and stabilizes until horizontal displacement remains relatively constant. In the case of 50 kPa, both natural soil and AM mixed soil exhibit dilation behavior after initial compression. However, AM mixed soil showed dilation after a comparatively smaller settlement/compression. This is due to the probability of AM elements dilating the soil in front of it when the shear force is applied. Moreover, this reduced displacement at lower normal stresses can be attributed to the confining effect of the AM elements, which improve the soil's internal structure and reduce compressibility. Furthermore, at higher normal stresses, the combined AM-soil mixture and natural soil showed compression behavior only as the higher confining stress suppressed the dilatancy of the soil and AM particles. The difference in the vertical displacement between the AM-mixed soil and natural marl soil is somewhat similar for each normal stress. For higher normal stresses (150 and 200 kPa), AM-mixed soil showed a vertical displacement higher than the natural soil. This may be due to the fact that the combined AM-soil mixture accelerated the activation of absorption friction energy and deformation capacity, leading to increased vertical displacement.

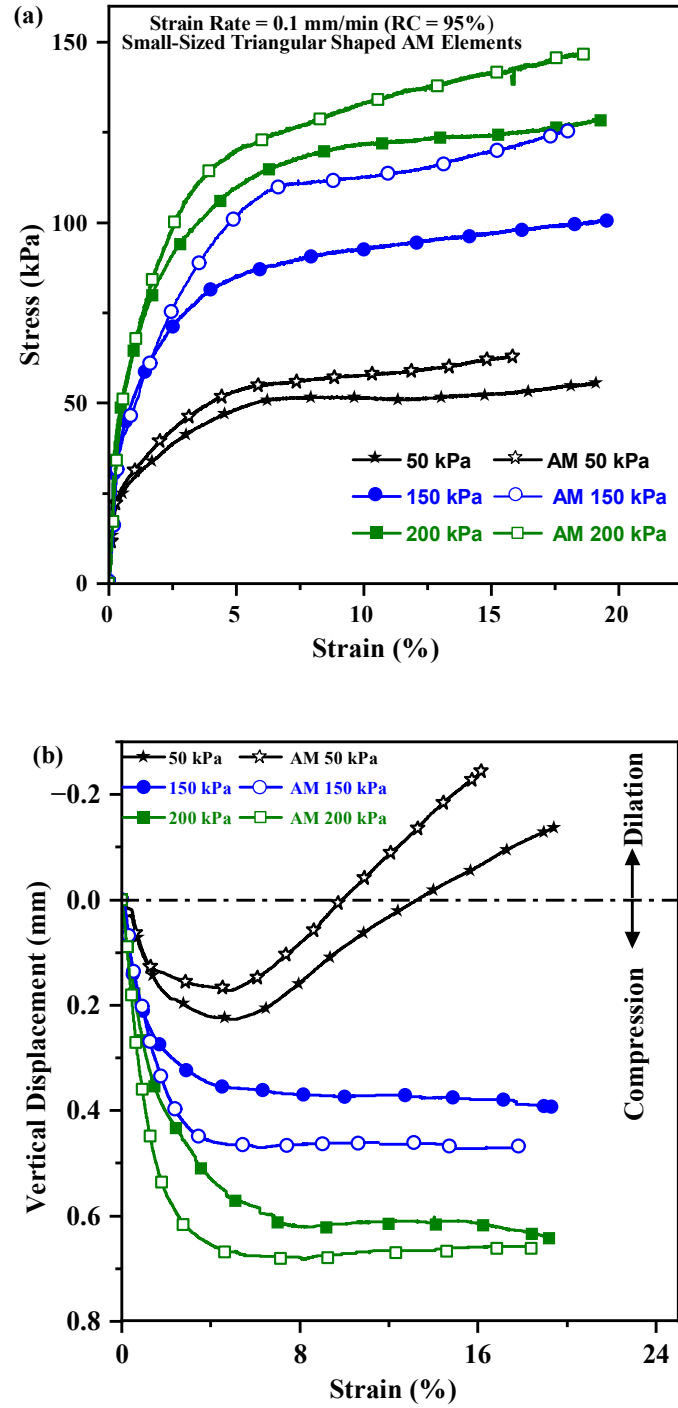


Figure 43. (a) Stress-strain curves (b) Volumetric change curves at different normal stresses

To compare the two, the percent increase between AM-mixed soil and natural marl soil for each normal stress is about 12%, except for the 150 kPa, which is 25% approximately (Figure 44). The

increased shear strength is due to the increased interface friction between soil and AM elements as the AM elements have rough surface.

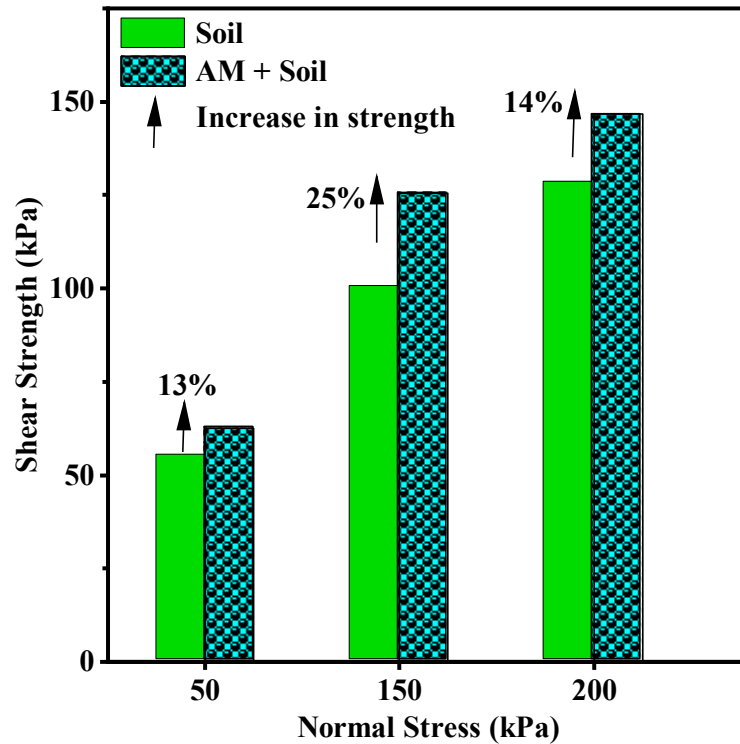
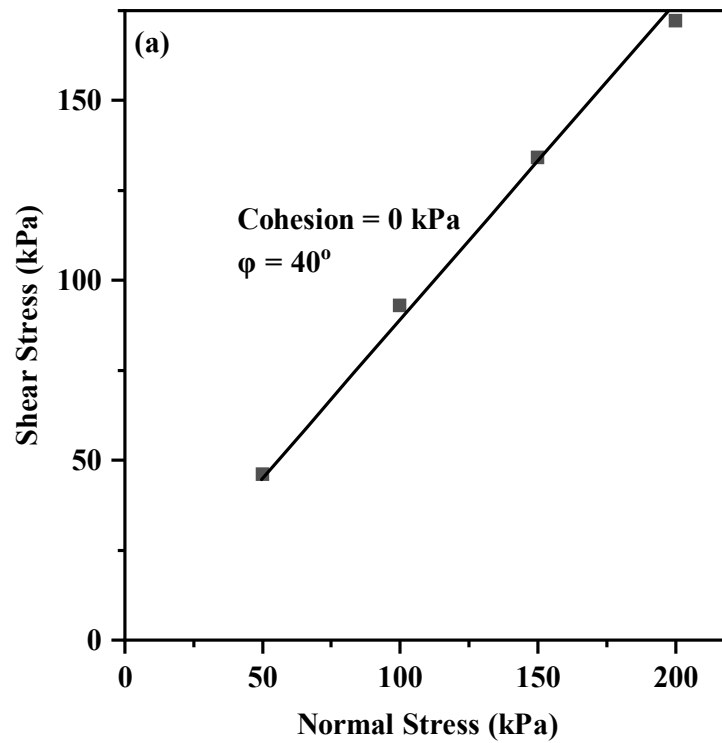


