Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
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A Numerical Study of a geosynthetic reinforced road embankment using nature-based basalt geogrid

Master's thesis in Geotechnics and Geohazards
Supervisor: Rao Martand Singh
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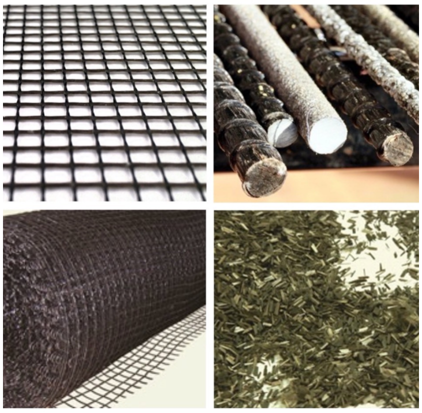

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Preface

This Master's thesis was conducted as a part of my MSc. in Geotechnics and Geohazards at the Department of Civil and Environmental Engineering at the Norwegian University of Science and Technology (NTNU) during the Spring semester of 2022. The thesis involves A Numerical Study of a geosynthetic reinforced road embankment using nature-based basalt geogrid. The topic is an outcome of the suggestion of my main supervisor Professor Rao Martand Singh.

Acknowledgment

I would like to take this opportunity to express my sincere gratitude to my supervisor Professor Rao Martand Singh, Department of Civil and Environmental Engineering at NTNU, for his continuous guidance, support, and valuable suggestions throughout- the thesis. I also would like to thank everyone at the geotechnical division, NTNU, for all the help and motivation during the entire duration.

I am most thankful to all known and unknown helping hands and minds that guided me through the thesis.

Muhammad Saleem Trondheim, 11 June 7, 2022

Abstract

It is challenging to construct roads and other structures on naturally soft soil in geotechnical engineering. Deformation difficulties frequently occur on embankments and lead to collapse. This is either a significant settlement or sliding due to insufficient shear strength of soft soil.

Deterministic design of reinforced road embankments employing natural and uncultivated materials in geosynthetic geogrid may address the problem. Environmental changings occurring across the globe are possibly a factor associated with increased risk when it comes to landslides and the movement of large amounts of soil and rock. A challenge we meet that is necessary to overcome is to reduce the usage of unfriendly material. This research tries to find environment-friendly materials which can later be used to replace unfriendly materials in the construction industry. This requires a deeper understanding and characterization of the nature-based materials which are commonly used in geosynthetic geogrid-reinforced process.

This research aims to overcome the challenges mentioned above by creating a geosynthetic geogrid using nature-based materials to reinforce a road embankment. Comparison of the results of nature-based and polymer-based materials which are used in the geosynthetic geogrid is the focus. Its purpose is to determine how much strengthening is provided by nature-based geogrid to structure and include that knowledge into the design approach. This research use PLAXIS 2D plane strain v8.6 with the Mohr-Coulomb model for analyzing the stability of road embankment slope while using basalt fiber and polymer-based material in geosynthetic geogrid. The project aims to examine current techniques for strengthening embankment slopes, justify using geogrid based on basalt fiber for reinforcing embankments and determine the optimal position of the layer in the embankment. The results show that basalt material should be used as an alternative material in geosynthetic geogrid. It gives more resistance to deformation in road embankments. This thesis concludes with the remark that nature-based geogrid provides more 32 % significant reinforcement to road embankment slopes rather than reinforced polymer-based geogrid throughout a comparison of three types of road embankment slopes.

Sammendrag

I geoteknikk er det utfordrende å bygge veier og andre konstruksjoner på naturlig myk jord. Deformasjonsvansker oppstår ofte på fyllinger og fører til kollaps. Resultater av dette er enten en betydelig setning eller utglidning på grunn av utilstrekkelig skjærstyrke av bløt jord.

Følgelig kan en deterministisk designtilnærming for å forsterke veifyllinger gjennom bruk av natur og unaturlig basert materiale i geosyntetisk geonett løse problemet. Miljøendringer som skjer over hele kloden, er muligens en faktor forbundet med økt risiko når det kommer til skred og bevegelse av store mengder jord og stein. En utfordring vi møter som er nødvendig å overkomme er å redusere bruken av uvennlig materiale. Denne forskningen prøver å finne miljøvennlig materiale som senere kan brukes til å erstatte uvennlig materiale i bygge bransjen. Dette krever en dypere forståelse og karakterisering av de naturbaserte materialene som vanligvis brukes i geosyntetiske geonett-forsterkede prosesser.

Denne forskningen tar sikte på å overvinne utfordringene nevnt ovenfor ved å lage et geosyntetisk geonett ved å bruke naturbaserte materialer for å forsterke en veifylling. Sammenligning av resultatene av naturbaserte og polymerbaserte materialer som brukes i det geosyntetiske geonettet er hovedfokus. Hensikten er å bestemme hvor mye styrking som gis av naturbasert geonett for å strukturere og inkludere den kunnskapen i designtilnærmingen. Denne forskningen brukte PLAXIS 2D plane strain v8.6 med Mohr-Coulomb-modellen for å analysere stabiliteten til veifyllingshellingene mens det ble brukt basaltfiber og polymerbasert materiale i geosyntetisk geonett. Prosjektet tar sikte på å undersøke aktuelle teknikker for å forsterke fyllingsskråninger, begrunne bruk av geonett basert på basaltfiber for å forsterke voll, og bestemme den optimale posisjonen til laget i fyllingen. Resultatene viser at basaltmateriale bør brukes som alternativt materiale i geosyntetisk geonett. Det gir mer motstand mot deformasjon i vegfylling. Denne oppgaven konkluderer med bemerkningen at naturbasert geonett gir 32 % større forsterkning til veifyllingshellinger i stedet for forsterket polymerbasert geonett gjennom sammenligning av tre typer veifyllingshellinger.

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List of Drawings and Figures

List of Tables

List of acronyms, abbreviations, and symbols

2D	Two-dimensional
3D	Three-dimensional
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
BF	Basalt fiber
CBR	California Bearing Ratio
E	Young's modulus
FRP	Fiber-reinforced plastic
FEA	Finite Element Analysis
GG-I	Geogrid type I
GG-II	Geogrid type II
GG-III	Geogrid type III
H	Horizontal
HD	High-Density Poly Ethylene
PET	Polyethylene terephthalate
LL	Liquid Limit
MC	Mohr CoulMohr-Coulomb Machine Direction
MDD	Maximum Dry Density
NGI	Norwegian Geotechnical institute
OCR	Over-consoilidation ratio
OMC	Optimum Moisture Content;
PET	Poly Ethylene Terephthalate; PL Plasticity Limit
PLAXIS	Plane strain and axial symmetry
PMMA	Poly methyl methacrylate
PET	Polyethylene terephthalate
PVC	Polyvinyl chloride
TBR	Traffic Benefit Ratio
UV	Ultraviolet
V	Vertical
XDM	DXM Cross-Machine Direction
α_r	Area ratio
γ	Bulk unit weight
γ_{sat}	Saturated unit weight
υ	Poisson's ratio
ϕ	The angle of the angle friction; and
ψ	Angle of dilatancy

Chapter 1

1. Introduction

1.1 Reinforced Soil and Geosynthetics, a historical perspective

The natural state of the soil may be kept together by the roots of plants, which in turn can hold the tremendous weight of the tree they are attached to. It is accurate to say that soil is one of the earliest building materials made accessible to humankind. It is also possible to presume, based on reasonable evidence, that efforts to drain swamps and marshes before the first documented attempts to compile historical information. According to several historical texts, the earliest kinds of wall and roof building included the use of ground material in addition to wood and straw. In the development of methods of buildings, use of materials that were preferred were the one accessible in the area, hence reinforced soil was employed in various ways, depending on the period and the place.