Figure 44. Increase in shear strength for each normal stress

Figure 45 demonstrates the shear strength parameters for the natural marl soil and AM mixed soil samples. The cohesion of the AM-mixed soil is about 20% increased as compared to the natural soil. However, the increase in friction angle is about 13%. The possible reason for this behavior can be explained by Figure 45a, which shows the shear strength parameters for AM elements only. There is no cohesion between AM elements. However, the friction angle is greater than the marl soil, which is due to the high surface roughness of AM elements. The increase in cohesion is because of the reason that the inclusion of AM particles could alter the soil's pore structure, potentially enhancing the capillary effects. Additionally, the roughness of AM particles not only

increases the friction angle but also enhances the contact area with surrounding soil particles. This larger contact area can promote better adhesion which results in higher apparent cohesion. The AM particles, when mixed with marl soil, might improve the overall packing density and contribute to increased cohesion.



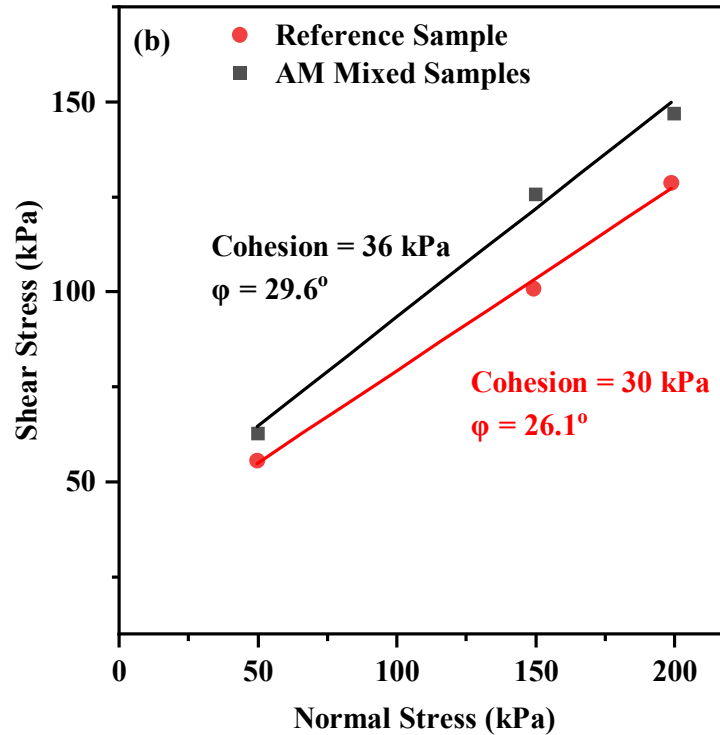


Figure 45. Shear strength parameters for (a) AM elements (b) AM + soil

4.5. Triaxial Compression Test

Unconsolidated undrained (UU) triaxial tests were performed on AM mixed and marl soils under the confining pressure of 200 kPa for different percentages of AM elements (Figure 46). The soil strength increases with the increase in percentage up to 2.5% and then decreasing trend for 3% and 3.5% AM dosage. The shear strength for 3% and 3.5% AM mixed soil is even less than that of marl soil. The curve for the 1.5% AM elements shows the same trend as the marl soil. This is because the percentage of AM elements is very small, and the soil particles dominate the behavior. The maximum increase in strength is 15% for 2.5% AM elements, and AM elements dominate the behavior over soil particles. The increase is due to the confining effect of hollow-shaped AM elements, as it is clear from the curves that stiffness is also increased. Also, the roughness of AM

elements interact with soil particles to increase the friction at the interface and improve the soil strength. In UU tests, pore water pressure plays a significant role in determining soil strength. The AM particles might alter the pore structure, preventing excessive pore pressure build-up during shearing. This effect leads to higher deviatoric stress at failure. The rigid AM elements help redistribute stresses more evenly throughout the soil matrix. This redistribution reduces localized stress concentrations and enables the soil mixture to resist higher deviatoric stresses before failure. However, beyond 2.5%, the strength is decreased as the contact area between the soil particles decreases, weakening the matrix with more AM elements. Soil strength highly depends on particle-to-particle interactions, which is disturbed by more AM elements. As compared to UCS tests the optimum percentage can be considered as 2.5% in the case of triaxial tests, which shows the importance of confining pressure.

The failure patterns for the virgin and AM-mixed marl soil is shown in Figure 47. It is the characteristic of cohesive soil under UU triaxial test. This mode of failure occurs due to the redistribution of internal stress as the applied deviatoric stress increases. The addition of AM particles did not substantially change the bulging failure mode. This is likely because the UU triaxial test primarily reflects pore water pressure responses rather than direct particle interactions. The AM particles act as rigid inclusions that may improve the soil's mechanical strength (e.g., increase in deviatoric stress), but they do not significantly alter the stress path or failure mechanism. The increase in deviatoric stress observed with AM inclusion is due to improved interlocking and frictional resistance at the particle level, but the bulk failure mode remains dominated by pore water responses under undrained conditions.