The usage of reinforced soil may be traced back to ancient civilizations when naturally occurring fibers were combined with compacted earth to produce a more durable composite building material. This process resulted in the creation of reinforced soil. The addition of a tensile-resistant substance to soil is meant to be conveyed by the phrase "reinforced soil," which signifies that the soil's strength has been increased. On the Iranian plateau, people have been using compacted dirt that has been supported with reed to build homes as far back as the fifth millennium before the present. When the Tower of Babel was made in the first millennium BC, reinforced earth was used in some foundations. Ziggurat Aqar Quf is a monument constructed near to wh Baghdad is situated now and dates back to between 1595 and 1171 BC[1]. It rises to the height of 54 meters. The building was constructed using river reeds to support pieces of compact dirt measuring 400 millimeters on a side used as building blocks[1].

Since the third millennium B.C., when clay fills were reinforced with reeds employed along the Tigris and Euphrates rivers, reinforced soil was also commonly utilized in river training works. This practice dates back to ancient times [1]. Since then, there have been several river training works that have used reinforced soil in various capacities. For example, some sections of the "Great Wall of China" in the Gobi desert were constructed using compacted sand and gravel reinforced with branches and reeds. The reinforcements were vertically spaced at 0.2 to

0.3 meters in segments where stone blocks and other conventional construction materials were scarce [2].

With time changes were made to stabilize slopes and lands. For example, "gabion walls" were constructed by placing crushed aggregates within steel mesh boxes and then tying the boxes together to stabilize slopes and make stable lands. Unconstructive training works and wooden reinforcements were used. Many people believe that the Frenchman Henry Vidal was the first person to apply engineered soil reinforcement in the year 1963 AD. Since then, reinforced soil has been involved in many different guises in various geotechnical contexts. In recent times, significant advances in soil reinforcing materials have been made in the form of polymeric polymers. Fibers and steel reinforcements are also used as reinforcing materials in some circumstances that call for it. Polymers are resistant to breakdown by biological and chemical agents, contributing to their widespread use. Polymeric materials are also popular because they are loaded according to the requirements of a particular application.

Approximately 32 years ago, in the month AD, the Norwegian Geotechnical Institute (NGI) used polymeric geosynthetics to create a reinforced soil structure in Skedsmo, located approximately 25 kilometers northeast of Oslo, Norway. Doing experiments and conducting research on the system's behavior and the reinforcements is still underway. A significant quantity of long-term data at the site and an analysis of synthetically reinforced structures' long/short-term performance have been carried out [3].

1.2 Modern use of geosynthetics for soil reinforcement

The use of geosynthetics presupposes that they are capable of performing four primary tasks, which are following: reinforcement, separation, filtration, and drainage. For each of these distinct roles, a specific kind of geosynthetic material is required to carry it out [4]. There are six different kinds of geosynthetics: geotextiles, geogrids, geonets, geomembranes, geosynthetic clay liners, and geocomposites. The last category, "geocomposites," is made up of geosynthetics that are made by combining two or more of the other types. When classifying geosynthetics, the drainage and filtration properties are the most important things to think about. This is because they significantly impact how well the final reinforced soil structure works and how strong it is.

The necessity to strengthen the roadbed and embankment slopes is decided by adequate calculations and selecting an ideal geosynthetic material. Considering soil qualities and local circumstances, which provides embankment stability and durability with the lowest financial expenditures [5]. Therefore, the most logical option is to utilize a geogrid comprised of continuous basalt fiber.

This project aims to examine current techniques for strengthening embankment slopes, justify using geogrid based on basalt fiber for reinforcing embankment slopes, and determine the optimal position of the layer in the embankment body.

2. Choice of subject

The subject of numerical analysis of nature-based material reinforced road embankment, subjected to traffic loading, was suggested by Professor Rao Martand Singh in NTNU. Problem definition and research method were worked out in consultation with Professor Rao Martand Singh.
This study was made to fit the academic interests and the notion that Norwegian engineers need to improve their knowledge related to the use of basalt fiber material to reinforce soft soil embankments. An important focus has been to understand the limited study in Norway about basalt material which is nature-based material.

3. Statement of the problem

It is still hard to build roads and other things on naturally soft clay in geotechnical engineering. Different ways of improving the soil needed to be used to stabilize the soft clay to increase the soil's ability to hold weight and reduce settlement[6]. Deformation problems are prevalent on embankments and induce collapse, resulting in either substantial settlement or sliding owing to insufficient shear strength. Average fill may be a mixture of diverse soils such as silty sand, clay sand, or silty clay, typically encountered as embankment material in various regions. Swelling or shrinkage-related soil movements in the grounds under infrastructures such as pavements, embankments, and light to medium-loaded residential and commercial buildings are widespread due to climate fluctuations.[7]

Environmental changings occurring across the globe are possibly a factor associated with increased risk when it comes to landslides and the movement of large amounts of soil and rock.

A challenge we meet that is necessary to overcome is to reduce the usage of unfriendly material. This research aims to predict the performance of basalt material reinforced soft clay through finite element modeling using PLAXIS 2D software, particularly the settlement, as essential criteria in embankment construction. Based on the results obtained, basalt geogrid, as a new alternative of synthetic material for the bearing capacity problem of soft clay, could be used with more confidence.

The selected case study for the master's thesis is based on Abdulsalam Usman Tufa's work at the Adama Science and Technology University, which carried out a numerical model study using widely used polymer-based geogrid to strengthen the road embankment. I have used a similar model and material properties in the embankment and subgrade soil layers. However, I am using basal fiber-based geosynthetic geogrid, which is nature-based material that have been not a part of a research before.

4. The Aim and objective

a. General objective

This project aims to use finite element analysis to do a numerical study of nature-based geogrid reinforced road embankments on soft soil.

b. Specific objective

- to determine deformation and settlement of embankment when reinforced with nature-based geogrid
- To explore the effects of various parameters on the performance of an embankment placed on soft soil, such as side slope, geogrid application layer and kind of geogrid, and the number of reinforcing layers.
- To try out the best possible geogrid application on the pavement

5. Scope of the Study

The study's analysis was limited to the numerical analysis of the most effective reinforcement type for the specified soil by determining embankment deformation and modifying embankment characteristics (side slope, geogrid application layer and kind of geogrid, and reinforcement layer number). PLAXIS 2D ultimate was utilized with the advanced Mohr-Coulomb model for this research.

6. Significance of the Study

This effort is expected to make significant contributions:

- First, improve knowledge of how reinforced road embankment weak soils respond.
- Develop a better understanding of the behavior of the nature-based solution
- Contribute as a source of motivation for future work.

7. Research methodology

The work was divided into the following tasks

- Literature review on how to reinforce the soft soil. This part aims to find the relevant case against which the numerical models can be compared. These include:

  Experimental studies

  Empirical studies

  Numerical studies

- Numerical modeling of the case history or model test discovered in the literature study on the general reaction of the embankment and compare exhibiting modeling results by using prior work
- Validation of material models for numerical analyses, for example, laboratory model test
- Study of crucial reinforcement parameters using developed numerical model
- Numerical analysis using geogrid, based on basalt fiber reinforced embankment, with the model's findings being checked using a prior numerical analysis model.

8. Structure of the Report

This thesis is divided into the following seven chapters:

- **Chapter 1: Introduction**

This chapter briefly introduces reinforced soil and geosynthetics and their application for stability. The objectives, scope, and significance of this thesis are stated in this chapter.

- **Chapter 2: Ground improvement techniques (Literature Review)**

  This chapter discusses the methods for ground improvement for embankments and materials used for reinforcement. Design considerations for road embankment and settlement analysis. Reinforcement mechanisms of reinforced Geogrid base reinforced pavement and numerical analysis of geosynthetic reinforced pavement

- **Chapter 3: Basalt fiber (Literature Review)**

  This chapter gives a brief introduction to basalt fibers and their background. Describing the process of Production technology of basalt fibers and various kinds of properties and their application in civil construction

- **Chapter 4: Material and methodology**

  Material parameters soil profile adopted for modeling, geogrid material.