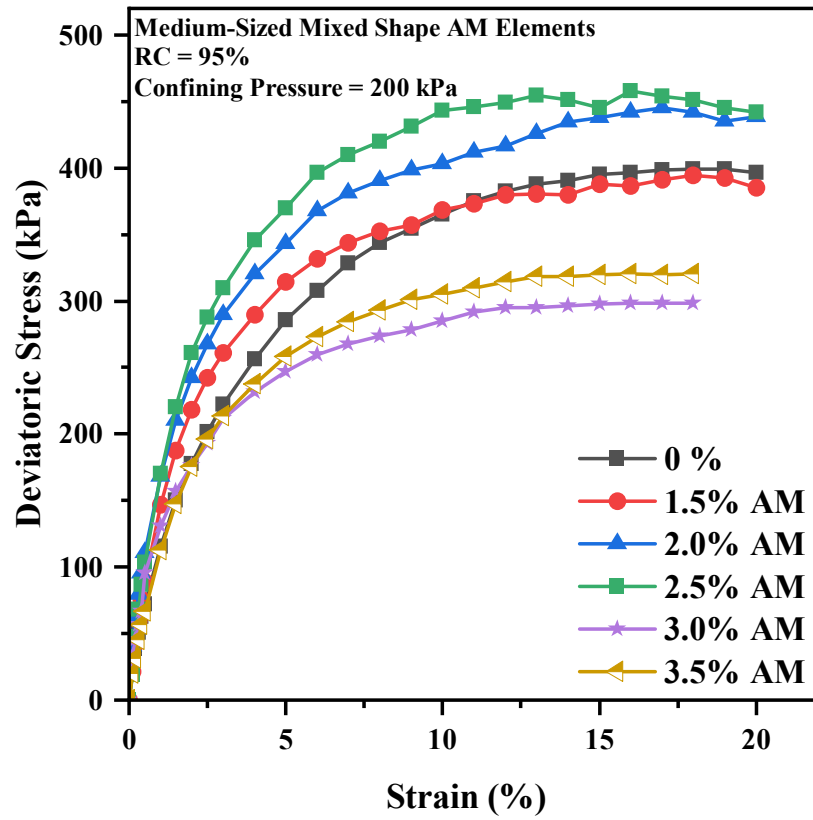


Figure 46. Stress-strain curves from triaxial tests





Figure 47. Failure pattern from triaxial test (a) Marl soil (b) AM + soil

4.6. Permeability Tests

The permeability test was evaluated using two approaches. In the first approach, the Total weight of the soil remains the same by increasing the percentage of the AM elements. So, more compactive effort will be required to tend the soil particles to come closer. Despite this, the permeability is increased due to the presence of AM particles. In the second approach, replace the soil with AM particles, which will decrease the soil weight in the overall sample. Figure 48 represents the effect of the percentage of AM elements on the permeability of marl soil for both cases. Overall, the permeability of the soil is increased for both cases, yet the increase is more prominent between 1.5-3% as the slope of the curve is steeper. Beyond 3%, the exponential increase is observed, and the slope of the curve is mild. In the first case, the increase in permeability as compared to the 0% AM is 3%, 8%, 28%, 38%, 43%, 48%, and 50%, corresponding to the AM elements percentages of 1.5%, 2%, 2.5%, 3%, 4%, 5%, and 6% respectively.

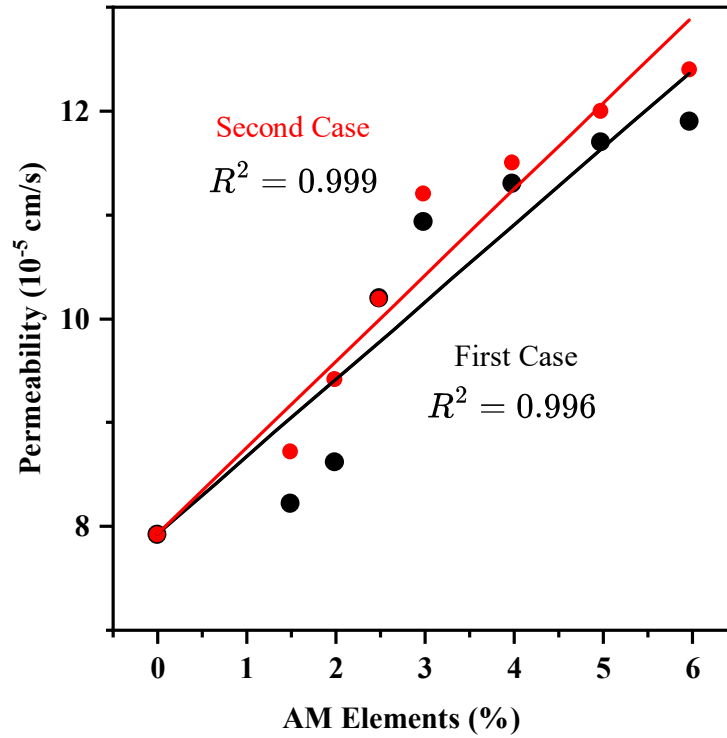


Figure 48. Falling head permeability test results

The increase in permeability is because the density of the sample decreased with the higher percentage of AM elements. Additionally, the hollow shape of AM elements provides the path to the flow, which increases with percentage. The soil-soil interaction is less than that of the soil-AM interaction, which results in higher voids at the interface and the hollow-shaped AM elements (Figure 49). The permeability of marl soil is higher for the second case compared to the first case because of the more voids at the interfaces. Additionally, the soil weight is replaced by the AM particles, which provide the seepage path. The results from both conditions were similar, with minor differences.

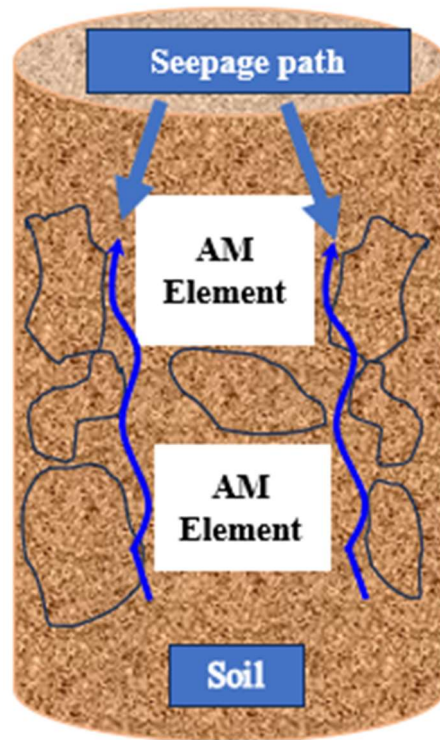


Figure 49. Flow path at the interface of soil and AM elements

4.7. Regression Analysis

The investigation started by analyzing the shear strength characteristics of AM-mixed marl. This provided foundational knowledge about how the soil behaves mechanically when mixed with AM particles. Afterward, statistical correlations were performed between key parameters, such as mechanical properties, AM particle dosage, MDD, and OMC. This step was crucial to uncover the interdependence of these variables, enhancing the understanding of how AM elements impact marl soil. Statistical analysis is a versatile tool that helps evaluate how one parameter influences another [93], [94], [95], allowing researchers to quantify relationships between variables systematically. In this case, it was employed to determine how experimental data trends align with a regression line, using the coefficient of determination (R^2) as a measure of model accuracy. This approach ensures that the observed data can be reliably predicted and understood. The R^2 value ranges from

0 to 1, with values closer to 1 indicating a model that accurately predicts outcomes. This is critical when creating predictive models to anticipate how changes in AM dosage affect soil properties. A higher R^2 suggests the model's ability to capture the true relationship between variables, making it an effective tool for designing AM-mixed soils.

The statistical correlations among AM dosage, maximum dry density (MDD), and optimum moisture content (OMC) are illustrated in Figure 50. Both the MDD and OMC have significant effects on the engineering properties of soil. It can be seen in Figure 50 that significant statistical models with R^2 values greater than 0.95 are developed to predict MDD and OMC with the increasing AM dosage. Following the trend depicted in Figure 50, both the MDD and OMC decrease with the increase in AM content in marl soil. Eqs. (1) and (2) can be used to predict the OMC and MDD of the stabilized soil matrix by varying the AM content, respectively. Likewise, a highly significant polynomial statistical model is developed for the OMC-MDD of AM elements-treated marl.

$$OMC (\%) = -0.1814(AM)^2 + 0.0632(AM) + 16.4757 \quad \text{Eq. 1}$$

$$MDD (kN/m^3) = -0.0304(AM)^2 - 0.0634(AM) + 18.1744 \quad \text{Eq. 2}$$

Where AM is the dosage of AM elements in percentage.