- **Chapter 5: Analysis of the result**

  Results from the PLAXIS 2D with basalt-based geogrid. I have also compared these results concerning various slopes and nature-based and non-nature-based geogrid.

- **Chapter 6: Summary and Conclusions**

  This chapter analyzes and discusses the results from all nature-based and non-nature-based geogrid.

- **Chapter 7: Recommendations and Further Works**

Chapter 2

2. Ground improvement techniques

2.1 Introduction

The road network, which is present globally plays a significant role in representation of the nation's economy. Because the network is such an important national asset, it is essential that good design, building, and maintenance standards be permanently adhered to. Only then it will be possible to provide an adequate level of service. Furthermore, when the length of the road network continues to expand, it becomes vital to choose suitable strategies to protect this investment from maximizing its value.

While there are several options of transportation, such as roads, railways, and airways, the most common means of transport are highways and roads. In the technique of road development, the alignment of the road must be forced to be built through soils that are able to handle the traffic loads. This can be a challenging and time-consuming process. When first working on this process there is a wide variety of ground improvement methods available, such as soil stabilization, stabilizing trenches, vertical sand drains, capillary cut-off, soil nailing, Vibro-compaction, Vibro-floatation, and usage of geo-textiles, Vibro-replacement, stone columns, dynamic compaction, and many more.

2.2 Ground Improvement Techniques

Construction sites are currently inflated (increased)[8]. Engineers have no choice except use nearby soft and weak soils which is later on robusted by using modern techniques to improve the ground. Some of the ways to improve the ground are using stone columns, dynamic compaction, Vibro compaction, soil reinforcement, vertical drains, soil replacement, in-situ densification, Vibro piers, grouting pre-loadings, and stability using admixtures. All these ways share a common goal which is to make the soil stronger, improve its qualities, and stop it from sinking. To improve the ground, glass, steel, and other polymers in the form of grids or strips and geosynthetics is added to make the soil stronger. Geosynthetics can be either impermeable or permeable, depending on what they are made and how they are used.

We can find lots of research about geosynthetics, geogrid, and other geo techniques. These techniques help to improve shear strength of the soil. One of these techniques are using of piles.

Piles are often used to support structures and to fix or replace old foundations. Grouting process is a way of pumping of material into a system to make stronger foundation of soil. Compared to the old way of grouting, jet grouting is very advanced in how fast it works and is done. Rapid growth in cities and factories means more land needs to be bought. To meet this need, people have cleaned up land and used land that is not right or is bad for the environment. Using one or more ground renovation methods, these building sites that could not be used before can now be used. Techniques for making the ground better have been recognized as a field[9].

The article written by Hausmann (1990) [9] compares the results of experiments done in the lab to test the strength of reinforced soil slabs made with geogrid and geotextile. Both geogrids and geotextiles did not get stronger after adding the correct number of layers or widths of reinforcement. When it comes to geotextile, bearing capacity increases as tensile strength increases. However, when it comes to geogrid, opening sizes affect carrying capacity [9].

2.2.1 Methods for ground improvement for pavement

There are several ways to improve the ground used to build pavements. These techniques include soil stabilization, vertical drains, ditches, capillary cut-off, soil nailing, Vibro compaction, dynamic compaction, etc. Soil stabilization is a broad term which define any chemical, physical, organic, or mixed method of changing a natural soil to meet design criteria or engineering features. Upgrades include making the pavement or road surface stronger by adding in-situ sub-soils, sands, and other waste materials and increasing its weight-bearing capacity. Mechanical stabilization, additive stabilization, portland cement stabilization, lime stabilization, bitumen stabilization, geogrid stabilization, and bio-enzyme-enhanced earth stabilization are all used to stabilize soil[10].

Slope instability is a common problem on road embankments. It can lead to embankment collapses due to pavement movement, which can cause large settlements or slide due to insufficient shear strength of soil. Different types of soil, such as silty sand, clayey sand, or silty clay are all examples of common materials used for regular fill embankment. However, due to changes in the weather, the soil under pavements and different kinds of loads and activities often leads to swells or shrinks of embankment. In addition, soil movement causes pavements to settle and crack, making it hard to drive on and expensive to repair and maintain [7, 10].

2.2.2 Ground Reinforcement

Reinforcement is a process which consist of improving soil bearing capacity and shear strength of the soft soil [11]. Different kind of material has been used in this process to reinforce soil strength. Reinforced material is strong in both tension and compression. In theory, it is similar to reinforced cement concrete. It can be done by putting continuous reinforcements (like strips, bars, sheets, mats, or nets) in a specific pattern inside a soil mass or mixing random fibers into a soil fill before installation. The first type is called "randomly distributed/oriented fiber-reinforced soil" or "fiber-reinforced soil." This is called "randomly distributed/oriented fiber-reinforced soil" or "fiber-reinforced soil" [11].

The reinforced soil mechanism seems to be easy to use and coinvent regarding price and time. It has made a big hit in geotechnical and transportation engineering for both temporary and permanent constructions. In geotechnical structures like retaining walls, soil slopes, bridge abutments, foundation rafts, and embankments, the main job of reinforcement is to resist tensile loads or keep the structure from deforming too much. The reinforcement functions as a tensile member bonded to the soil or filled material by friction, adhesion, interlocking, or confinement. This technique makes the soil mass more stable [11].

Soil is designed to have low tensile strength and high compressive strength. The goal of adding soil reinforcement is to help the structure handle tensile loads or shear stresses. Shear or too much distortion can cause designs that do not have reinforcement. When an axial load is put on soil that has been reinforced, axial compressive and lateral tensile strains are made. If the reinforcement has a higher axial tensile stiffness than the soil, the earth will only move if it can move relative to the reinforcement. When the ground moves relative to the reinforcement, shear stresses are made at the interface between the soil and the reinforcement. These shear stresses are redistributed back into the soil as internal confining stress. For the same amount of stress, this means that the strain in the reinforced soil mass is less than the strain in the unreinforced soil mass, as long as the surface of the reinforcement is tough enough to stop relative movement and the axial tensile stiffness of the support is higher than that of the soil [11].

2.2.2.1 Soil reinforcement interaction

For soil reinforcement to work, different kind of material are used which cooperate together to release stresses that would cause failure and now is been absorbed. In this case, a break in the reinforcement or a loss of the link between the soil and the reinforcement could cause the structure to fall apart because the ground and reinforcement interact. A Limit state happens in serviceability when the amount of deformation is greater than the acceptable limit or when the amount of strain in the reinforcement exceeds the specified limit. If the soil does not stick together well, the bond resistance is friction based on the roughness of the surface and the ground. If the earth sticks together, the bond stress will be adhesive. The bond stress is based on the soil's shear strength and how rough the reinforcement is when grid reinforcement is used. After taking on a load, the reinforcement must keep that load for the rest of its design life without breaking or deforming in a way that depends on time and could cause a serviceability limit. Flexible reinforcing is put horizontally to match the primary tensile strain and get the most out of the tensile load capacity. The reinforcement takes up axial forces that are determined by statics [12].

2.2.2.2 Materials used for reinforcement

Most modern civil engineering projects use geosynthetic sheets or strips of galvanized steel as reinforcement. These are usually placed horizontally or in the directions where the soil is subject to unwanted tensile strains [13].

Ultra-high modulus polyethylene, glass fibers, and carbon fibers are three ways that have been looked into to improve material properties. Composite materials have been around since the middle of the 20th century. Today, they are one of the most researched topics in technology. Because of their valuable properties can be used in a wide range of industries, such as sports, aerospace, construction, automotive, biomedical, and many more. These materials have great structural and mechanical qualities, such as a high strength-to-weight ratio, chemical resistance, fire resistance, wear resistance, and corrosion resistance. They are also inexpensive to make [14].