To evaluate the relationship between unconfined compressive strength (UCS) and AM dosage, statistical methods were employed to develop predictive models with a high coefficient of determination ($R^2 = 0.84$). This indicates that 84% of the variability in UCS can be explained by changes in AM dosage, demonstrating a significant correlation. Figure 51 clearly illustrates this trend, providing visual confirmation of the model's reliability. Tailored with the UCS results shown in Fig. 6, a consistent observation emerges: UCS strength decreases as the dosage of AM

elements increases. This inverse relationship is critical in understanding how AM content affects soil strength, as excessive dosages may compromise strength. Eq. 3 is developed to predict the UCS strength from AM elements.

$$UCS (kPa) = 3.63(AM)^4 - 24.0374(AM)^3 + 41.0975(AM)^2 - 6.5051(AM) + 28.2302$$

Eq. 3

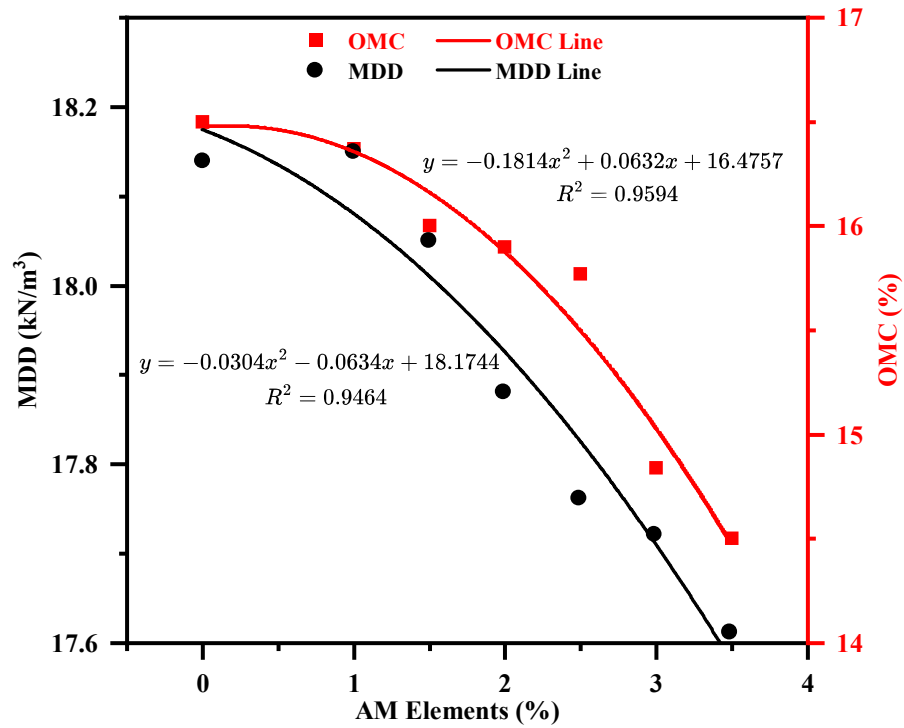


Figure 50. Statistical Correlations for MDD, OMC and Percentage of AM elements

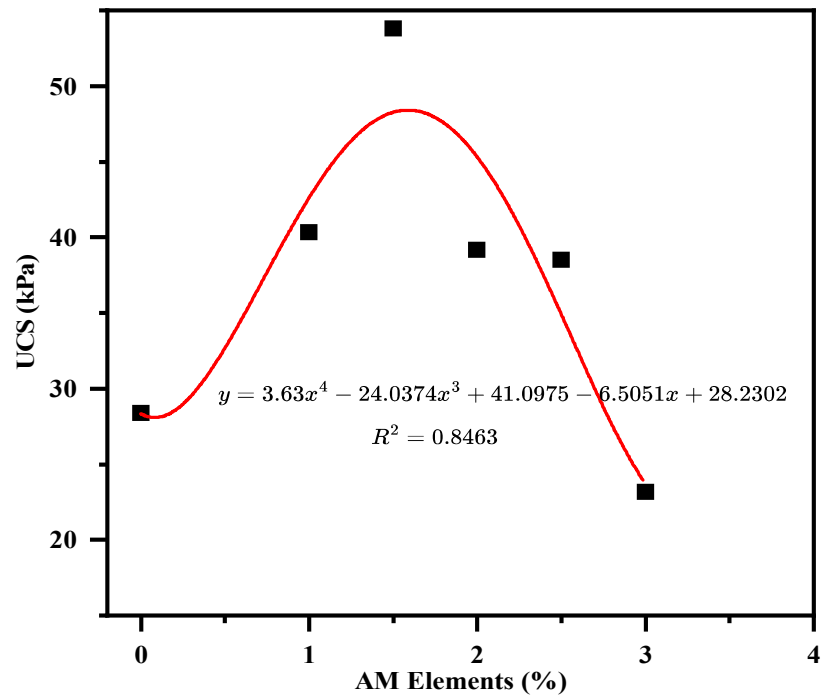


Figure 51. Statistical Correlation for UCS and AM Dosage

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1. Conclusion

This study utilized additive manufacturing (AM) to address a geotechnical engineering challenge. This was accomplished through experimental studies that assessed the efficiency of AM components in stabilizing the marl soil using UCS and direct shear testing. AM components were manufactured using fused deposition modeling from ABS material. UCS tests were conducted after each percentage's compaction test to determine the optimal amount of AM components. The effect of AM components' size and shape was then assessed using the UCS test. The shear strength values for AM mixed and marl soil were determined by conducting a direct shear test under varied normal stresses. Based on the analysis, the following conclusions are noted:

1. AM particles of different shapes (triangle, square, and circle) and sizes were successfully produced using fused deposition modeling techniques from recycled and virgin ABS plastic.
2. AM elements showed durability/stability against high-temperature variations, showing their suitability for practical applications. Meanwhile, they are chemically inert when mixed with the soil.
.
3. The lower concentration, i.e., 1.5 % of AM Elements, shows high strength and is considered an optimum percentage for the study.
4. The soil with smaller size and triangular-shaped AM Elements has more strength and ultimately shows high unconfined compressive strength (UCS). This is because the triangular shape helps in the stress distribution, and the angularity of the triangle increases

the packing, resulting in high strength. For small AM elements, the strength is higher due to higher contact density than medium- and large-sized AM elements.

5. Major change was observed as the failure pattern for the reference sample is prominently bulging while it was changed to shear and compression failure due to the addition of AM elements.
6. The direct shear test results indicate that the shear strength of AM-mixed soil is enhanced compared to virgin soil, owing to the confinement provided by the hollow-shaped elements and the rough texture of the AM elements.
7. Confining stress enhanced the soil's stress-strain behavior compared to unconfined conditions, responding more representative of in-situ field scenarios.
8. The permeability of the soil increases significantly when AM particles are mixed, specifically in the range of 1.5%- 3%. Higher voids at the interface and inside the hollow-shaped AM elements developed the flow path.
9. Regression analysis and predictive models presented the relationship between AM element percentage, Maximum Dry Density (MDD), and Optimal Moisture Content (OMC). The predictive models showed significant results with high R^2 values, indicating predictive accuracy

5.2. Future Recommendations

1. Investigating the Influence of AM Element Surface Roughness on Shear Strength

Future research should focus on quantifying the impact of surface roughness of additively manufactured (AM) elements on the shear strength parameters of AM-mixed soils. Surface roughness is a critical factor influencing particle interlocking, frictional resistance,

and the overall soil-structure interaction. By conducting controlled experiments to systematically vary and measure the roughness of AM particles, researchers can better understand how micro-scale surface properties translate into macro-scale mechanical behavior enhancements.

2. Conducting Large-Scale Loading Tests on AM-Mixed Soils

It is recommended to extend the research to large-scale loading tests to simulate field conditions and better understand the real-world performance of AM-mixed soils. Laboratory-scale tests often provide only limited insights into the behavior of soils under full-scale loading scenarios. Large-scale testing will help evaluate the practical effectiveness of AM inclusions in improving load-bearing capacity, settlement characteristics, and failure mechanisms under realistic stress conditions, ensuring better alignment with geotechnical engineering applications.

References

- [1] H. Tumwiine *et al.*, “Pore fluid salinity effects on post-stabilization performance of cement-treated Marl,” *Case Studies in Construction Materials*, vol. 20, p. e03193, Jul. 2024, doi: 10.1016/j.cscm.2024.e03193.
- [2] H. Venkateswarlu, A. SaiKumar, and G. M. Latha, “Sand-geogrid interfacial shear response revisited through additive manufacturing,” *Geotextiles and Geomembranes*, vol. 51, no. 4, pp. 95–107, Aug. 2023, doi: 10.1016/j.geotexmem.2023.04.001.
- [3] N.-D. Ciobota, G. I. Gheorghe, and V. Despa, “Additive Manufacturing as an Important Industry Player for the Next Decades,” *Scientific Bulletin of Valahia University - Materials and Mechanics*, vol. 17, no. 16, pp. 68–71, May 2019, doi: 10.2478/bsmm-2019-0010.
- [4] A. Meddah, A. E. Goufi, and L. Pantelidis, “Improving Very High Plastic Clays with the Combined Effect of Sand, Lime, and Polypropylene Fibers,” *Applied Sciences (Switzerland)*, vol. 12, no. 19, Oct. 2022, doi: 10.3390/app12199924.
- [5] C. H. Dowding and R. D. Hryciw, “A Laboratory Study of Blast Densification of Saturated Sand,” *Journal of Geotechnical Engineering*, vol. 112, no. 2, pp. 187–199, Feb. 1986, doi: 10.1061/(ASCE)0733-9410(1986)112:2(187).
- [6] J. Chu, B. Indraratna, S. Yan, and C. Rujikiatkamjorn, “Overview of preloading methods for soil improvement,” *Proceedings of the Institution of Civil Engineers - Ground Improvement*, vol. 167, no. 3, pp. 173–185, Aug. 2014, doi: 10.1680/grim.13.00022.
- [7] S. Chandrawanshi and R. Kumar, “Settlement Behaviour of Very Soft Soil Reinforced with Stone Columns,” 2021, pp. 345–355. doi: 10.1007/978-981-33-6444-8_31.

- [8] P. Dobrzycki and P. Rychlewski, "Site control procedures for applicability and quality of Rapid Impulse Compaction," *MATEC Web of Conferences*, vol. 251, p. 02018, Dec. 2018, doi: 10.1051/mateconf/201825102018.
- [9] M. Singh and P. Garg, "singh and garg," *Journal of University of Shanghai for Science and Technology*, vol. 23, no. 8, pp. 538–548, Aug. 2021.
- [10] A. Yousefi, H. Jahanian, and M. Azadi, "Effect of adding cement and nanocement on mechanical properties of clayey soil," *Eur Phys J Plus*, vol. 135, no. 8, Aug. 2020, doi: 10.1140/epjp/s13360-020-00639-7.
- [11] D. Toksöz Hozatlıoğlu and I. Yılmaz, "Shallow mixing and column performances of lime, fly ash and gypsum on the stabilization of swelling soils," *Eng Geol*, vol. 280, p. 105931, Jan. 2021, doi: 10.1016/j.enggeo.2020.105931.
- [12] K. C. Onyelowe, "Nanosized palm bunch ash (NPBA) stabilisation of lateritic soil for construction purposes," *International Journal of Geotechnical Engineering*, pp. 1–9, May 2017, doi: 10.1080/19386362.2017.1322797.
- [13] B. Van Duc and O. Kennedy, "Adsorbed complex and laboratory geotechnics of Quarry Dust (QD) stabilized lateritic soils," *Environ Technol Innov*, vol. 10, pp. 355–363, May 2018, doi: 10.1016/j.eti.2018.04.005.
- [14] K. C. Onyelowe, "Review on the role of solid waste materials in soft soils reengineering," *Mater Sci Energy Technol*, vol. 2, no. 1, pp. 46–51, Apr. 2019, doi: 10.1016/J.MSET.2018.10.004.
- [15] M. Gaafer, H. Bassioni, and T. Mostafa, "Soil improvement techniques," *Int. J. Sci. Eng. Res*, vol. 6, no. 12, pp. 217–222, 2015.

- [16] M. Waheed and N. Asmael, "Improvement of engineering soil properties using non -traditional additives," *MATEC Web of Conferences*, vol. 162, p. 01027, May 2018, doi: 10.1051/mateconf/201816201027.
- [17] S. K. Shukla, "Geosynthetics and Ground Engineering: Sustainability Considerations," *International Journal of Geosynthetics and Ground Engineering*, vol. 7, no. 1, p. 17, Mar. 2021, doi: 10.1007/s40891-021-00256-z.
- [18] A. M. Al-Swaidani and A. Meziab, "Restriction of Volume Change and Improvement of Strength Properties of Problematic Soils Using Nano-natural Additives," *Indian Geotechnical Journal*, vol. 51, no. 5, pp. 992–1010, Oct. 2021, doi: 10.1007/s40098-021-00499-7.
- [19] Y. Yang *et al.*, "Plastic wastes (PWs) and microplastics (MPs) formation: Management, migration, and environmental impact," *J Environ Chem Eng*, vol. 12, no. 3, p. 112926, Jun. 2024, doi: 10.1016/j.jece.2024.112926.
- [20] W. Kong *et al.*, "Microplastics (MPs) in wastewater treatment plants sludges: Substrates, digestive properties, microbial communities, mechanisms, and treatments," *J Environ Chem Eng*, vol. 11, no. 6, p. 111408, Dec. 2023, doi: 10.1016/j.jece.2023.111408.
- [21] A. S. Nizami *et al.*, "An argument for developing waste-to-energy technologies in Saudi Arabia," *Chem Eng Trans*, vol. 45, pp. 337–342, Oct. 2015, doi: 10.3303/CET1545057.
- [22] K. Andrews, S. Dernayka, M. Amin Mir, and M. Ali Khasawneh, "Review of the utilization of plastic waste in asphalt pavements in hot climate conditions – KSA as a case study," *Mater Today Proc*, Jun. 2023, doi: 10.1016/j.matpr.2023.05.463.
- [23] A. Almadhi, A. Abdelhadi, and R. Alyamani, "Moving from Linear to Circular Economy in Saudi Arabia: Life-Cycle Assessment on Plastic Waste Management," *Sustainability*, vol. 15, no. 13, p. 10450, Jul. 2023, doi: 10.3390/su151310450.