Timber is a nature-based material that can be found in large amounts and is easy to use in the countryside of developing countries. Bamboo grows mainly in tropical and subtropical areas, from sea level to the tops of snow-covered mountains. A few species can also be found in temperate regions. Most of the time, bamboo is used in the building and housing industries. People all over the world live in homes made of bamboo. Since ancient times, this material has been used to build things, and it is still used today. Structural elements include supports, frames, floors, walls, scaffolding, roofs, foundations, and trusses. The grid is made stronger by tying bamboo stalks together. Using grid reinforcement and putting it in soft clay can fix problems with embankments that are getting out of shape[15].

2.2.2.3 Geosynthetics

Traditional ways of building infrastructure release a lot of carbon dioxide into the air, making the carbon footprint bigger. Engineers are critical to planning, building, designing, maintaining, and improving structures, facilities, and other infrastructure for sustainable development, such as transportation and energy systems. To reach sustainable goals, they must develop new or alternative building materials, waste from different operations, and sustainable building processes and techniques [16].

Geosynthetics is a general term for a wide range of products, such as geogrids, geonets, geocells, geotextiles, geofoams, geomembranes, and geocomposites. Geosynthetics are made of several polymers, which are plastics that we use every day. The most common materials are polyolefin and polyester, but rubber, fiberglass, and nature-based materials are also used. Geosynthetics can be used as separators, filters, planar drains, reinforcement, cushions or protection, and liquid and gas barriers [17].

The functions of the geosynthetics are following:

I. It functions as a barrier to resist the migration of materials like liquids or gases.

II. They're utilized as containment to keep dirt or sediments in a precise shape and prevent them from escaping. The confined fill assumes the form of the geosynthetic container's inflated at-rest geometry.

III. Geosynthetics can also be used as drainage layers to collect and transport fluids.

IV. Filter layers enable fluids to flow through the soil while limiting uncontrolled soil particle passages.

V. As a limited stress reduction layer, protection layers prevent or decrease damage to a specific surface or layer.

VI. Reinforcement in geotechnical constructions to avoid stresses or deformation.

VII. Partition layer for preventing intermixing of two distinct geotechnical materials.

VIII. Surficial erosion controller, designed to reduce soil particle surface erosion caused by surface water run-off and wind pressures.

IX. A frictional interlayer is a layer added to an interface to increase or decrease friction across it.

Geogrids look like open grids, which means they have big holes and are almost always used to strengthen the soil [17]. Geogrids are often used to strengthen retaining walls, sub-bases, and sub-soils under roads and buildings. Geogrid is also a type of geosynthetic made up of a regular network of connected parts. It has holes bigger than 6.35 mm (1/4 inch) to connect with the soil, rock, earth, and other materials around them for primary reinforcement. Geogrids are materials that look like a matrix and have large open spaces called apertures. The longitudinal and lateral rib spaces are usually 10 to 100 mm. The ribs themselves can be made of different materials, and there are various ways to join or bond ribs that cross over each other. The main job of geogrids is to strengthen structures.

2.2.2.5 Effect of geogrid properties

The main requirements for reinforcing materials are strength and stability (low potential to creep), durability, ease of handling, a high coefficient of friction and soil adhesion, and low cost and immediate availability [18]. Before a fabric can be used in a building, its features and qualities must be suitable. The main things that affect how well geogrids work are their physical properties, mechanical properties, and how long they last. Many of the physical properties of geogrids, such as their weight (mass), type of construction, rib size, type of connection, aperture size and thickness, can be easily and directly measured. Mass per unit area, which can be anywhere from 200 to 1000 g/m^2 and percent open space, which can be anywhere from 40% to 95%, are also important [18].

Some of the mechanical properties of geogrids are stiffness, peak tensile strength, modulus of elasticity, upper yield strength, lower yield strength, tensile strength, non-proportional extension strength, total extension strength, fracture elongation, elongation at maximum load and total elongation. Geogrids are used to build roads and reinforce slopes. Their strength ranges from 20 to 250 kN/m. There are two different kinds of geogrids. Geogrids are usually high-density polyethylene and have a single mesh (HDPE). Most flexible geogrids are polyethylene terephthalate (PET) and have a PVC or acrylic coating. The longitudinal and transverse pieces are mechanically connected. Geogrids are very useful as soil and aggregate reinforcement because they are stiff and have high tensile strength [18].

2.3 Road Embankment

Embankments are an essential part of every road and train track. It must hold up the road pavement or railway structure and spread the forces across the subsurface without showing too much deformation [19]. When building an embankment, you have to think about many different things about the building materials and the ground underneath. How well the road pavement or railroad construction on top works depends on how stable the embankment is. Since the embankment is made of soil, it is an important building material in road and railway engineering [18],[19].

Several things affect how stable the embankment is, for example traffic load, dead load, type of soil, weather, water etc. Some of these factors are naturally considered when building the road pavement or the railroad. While harm from other factors can be lessened with a strong structure and good road or railway construction. For example, settlements are possible when a embankment is built over soft soil surface. The size of these settlements is determined by the amount of loading or the deadweight of the embankment and the way the subsoil moves. Because both the amount of stress and the way the subsoil deforms are usually different, the way subgrade soil deformation is often the same.

Settlements happen when poor quality of soil has been used in the process of embankment. The grain structure of the subsurface must be able to support the increased deadweight load of the embankment as well as the usual stresses and shear stresses that form where the grains touch each other. When shear forces are too strong, the grain skeleton reorients, which reduces the size of the pores and increases the number of points where grains touch each other to become tougher. This brings the material back to a state of equilibrium. When the number of pores in the subsurface goes down, settlements happen. These are the main places where people live. In addition to the main settlement, there is also a secondary settlement on the ground. These secondary settlements are caused by the grains' movement, which is caused by the extra weight of the embankment.

2.3.1 Embankment on soft ground

Horizontal earth forces act on the embankment from the inside which causes embankments on the soft ground tend to get wider [20]. These earth pressures cause horizontal shear strains at the base of the embankment. These strains must be stopped by the shear strengths of the foundation soils. Soils that are too soft do not have enough shear strength, which can cause them to break. Because of this, embankments on soft soils should be built so that the stress does not go up too much. This means that the embankments should be shallow. Most embankment fills are more robust and stiffer than foundations built on soft ground. This makes it more likely that embankment will bend when its foundation gives way under its weight. It also makes it more likely that the embankment will slowly fall apart because the stress and strain of the embankment and its foundation do not match up. Reason for this is the maximum strengths of the embankment soils and the foundation soils do not come together simultaneously. Stability calculations are based on peak soil strengths of the overestimated safety factors [20].

When building embankments on soft ground, the stability and settlement of the fill material must be carefully looked for. Because it is hard to get samples of these soils without disturbing them for testing in a lab. Vane shear apparatus must be used to test some very soft and highly organic materials where they are. The groundwater level should also be measured, and its changes should be kept an eye on. It is important to focus on the stability of the interface between the embankment and the foundation, not only on the soils of the embankment or the foundation. Before building the embankment, it might be good to remove the soft layer underneath and replace it with something that does not hold water [21].

2.4 Road embankment design considerations

The stability and settlement characteristics of the foundation soils and the bearing capacity at the base are the most critical geotechnical challenges [22]. These issues and how they affect building phases should also be considered during the design process. If the extra stress from traffic loads and road construction does not go over the soil's shear strength, embankments can support highways. If the embankment is overworked, the slope could break. Concerns about the stability of the side slopes must be taken into account, and any possible settlement problems. Short-term settlement can be caused by putting more pressure on the soil under the embankment (bearing failure during fill placement), while long-term accommodation can be caused by consolidation.

The main design concern is whether or not the existing foundation soil can support the increased embankment loads without the bearings failing or the embankment sinking too much. When there are soft, sticky soils under the embankment, these qualities makes the situation even more critical. It may be necessary to think about staged construction, in which the embankment is built in stages, and extra pore water pressure is let out over time before the next lift is produced. At the beginning of the building process, sometimes trial embankments are constructed to test assumptions made during the design process [23].

Seismic loading is a type of load that can happen in embankments. Most places do not see this kind of load often, but it could be imperative. During the design earthquake, the most crucial geotechnical issue is the risk of liquefaction in the foundation soils under the bearing failures, side slope collapses, and post-liquefaction settling are all possible consequences liquefaction. One thing to think about when designing is how a side slope could fail without liquefying. Even though pore-water pressures can change after an earthquake, leading to liquefaction-related failures that can happen many minutes after the main quake. The period of loading during a seismic event is usually short [22].

Most embankments do not need a complete geotechnical study and analysis if they are less than 5 m high and have a slope of less than 1.5H:1V. These embankments can be chosen based on what has been done in the area before and what engineers think is the best. Also, embankments that are more than 5 meters high or that are built on the soft ground almost always need a complete geotechnical analysis.

2.4.1 Settlement analysis

Settlement is the vertical displacement when a load is applied, or an embankment is built over compressible soils [22]. The settlement could be caused by the consolidation of the embankment and the grounds below. The total settlement of an embankment is caused by three things: the immediate settling of the fill or foundation soil, the primary consolidation of the foundation soil, and the secondary compression of the foundation soil skeleton, which is controlled by its composition and structure. The settling that happens when the foundation soil shifts laterally at the edges of the embankment is not taken into account [22].

The fill soil and foundation soil, settle right away during construction, but this usually does not affect the final pavement. So, the focus of the settlement study for embankment design is on the primary consolidation and secondary compression of the foundation soil. The main problems with settlement in embankment design are direct consolidation and secondary reduction, which can go on for a long time after the embankment is done (after construction settlement). Settling after construction can often damage buildings inside the embankment. This is especially true if these buildings are also supported by soils nearby that do not settle as much, causing different levels of settlement. In addition, differential settlements along the longitudinal axis of the embankment could cause transverse cracking on the surface due to differences in how well the clays beneath the embankment hold together [22].

2.4.1.1Primary consolidation

Primary consolidation is the settling caused by the readjustment of soil particles caused by water migration out of cavities. The soil's initial void ratio determines the quantity of direct consolidation [24]. The initial void ratio is higher if more water can be squeezed out, and the primary consolidation is more enormous. How fast direct consolidation happens depends on how fast water is pushed out of soil voids. How foundation soils react to loads depends on how they were stressed in the past. Settlement happens when the weight of the embankment is more than what the ground has been emphasized in the past [24].

Depending on how big the adequate current pressure is compared to the highest previous effective stress at a certain depth, foundation soils can be consolidated, over-consolidated, or under-consolidated. When the current load is the same as the historical load, the earth is said to be well-compacted. In soils that have been compacted too much, the pre-compaction pressure is higher than the current vertical effective stress. Soils are called "under-consolidated" if they continue to settle under the load they already have and continue to do so until "primary consolidation" is reached, even if no extra load is added [24].

The first step in figuring out settlement is to separate the soil profile into layers. Each layer shows how the properties of the soil change. Because the settlement calculations are based on the stress conditions in the middle of a layer, thick layers with similar qualities are also broken up to make the analysis better (i.e., it is preferable to evaluate a 6 m thick layer as two 3 m thick layers). The total settlement is the sum of how much each of the layers that can be compressed has moved. If buildings are supported by soils nearby that do not settle as much often cause damage to buildings inside the embankment. This is called "*differential settlement*". Differential settlements along the longitudinal axis of the embankment could cause transverse cracking on the surface due to differences in how well the clays beneath the embankment hold together [24].

2.4.1.2 Secondary compression

The amount of compression that develops during the required time for excess pore-water pressure to decrease due to increased effective stress is called the end of primary consolidation [24]. When the soil continues to settle after the excess pore water pressures have been reduced to a negligible level, which means that direct consolidation has been done. Secondary compression, primary settlement can take years, and secondary compression can take decades to finish. Secondary reduction happens no matter how much stress there is, and in theory, it is just a function of time and the second compression index [24].

Just like it does for figuring out the amount of initial consolidation, the literature gives detailed numerical procedures for figuring out the amount of secondary compression. Most of the time, the contributions from the different soil layers are added together to figure out how much the whole area has settled. Surcharging to cause settlement before it happens is often only partially effective at reducing the effects of secondary compression. This is because secondary reduction has nothing to do with the amount of stress in the soil but instead with how the soil breaks down over time. If a cost-benefit analysis shows that ways to fix the problem, like using lightweight fill or over-digging, are too expensive, the owner may have to deal with the risks and costs of secondary compression [24].

2.4.2 Stability of road embankment

In construction activity, ground excavation and land reclamation both are equally important. In addition, the embankment must bear the structure to ensure the construction structure is safe [25]. Most of the time, the stability of a road embankment is essential because of the process of consolidation that happens during and after building. Surveys show that settlement, geotechnical parameters, slope stability, and seismic activity all affect the strength of an embankment. Even though building embankments is the oldest technology, the engineering challenges in the design process are complex, especially when it comes to estimating settlement. It is shown in figure 2.1, failure and stability mechanism of embankment [25].

When designing embankments, you should think about more than just settlement. You should also think about side slope stability and bearing capacity. When the embankment is built on soft soils like silts and clays with low strength or when the foundation soil is overstressed during or right after construction, rotational or sliding block failures are most likely to happen. Loss can occur if the fill materials are not packed to the correct specifications. Also, failures could occur if the fill materials at the toe of the embankment erode. Dynamic forces like earthquakes, blasting, or pile driving can also cause embankment slopes to fail. Most of the time, short-term stability is more important than long-term stability for embankments on cohesive soil. This is because the foundation soil will gain shear strenght [26].

The following are examples of how an embankment slope can fail:
Rotational slip failure happens when the properties and strengths of the layer underneath are very different. For example, circular slips happen when the soil is homogeneous and isotropic. However, when the soil is not homogeneous, non-circular mistakes happen. Failures of embankments constructed over relatively deep deposits of soft soils have generally shown that the embankment lowers, the ground around it rises, and the failure surface follows a circular arc. Failures can happen in the base circle, the toe circle, or the slope circle. A base slip circle forms when there is a sizeable unstable foundation soil. The base of the failure arc is parallel to the floor of the weak layer, and the failure arc will spend a lot of time in the soft soil. A slip circle forms inside the bank and meets the slope at the toe of the embankment. A toe slip circle forms and meets. Sometimes this happens when the material on the bank gets wet and gives way [26].

The following are the driving and resisting forces at failure:

- The weight of the slope is what moves happen. The driving moment is equal to the importance of the embankment acting through its center of gravity multiplied by the horizontal distance between the center of gravity and the center of rotation.
- The total shear strength operating along the slip plane is the resisting force. The resisting moment is equal to the product of the resisting force and the circle radius (LS) [27].