- [24] D. C. Lucarelli, H. N. Pitanga, M. E. S. Marques, T. O. da Silva, R. L. Ferraz, and D. M. Nunes, "Study of the geotechnical behavior of soil-cement reinforced with plastic bottle fibers," *Acta Scientiarum - Technology*, vol. 44, 2022, doi: 10.4025/actascitechnol.v44i1.57826.
- [25] P. Gangwar and S. Tiwari, "Stabilization of soil with waste plastic bottles," *Mater Today Proc*, vol. 47, pp. 3802–3806, 2021, doi: 10.1016/j.matpr.2021.03.010.
- [26] I. A. Wani, I. M. Sheikh, T. Maqbool, and V. Kumar, "Experimental investigation on using plastic wastes to enhance several engineering properties of soil through stabilization," *Mater Today Proc*, vol. 45, pp. 4571–4574, 2021, doi: 10.1016/j.matpr.2021.01.006.
- [27] O. O. Ojuri *et al.*, "Eco-friendly stabilization of highway lateritic soil with cow bone powder admixed lime and plastic granules reinforcement," *Cleaner Waste Systems*, vol. 2, p. 100012, Jul. 2022, doi: 10.1016/j.clwas.2022.100012.
- [28] S. C. Boobalan, P. K. Anandakumar, and M. Sathasivam, "Utilization of waste plastic sheets as soil stabilization materials," *Mater Today Proc*, Jul. 2023, doi: 10.1016/j.matpr.2023.07.184.
- [29] kiyoshi Omine, H. Ochiai, and Yasufuku, "Article_Development of New Geomaterials using Plastic Wastes (1)," *Proceedings of International Workshop*, pp. 1–8, Mar. 2002.
- [30] M. Ghazavi and A. A. Lavasan, "Interference effect of shallow foundations constructed on sand reinforced with geosynthetics," *Geotextiles and Geomembranes*, vol. 26, no. 5, pp. 404–415, Oct. 2008, doi: 10.1016/j.geotexmem.2008.02.003.
- [31] G. M. Latha, S. K. Dash, and K. Rajagopal, "Numerical Simulation of the Behavior of Geocell Reinforced Sand in Foundations," *International Journal of Geomechanics*, vol. 9, no. 4, pp. 143–152, Aug. 2009, doi: 10.1061/(ASCE)1532-3641(2009)9:4(143).

- [32] G. Madhavi Latha, K. Rajagopal, and N. R. Krishnaswamy, “Experimental and Theoretical Investigations on Geocell-Supported Embankments,” *International Journal of Geomechanics*, vol. 6, no. 1, pp. 30–35, Jan. 2006, doi: 10.1061/(ASCE)1532-3641(2006)6:1(30).
- [33] J. Derksen, M. Ziegler, and R. Fuentes, “Geogrid-soil interaction: A new conceptual model and testing apparatus,” *Geotextiles and Geomembranes*, vol. 49, no. 5, pp. 1393–1406, Oct. 2021, doi: 10.1016/j.geotexmem.2021.05.011.
- [34] R. Baadiga, U. Balunaini, and S. Saride, “Influence of Geogrid Aperture Size on the Behavior of Mechanically Stabilized Pavements,” *Airfield and Highway Pavements*, pp. 271–282, 2021.
- [35] J. Neves, H. Lima, and M. Gonçalves, “A Numerical Study on the Implications of Subgrade Reinforcement with Geosynthetics in Pavement Design,” *Procedia Eng*, vol. 143, pp. 888–895, 2016, doi: 10.1016/j.proeng.2016.06.151.
- [36] A. M. Hegde and P. S. Palsule, “Performance of Geosynthetics Reinforced Subgrade Subjected to Repeated Vehicle Loads: Experimental and Numerical Studies,” *Front Built Environ*, vol. 6, Feb. 2020, doi: 10.3389/fbuil.2020.00015.
- [37] A. Al Rashid, S. A. Khan, S. G. Al-Ghamdi, and M. Koç, “Additive manufacturing: Technology, applications, markets, and opportunities for the built environment,” *Autom Constr*, vol. 118, p. 103268, Oct. 2020, doi: 10.1016/j.autcon.2020.103268.
- [38] T. Tabassum and A. Ahmad Mir, “A review of 3d printing technology-the future of sustainable construction,” *Mater Today Proc*, Aug. 2023, doi: 10.1016/j.matpr.2023.08.013.
- [39] V. J. Kharat *et al.*, “Additive manufacturing (3D printing): A review of materials, methods, applications and challenges,” *Mater Today Proc*, Nov. 2023, doi: 10.1016/j.matpr.2023.11.033.
- [40] A. Y. Alqutaibi, M. A. Alghauli, M. H. A. Aljohani, and M. S. Zafar, “Advanced additive manufacturing in implant dentistry: 3D printing technologies, printable materials, current

- applications and future requirements,” *Bioprinting*, vol. 42, p. e00356, Oct. 2024, doi: 10.1016/j.bprint.2024.e00356.
- [41] K. Aghaee, L. Li, A. Roshan, and P. Namakiaraghi, “Additive manufacturing evolution in construction: From individual terrestrial to collective, aerial, and extraterrestrial applications,” *Journal of Building Engineering*, vol. 96, p. 110389, Nov. 2024, doi: 10.1016/j.jobbe.2024.110389.
- [42] J. Jauk, L. Gosch, H. Vašatko, M. Königsberger, J. Schlusche, and M. Stavric, “Filament-Reinforced 3D Printing of Clay,” *Materials*, vol. 16, no. 18, p. 6253, Sep. 2023, doi: 10.3390/ma16186253.
- [43] T. Makki *et al.*, “3D and 4D printing: A review of virgin polymers used in fused deposition modeling,” *Composites Part C: Open Access*, vol. 14, p. 100472, Jul. 2024, doi: 10.1016/j.jcomc.2024.100472.
- [44] J. R. C. Dizon, C. C. L. Gache, H. M. S. Cascolan, L. T. Cancino, and R. C. Advincula, “Post-Processing of 3D-Printed Polymers,” *Technologies (Basel)*, vol. 9, no. 3, p. 61, Aug. 2021, doi: 10.3390/technologies9030061.
- [45] A. Paolini, S. Kollmannsberger, and E. Rank, “Additive manufacturing in construction: A review on processes, applications, and digital planning methods,” *Addit Manuf*, vol. 30, p. 100894, Dec. 2019, doi: 10.1016/j.addma.2019.100894.
- [46] A. H. Espera, J. R. C. Dizon, Q. Chen, and R. C. Advincula, “3D-printing and advanced manufacturing for electronics,” *Progress in Additive Manufacturing*, vol. 4, no. 3, pp. 245–267, Sep. 2019, doi: 10.1007/s40964-019-00077-7.
- [47] J. Z. Manapat, J. D. Mangadlao, B. D. B. Tiu, G. C. Tritchler, and R. C. Advincula, “High-Strength Stereolithographic 3D Printed Nanocomposites: Graphene Oxide Metastability,” *ACS Appl Mater Interfaces*, vol. 9, no. 11, pp. 10085–10093, Mar. 2017, doi: 10.1021/acsami.6b16174.