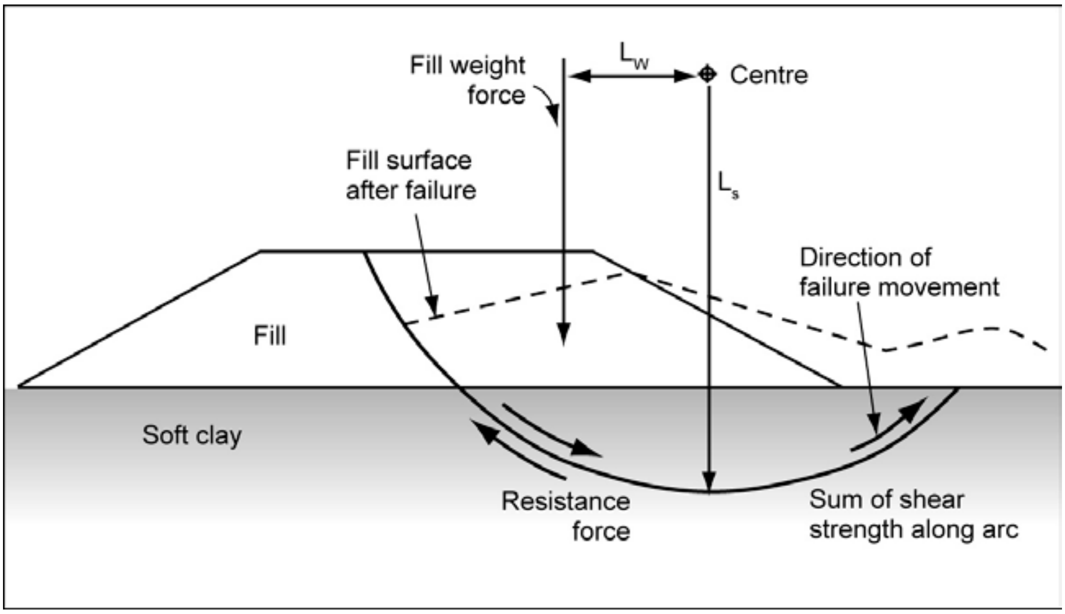

Figure 2. 1: embankment stability and failure mechanism [ERA's Geotechnical design]

A minimum design safety factor of 1.3 calculated using the standard method of slicing is enough to keep the side slopes of any road embankment stable over time. The minimum safety factor for slopes that support or could damage structures that are not critical should be 1.3. The design safety factor should be increased by 1.3 and 1.5 for slopes near bridge abutments, important retaining structures, and major highways that would cause more damage if they failed. All bridge approach embankments and those that hold up important structures should have a safety factor of 1.5. The most important structures are the ones that, if they fell, would hurt other things. For example, if benches are put on an embankment, they must be at least 1.5 meters wide and no more than 6 meters apart vertically. If there are springs or seepages along the embankment, drains should be placed to collect the water[27]. The finite element method using PLAXIS 2D can measure the road embankment's stability analysis.

Mainly three types of sequence modeling are used.

- The stability of road embankment without any reinforcement.
- Determination of the length of geogrid reinforcement considering the stability of the model road embankment.
- Investigation of the stability of model reinforced embankment with different tensile strengths of geogrid reinforcement [28].

2.4.2.1 Base reinforcement

Researchers have done a lot of lab work to figure out how soil and geosynthetics work together. They found that geosynthetic reinforcement improves flexible pavement performance by making it last longer or thinner than the base course[29]. Over soft soils, geogrids stabilize the ground and strengthen the base. They are usually called triaxial and biaxial geogrid. They are used in constructing roads and parking lots to make pavements stronger in many directions and last longer. Geogrid aggregate interlock is the primary way that unbound aggregate, base, and subbase layers of flexible pavements are made stronger by geogrids. Geogrids keep aggregate material from moving side to side when wheels are driven over it. This causes the local strength and stiffness of the base layer better[30]. There are many different shapes and sizes of geosynthetics. When used alone or together, weak subgrades are more robust and stable. Due to their strength, resistance to stretching, and structure, they can stop the base materials they touch from moving side to side. They can also be used as a layer between the subgrade soils and the aggregate base to keep them from mixing. Using geosynthetics in construction makes the building work better and last longer, which saves money in the long run.

The base reinforcement can be built to be used either temporarily or permanently. Most base reinforcement applications are temporary, meaning that they are only needed until the shear strength of the soil below the embankment has improved enough because of the weight of the embankment. When designing a reinforced slope or a base reinforcement, the same limit equilibrium slope stability methods are used to determine how much strength is needed to reach the desired safety factor. Base reinforcement materials should be put together in long strips that run in the same direction as the primary reinforcement. Geogrid should not have any joints in the strength direction perpendicular to the slope. Instead of lapped seams, geotextiles should have seams that are sewn. Geogrids should also be connected with pins instead of just being laid on top of each other. When the foundation needs to be strengthened, gravel borrow areas may be a better choice than earth materials to make the embankment stronger.

2.5 Geogrid Reinforced Bases in Flexible Pavements

Pavement structures are made to hold up and safely distribute the weight of traffic vehicles to the soil below. A traditional flexible pavement comprises a subgrade layer, an asphalt (AC) surface layer, and a granular base course layer. Pavement design methods try to find the best combination of AC and base layer thicknesses and materials in terms of cost, considering the quality of the subgrade and the traffic loads that will be carried over the life of the road[31].

Under static stress, adding the geogrid reinforcing layer(s) made the base course materials stronger and stiffer. At higher levels of strain, the benefit was more straightforward. Also, the results showed that the geogrid significantly reduced the permanent deformation of the base course materials under cyclic loading but had no effect on their resilient deformation. During the first stage after compaction, when stress levels were lower than the plastic shakedown stress limit, the geogrid didn not add much to the soil's resistance to permanent deformation. However, during the second stage, it made a big difference. The results also showed that changing the moisture level in the foundation material changed how stressed it was, which significantly affected how well the geogrid improved[32]. The main job of a base layer is to give the asphalt layer a stable place to be built on and reduce the amount of stress in the asphalt layer caused by compression and tension. The foundation layer should be able to spread out the pressures that the weight of traffic puts on the surface of the pavement. These strains must be kept in check to keep the subgrade soil from getting too stressed. It illustrates in figure 2.2[32].

If the base course layer is not strong enough to support the upper layers or is not stiff enough, it might not transfer the load evenly to the subgrade, which can cause localized subgrade overloading and deep pavement. When these kinds of pavement problems happen, the whole pavement needs to be rebuilt instead of just the surface. When building a pavement on a weak subgrade soil layer, it may be necessary to increase the thickness of the foundation layers or use good quality base course material. On the other hand, high-quality aggregates are being used quickly because roadway networks are getting more and more traffic. Also, there are usually limits on how thick the pavement structures can be. Because of these problems, researchers are looking for ways to improve the way roads are built and fixed. Geogrid reinforcement in the base course layer is one way to do this[33].

The usage of geogrids for carriageway strengthening dates back to the 1970s. Since then, geogrid reinforcement has become more popular, and numerous studies have been conducted to understand better how geogrid reinforcement behaves in roadway applications. [34] The results of numerical studies reported in literature showed that geogrid reinforcement in pavement structures could extend the pavement‟s service life, reduce base course thickness for given service life, delay rutting development, and help construct pavements over soft subgrades. [35] [36].

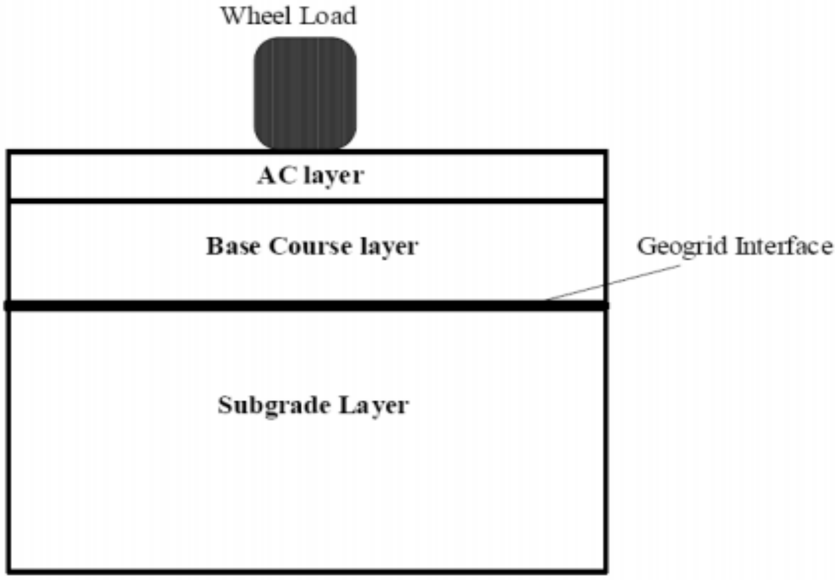

Figure 2. 2: section layout of geogrid reinforced base in flexible pavement [37]

The Traffic Benefit Ratio (TBR), which is the number of load cycles needed to create a certain depth of rut in a reinforced section compared to an unreinforced quarter with the same thickness, material properties, and loading characteristics, is often used to measure the increase in the service life of a pavement structure. The Base Course Reduction (BCR) factor is often used to measure the reduction in base thickness. It is defined as the ratio of reinforced base thickness to the unreinforced base thickness of the same performance under a particular traffic load level. The geosynthetic material gives the pavement segment structural support by changing how the pavement responds to loads. [38]. Geogrid reinforcement resulted in an equal load distribution by spreading the load over a broader area and reducing rut depth at the asphalt course's surface [39].