- [48] A. Bandyopadhyay and B. Heer, “Additive manufacturing of multi-material structures,” *Materials Science and Engineering: R: Reports*, vol. 129, pp. 1–16, Jul. 2018, doi: 10.1016/j.mser.2018.04.001.
- [49] A. H. Alami *et al.*, “Additive manufacturing in the aerospace and automotive industries: Recent trends and role in achieving sustainable development goals,” *Ain Shams Engineering Journal*, vol. 14, no. 11, p. 102516, Nov. 2023, doi: 10.1016/j.asej.2023.102516.
- [50] K. Morshed-Behbahani, A. Aliyu, D. P. Bishop, and A. Nasiri, “Additive manufacturing of copper-based alloys for high-temperature aerospace applications: A review,” *Mater Today Commun*, vol. 38, p. 108395, Mar. 2024, doi: 10.1016/j.mtcomm.2024.108395.
- [51] R. Raj and G. Singh, “A review on process prerequisites and biomedical applications of additively manufactured zirconia,” *Engineering Science and Technology, an International Journal*, vol. 59, p. 101876, Nov. 2024, doi: 10.1016/j.jestch.2024.101876.
- [52] Y. Liu *et al.*, “Recent advances in additive manufacturing for tooth restorations,” *Appl Mater Today*, vol. 39, p. 102275, Aug. 2024, doi: 10.1016/j.apmt.2024.102275.
- [53] J. I. Lipton, M. Cutler, F. Nigl, D. Cohen, and H. Lipson, “Additive manufacturing for the food industry,” *Trends Food Sci Technol*, vol. 43, no. 1, pp. 114–123, May 2015, doi: 10.1016/j.tifs.2015.02.004.
- [54] V. Mohanavel, K. S. Ashraff Ali, K. Ranganathan, J. Allen Jeffrey, M. M. Ravikumar, and S. Rajkumar, “The roles and applications of additive manufacturing in the aerospace and automobile sector,” *Mater Today Proc*, vol. 47, pp. 405–409, 2021, doi: 10.1016/j.matpr.2021.04.596.
- [55] J. Yang, B. Li, J. Liu, Z. Tu, and X. Wu, “Application of Additive Manufacturing in the Automobile Industry: A Mini Review,” *Processes*, vol. 12, no. 6, p. 1101, May 2024, doi: 10.3390/pr12061101.

- [56] H. Venkateswarlu, A. SaiKumar, and G. M. Latha, “Sand-geogrid interfacial shear response revisited through additive manufacturing,” *Geotextiles and Geomembranes*, vol. 51, no. 4, pp. 95–107, Aug. 2023, doi: 10.1016/j.geotexmem.2023.04.001.
- [57] J. Pegna, “Exploratory investigation of solid freeform construction,” *Autom Constr*, vol. 5, no. 5, pp. 427–437, Feb. 1997, doi: 10.1016/S0926-5805(96)00166-5.
- [58] G. Ji, T. Ding, J. Xiao, S. Du, J. Li, and Z. Duan, “A 3D Printed Ready-Mixed Concrete Power Distribution Substation: Materials and Construction Technology,” *Materials*, vol. 12, no. 9, p. 1540, May 2019, doi: 10.3390/ma12091540.
- [59] A. Pajonk, A. Prieto, U. Blum, and U. Knaack, “Multi-material additive manufacturing in architecture and construction: A review,” *Journal of Building Engineering*, vol. 45, p. 103603, Jan. 2022, doi: 10.1016/j.jobbe.2021.103603.
- [60] M. H. Raza and R. Y. Zhong, “A sustainable roadmap for additive manufacturing using geopolymers in construction industry,” *Resour Conserv Recycl*, vol. 186, p. 106592, Nov. 2022, doi: 10.1016/j.resconrec.2022.106592.
- [61] O. B. Carcassi and L. Ben-Alon, “Additive manufacturing of natural materials,” *Autom Constr*, vol. 167, p. 105703, Nov. 2024, doi: 10.1016/j.autcon.2024.105703.
- [62] F. Hasiuk, “Making things geological: 3-D printing in the geosciences,” *GSA Today*, pp. 28–29, Aug. 2014, doi: 10.1130/GSATG211GW.1.
- [63] S. Ishutov, F. J. Hasiuk, C. Harding, and J. N. Gray, “3D printing sandstone porosity models,” *Interpretation*, vol. 3, no. 3, pp. SX49–SX61, Aug. 2015, doi: 10.1190/INT-2014-0266.1.
- [64] D. Head and T. Vanorio, “Effects of changes in rock microstructures on permeability: 3-D printing investigation,” *Geophys Res Lett*, vol. 43, no. 14, pp. 7494–7502, Jul. 2016, doi: 10.1002/2016GL069334.

- [65] S. Fereshtenejad and J.-J. Song, “Fundamental Study on Applicability of Powder-Based 3D Printer for Physical Modeling in Rock Mechanics,” *Rock Mech Rock Eng*, vol. 49, no. 6, pp. 2065–2074, Jun. 2016, doi: 10.1007/s00603-015-0904-x.
- [66] C. Jiang and G.-F. Zhao, “A Preliminary Study of 3D Printing on Rock Mechanics,” *Rock Mech Rock Eng*, vol. 48, no. 3, pp. 1041–1050, May 2015, doi: 10.1007/s00603-014-0612-y.
- [67] C. Jiang, G.-F. Zhao, J. Zhu, Y.-X. Zhao, and L. Shen, “Investigation of Dynamic Crack Coalescence Using a Gypsum-Like 3D Printing Material,” *Rock Mech Rock Eng*, vol. 49, no. 10, pp. 3983–3998, Oct. 2016, doi: 10.1007/s00603-016-0967-3.
- [68] Q. Jiang, X. Feng, L. Song, Y. Gong, H. Zheng, and J. Cui, “Modeling rock specimens through 3D printing: Tentative experiments and prospects,” *Acta Mechanica Sinica*, vol. 32, no. 1, pp. 101–111, Feb. 2016, doi: 10.1007/s10409-015-0524-4.
- [69] P. Liu, Y. Ju, P. G. Ranjith, Z. Zheng, L. Wang, and A. Wanniarachchi, “Visual representation and characterization of three-dimensional hydrofracturing cracks within heterogeneous rock through 3D printing and transparent models,” *Int J Coal Sci Technol*, vol. 3, no. 3, pp. 284–294, Sep. 2016, doi: 10.1007/s40789-016-0145-y.
- [70] Y. Ju, L. Wang, H. Xie, G. Ma, Z. Zheng, and L. Mao, “Visualization and Transparentization of the Structure and Stress Field of Aggregated Geomaterials Through 3D Printing and Photoelastic Techniques,” *Rock Mech Rock Eng*, vol. 50, no. 6, pp. 1383–1407, Jun. 2017, doi: 10.1007/s00603-017-1171-9.
- [71] Y. Ju *et al.*, “Visualization of the complex structure and stress field inside rock by means of 3D printing technology,” *Chinese Science Bulletin*, vol. 59, no. 36, pp. 5354–5365, Dec. 2014, doi: 10.1007/s11434-014-0579-9.

- [72] Y. Xia *et al.*, “Application of 3D Printing Technology in the Mechanical Testing of Complex Structural Rock Masses,” 2021, *Hindawi Limited*. doi: 10.1155/2021/7278131.
- [73] L. Song *et al.*, “Feasibility Investigation of 3D Printing Technology for Geotechnical Physical Models: Study of Tunnels,” *Rock Mech Rock Eng*, vol. 51, no. 8, pp. 2617–2637, Aug. 2018, doi: 10.1007/s00603-018-1504-3.
- [74] Q. Jiang, X. Feng, Y. Gong, L. Song, S. Ran, and J. Cui, “Reverse modelling of natural rock joints using 3D scanning and 3D printing,” *Comput Geotech*, vol. 73, pp. 210–220, Mar. 2016, doi: 10.1016/j.compgeo.2015.11.020.
- [75] D. Stathas, J. P. Wang, and H. I. Ling, “Model geogrids and 3D printing,” *Geotextiles and Geomembranes*, vol. 45, no. 6, pp. 688–696, Dec. 2017, doi: 10.1016/j.geotextmem.2017.07.006.
- [76] G. J. Fowmes, N. Dixon, L. Fu, and C. A. Zaharescu, “Rapid prototyping of geosynthetic interfaces: Investigation of peak strength using direct shear tests,” *Geotextiles and Geomembranes*, vol. 45, no. 6, pp. 674–687, Dec. 2017, doi: 10.1016/j.geotextmem.2017.08.009.
- [77] D. Stathas and J. Wang, “The Performances of Three Soil Retaining Structures: Gabion, Modular Block and Geocell,” in *5th International Conference on Geotechnique, Construction Materials and Environment (GEOMATE)*, Osaka, Japan: The GEOMATE International Society, 2015, pp. 407–412.
- [78] D. A. H. Hanaor, Y. Gan, M. Revay, D. W. Airey, and I. Einav, “3D printable geomaterials,” *Géotechnique*, vol. 66, no. 4, pp. 323–332, Apr. 2016, doi: 10.1680/jgeot.15.P.034.
- [79] M. Xu, D. Jin, and W. Zhou, “An experimental study on the time-dependent behavior of crushable granular materials using 3D-printed particles,” *Acta Geotech*, vol. 17, no. 1, pp. 93–104, Jan. 2022, doi: 10.1007/s11440-021-01232-7.

- [80] M. Z. Miskin and H. M. Jaeger, “Adapting granular materials through artificial evolution,” *Nat Mater*, vol. 12, no. 4, pp. 326–331, Apr. 2013, doi: 10.1038/nmat3543.
- [81] D. A. H. Hanaor, Y. Gan, M. Revay, D. W. Airey, and I. Einav, “3D printable geomaterials,” *Géotechnique*, vol. 66, no. 4, pp. 323–332, Apr. 2016, doi: 10.1680/jgeot.15.P.034.
- [82] J. Landauer, M. Kuhn, D. S. Nasato, P. Foerst, and H. Briesen, “Particle shape matters – Using 3D printed particles to investigate fundamental particle and packing properties,” *Powder Technol*, vol. 361, pp. 711–718, Feb. 2020, doi: 10.1016/j.powtec.2019.11.051.
- [83] S. S. Ahmed and A. Martinez, “Modeling the mechanical behavior of coarse-grained soil using additive manufactured particle analogs,” *Acta Geotech*, vol. 15, no. 10, pp. 2829–2847, Oct. 2020, doi: 10.1007/s11440-020-01007-6.
- [84] Y. Li, H. Zhou, H. Liu, X. Ding, and W. Zhang, “Geotechnical properties of 3D-printed transparent granular soil,” *Acta Geotech*, vol. 16, no. 6, pp. 1789–1800, Jun. 2021, doi: 10.1007/s11440-020-01111-7.
- [85] H. Lei, Z. Chen, and X. Kang, “Examination of particle shape on the shear behaviours of granules using 3D printed soil,” *European Journal of Environmental and Civil Engineering*, vol. 26, no. 9, pp. 4200–4219, Jul. 2022, doi: 10.1080/19648189.2020.1845983.
- [86] H. Lei, Z. Chen, and X. Kang, “Examination of particle shape on the shear behaviours of granules using 3D printed soil,” *European Journal of Environmental and Civil Engineering*, vol. 26, no. 9, pp. 4200–4219, Jul. 2022, doi: 10.1080/19648189.2020.1845983.
- [87] S. Matsumura, S. Kawamura, L. Kandpal, and P. Vangla, “3D printed porous particle and its geotechnical properties,” *Acta Geotech*, vol. 18, no. 11, pp. 5735–5753, Nov. 2023, doi: 10.1007/s11440-023-01981-7.

- [88] F. M. Mwema and E. T. Akinlabi, “Basics of Fused Deposition Modelling (FDM),” in *SpringerBriefs in Applied Sciences and Technology*, Springer, 2020, pp. 1–15. doi: 10.1007/978-3-030-48259-6_1.
- [89] J. R. C. Dizon, C. C. L. Gache, H. M. S. Cascolan, L. T. Cancino, and R. C. Advincula, “Post-Processing of 3D-Printed Polymers,” Sep. 01, 2021, *MDPI*. doi: 10.3390/technologies9030061.
- [90] J. Bai, Y. Zhang, and S. Wu, “Review Study of Physical and Mechanical Characteristics on Mixed Soil with Scrap Tire Rubber Particles,” 2020.
- [91] S. Singh, U. Dhiman, and R. Sharma, “Soil Stabilization using Scrap Rubber Tyre,” *International Research Journal of Engineering and Technology*, 2017, [Online]. Available: www.irjet.net
- [92] N. C. Consoli, J. P. Montardo, P. D. M. Prietto, and G. S. Pasa, “Engineering Behavior of a Sand Reinforced with Plastic Waste,” *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 128, no. 6, pp. 462–472, Jun. 2002, doi: 10.1061/(ASCE)1090-0241(2002)128:6(462).
- [93] Z. Ullah, M. I. Qureshi, A. Ahmad, S. U. Khan, and M. F. Javaid, “An experimental study on the mechanical and durability properties assessment of E-waste concrete,” *Journal of Building Engineering*, vol. 38, p. 102177, Jun. 2021, doi: 10.1016/j.job.2021.102177.
- [94] A. Ahmad, D. S. Karunatilaka, V. Anggraini, and M. E. Raghunandan, “Mechanical, microstructural, and environmental performance of industrial byproducts in peat reinforcement,” *Constr Build Mater*, vol. 451, p. 138780, Nov. 2024, doi: 10.1016/j.conbuildmat.2024.138780.
- [95] K. Sangprasat, A. Puttiwongrak, and S. Inazumi, “Comprehensive analysis of correlations between soil electrical resistivity and index geotechnical properties,” *Results in Engineering*, vol. 23, p. 102696, Sep. 2024, doi: 10.1016/j.rineng.2024.102696.

Vitae

Name : Aqeel Ur Rehman

Nationality: Pakistani

Date of Birth: 2/15/1999

Email : aqeel004u@gmail.com

Address: Qtr#52/2 PAF Rafiqui Camp Peshawar Cantt Pakistan: 25000

Academic Background: Civil Engineering

Bachelor of Science (BSc) in Civil Engineering

September 2021

University of Engineering and Technology, Peshawar, Pakistan.

Master of Science in Civil Engineering

December 2024

King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia.

Research Work

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