The degree of improvement in pavement performance achieved by inserting geogrid in the base layer is dependent on several criteria, including the strength of the subgrade, geogrid qualities, geogrid location in the pavement, base layer thickness, and so on. [40]. According to previous research, when employed as a reinforced member, geogrids outperform geogrid. As a result, geogrids will be the sole reinforcement in this dissertation's investigation of reinforced bases in flexible pavements [41] [42].

2.5.1. Reinforcement Mechanisms of Reinforced Geogrid Base Reinforced Pavement

The reinforcement processes in geogrid base pavement sections are lateral restraint, enhanced bearing capacity, and the tension membrane effect.

2.5.1.1 Lateral Confinement Mechanism

The lateral constraint is the ability of the geogrid to keep aggregate particles in the plane of the grid. Once the aggregate goes through the holes in the geogrid, it can not move as much. As a result, the layer of stabilized aggregate is made stiffer. The first lesson The primary way to strengthen paved roads is through lateral restraint. Vertical loads on the highway surface cause the base course to move from side to side. Tensile lateral strains are made in the base as the material moves down and away from the load. The ground can not get from move side to side because the geosynthetic holds it in place. "Lateral restraint" is several ways to make something more vital., including:

- i *Lateral movement of base aggregate restraint [43]*
- ii *Increased stiffness of the base course aggregate layer [44]*
- iii *Reduced shear stress in the subgrade soil*
- iv *Improved vertical stress distribution.*

Fiber-reinforced plastic (FRP) composites can be wrapped in a spiral pattern on the surface of the concrete to increase its compressive strength and ultimate strain (pseudo-ductility). It could also stop longitudinal steel from bending and provide a way to resist shear. Buckling reinforcement Because of lateral confinement, concrete members are held in place on both sides. People think that technology that helps strengthen and fix things will make a difference in the future. Renovating and fixing up buildings and infrastructure Buildings that have been damaged, need to meet new code requirements, or are being used for the key aims can be used in various ways, from light to heavy [45]. The component stiffness approach is a way to determine how much force is needed to hold a Z-section roof on the side. A bay of Z-sections is thought of as a system with one degree of freedom. The stiffness formulation is used to figure out how much the different parts of the system contribute to the resistance to sideways movement. The roof system creates forces that need to be stopped. These forces come from the science of mechanics. It describes in figure 2.3

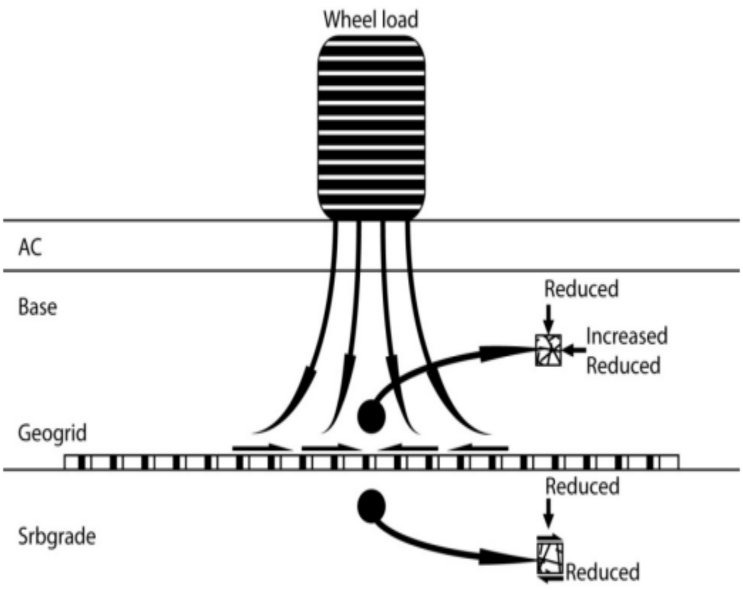

Figure 2. 3:schematic illustration of lateral restraint mechanism [46]

2.5.1.2 Increase of the Bearing Capacity Mechanism

The carrying capacity of soil varies depending on the soil's mechanical qualities and structural stability [47]. Most geotechnical engineering projects use different soil mechanics tests, which must be interpreted before using them. Because soils interact mechanically, it is hard to predict how much they can hold. But to make construction projects safer, the results of soil tests and design must be correctly interpreted and used in a geotechnical engineering project. The pavement system's failure envelope is moved from the weaker subgrade to the more robust base layer. This gives the pavement a better ability to support the weight. So, the subgrade bearing failure model may change from punching failure with no reinforcement to general failure with ideal reinforcement. It describes in figure 2.4[47].

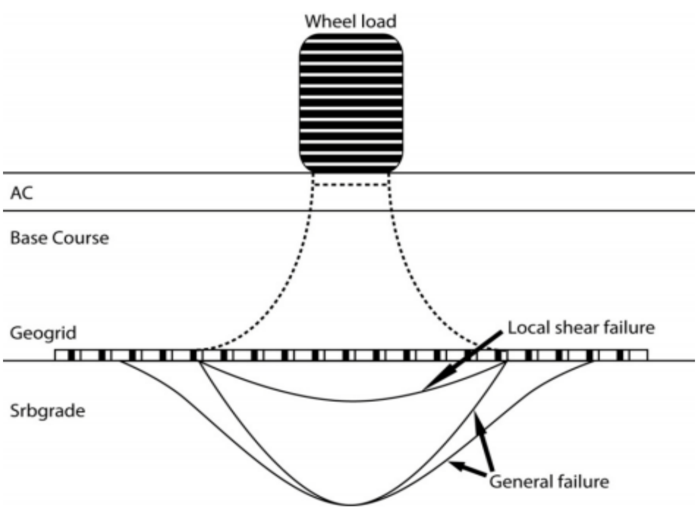

Figure 2. 4: schematic illustration of improved bearing capacity [46]

2.5.1.3 Tension Membrane Mechanism

The tension membrane effect occurs when vertical distortion in the tensioned geogrid layer creates a concave shape. [48] The good part of the tension membrane force can lower the vertical stress on the subgrade. To use the tension membrane effect, there must be some movement. As the stiffness of the geogrid goes down, the tensile membrane resistance needs to be moved by a more considerable deformation. The geosynthetic must have a deep rut and stiff to make the membrane effect work and increase the subgrade's ability to hold weight.[49] For this type of reinforcement mode to be significant, there is a consensus that the subgrade CBR should be less than 3 [50]. It is process shown in figure 2.5.

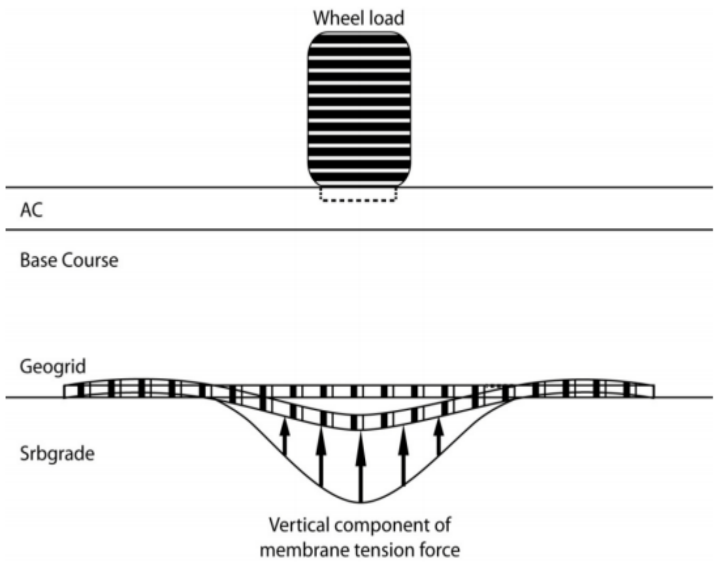

table 2. 1:schematic illustration of tension mechanism [46]

2.6 Numerical Analyses of Geosynthetic Reinforced Pavement

Several numerical analyses were done to look at pavement sections and determine how helpful geosynthetic reinforcement would be. For most numerical studies, the finite element method was used. Comparing different constitutive models helped find the best one for describing the stresses and changes in a reinforced pavement. Traditional plasticity models with isotropic hardening rules can predict permanent strain during a single load cycle. However, when stress is applied repeatedly at the same level as during the first load cycle, the result is just elastic behavior with no permanent strain accumulation. Therefore, plasticity-based material models with kinematic hardening principles must be used to predict how permanent strain will build up in pavement layers when traffic loads are put on them repeatedly[51].

Most assessments of flexible pavements assume that the materials in the pavement behave like linear elastic materials. On the other hand, materials used for pavement do not act like linear elastic materials. They can be better modeled by using elastic-plastic relationships. The growth of permanent surface deformation can be better predicted using plasticity models with kinematic hardening criteria. This plasticity model has been around since the 1970s ([51]), but it was recently applied to pavement modeling[52]). Developed and compared a bounding surface plasticity model to the results of repeated load triaxial tests.

The idea of a bounding surface is very general, so it can include any kind of formula for a yield surface, which is then used to describe the procedure for the bounding surface.

Finite element methods are often used to solve structural, hydrodynamic, and multiphysics problems numerically. Because engineers use the methods often, they are used by many people. Scientists can use math and numbers to solve challenging problems by simulating them. Engineering evaluations are done to judge designs, and most scientific analyses are done to understand natural phenomena and, if possible can predict them. It is beneficial to predict how a plan will work and if and when a natural event will happen. It is possible to make designs that are both safer and less expensive. For example, it might be helpful to understand and predict nature. For example, to avoid bad things. The three finite element programs with the most impact were ASKA, NASTRAN, and SAP (7–9). Both NASTRAN and ASKA quickly became more critical. In the aerospace and automotive industries, analysis tools are used. SAP software was widely utilized in the civil and mechanical engineering industries and universities. [53]

A finite element model for the response of geogrid reinforced flexible pavements was developed by Kwon et al [52]). According to the results of this study, the benefits of putting geogrids at the interface between the granular base and the subgrade can be estimated by looking at the concentrations of residual stresses right above the geogrid reinforcement. These residual stresses significantly increased the expected resilient moduli in the base and subgrade of a modeled pavement section. The study also found that when residual stress concentrations were given near the geogrid, low subgrade vertical strains were expected to have a lower subgrade rutting potential[54].

Wathugala et al. developed a finite element model for pavements with geogrid reinforced bases using a limited element software package. The analyses' findings were compared to unreinforced pavement sections of similar geometry and material parameters. According to the comparisons, geogrid reinforcement reduced permanent deformations (rutting) by 20% for a single load cycle. This improvement was due to the geosynthetics' flexural rigidity, produced by the authors' model presentation [54, 55]. Nazzal et al. used the PLAXIS 2D software package to create a finite-element model to study the influence of geosynthetic reinforcement in the base course layer on the response of a flexible pavement system. Different unreinforced and geosynthetic reinforced flexible pavement sections were subjected to finite-element analysis. This study showed that the modified critical state two-surface constitutive model could accurately predict the response of the examined base course material when subjected to cyclic and static loads at its optimal field conditions.

According to the results of the finite-element studies, the geosynthetic reinforcement reduced lateral strains inside the base course and subgrade layers. Furthermore, the addition of the geosynthetic layer reduced vertical, and shear stresses at the top of the subgrade layer significantly. The geosynthetic layer's improvement was more evident in the growth of plastic strains than in the development of resilient strains. As the material's elastic modulus increased, so did the benefits of reinforcement.

Another researcher Dondi conducted a three-dimensional finite element analysis on geosynthetic-reinforced pavements using a finite element-based software suite. The usage of the reinforcement improved the carrying capacity of the subgrade layer and reduced the shear loads and strains on top of it, according to the findings of this study. In addition, due to the introduction of geosynthetic reinforcement, vertical displacements (rutting) were decreased by 15 to 20%. The longevity of the reinforced parts was estimated to be improved by a factor of 2 to 2.5 compared to the unreinforced sections using an empirical power expression [42].

Barksdale used finite element analysis to show that raising the stiffness of the reinforcement enhanced the bearing capacity ratio value. The magnitude of the bearing capacity ratio was reduced by increasing the thickness of the AC or base course layers. The best location for the reinforcement was between the bottom of the base course layer and 1/3 into the base layer. To study the performance of reinforced unpaved pavement sections, [56] Leng and Gabr used FE software to conduct a numerical analysis. The version of the generated finite element model of the geosynthetic reinforced pavements by Leng and Gabr was validated using their earlier experimental data (2002) [56].

The researchers found that as the modulus ratio of the aggregate layer to the subgrade fell, the reinforced section's performance improved. Higher modulus geogrid or better soil/aggregate-geogrid interface property significantly lowered critical pavement responses. On reinforced and unreinforced pavement sections[57]) Miura et al. did a finite element analysis. They compared the finite element analysis results to experimental measurements taken on similar parts. The results showed that the finite element analysis prediction did not match the behavior observed in the tests. The expected reduction in surface displacements was 5%, whereas the actual displacement reduction followed by the testing was 35% [57].

Chapter 3

3. Basalt Material

3.1 Introduction

The development of landslides for highway building is continually growing nowadays the shrinking amount of available land, the activation of existing landslides, and the formation of new ones[58]. The stabilization of slopes prevents the activation of already occurring landslides and the formation of new ones. When slopes are fortified, soil erosion processes stabilize, and the likelihood of their being destroyed by their weight or sliding due to inertia forces decreases. In other words, weak soil is transformed into a stable and long-lasting material when this occurs. When deciding on a material for slope reinforcement, a few different elements, including the steepness of the slope, the loading, the presence or absence of vibration, and the composition of the soil, should be considered [58]

Slopes are reinforced using a variety of ways, including retaining walls and other volumetric structures. However, using goods constructed of geosynthetic materials is the most successful way thus far.[59] A wide variety of products, including geo-grates, geogrids, geo-composites, and geo-mats, are used to produce geosynthetic materials. The earthen bed makes up most of the roadway. The sturdiness and longevity of each of the layers of road covering described above are directly related to the functionality of those layers. When selecting a material for strengthening the slopes of the embankment, it is vital to examine the influence that the material will have on the durability of the slope and guarantee that the overall road construction will be reliable. The necessity to strengthen the roadbed and embankment slopes is decided by adequate calculations and choosing an ideal kind of geosynthetic material, considering the qualities of soil and local circumstances. This will guarantee that the embankment is stable and durable with low financial expenditures[5]. Using the BV-I geo-mat, which is constructed of continuous basalt fiber, is the choice that makes the most sense. This study examines the various techniques currently used to reinforce the slopes of embankments, justifies geogrid constructed from basalt fiber to strengthen the slopes of embankments and determines the optimal placement for the layer inside the embankment body [59].

Although various fibers may be utilized for structural purposes, glass, carbon, and aramid compounds are the most common. Vegetable fibers (based on cotton, hemp, jute, and flax, for example), wood fibers (usually distinct from vegetable fibers), and mineral fibers may be mentioned.[60, 61] Furthermore, because of the excellent physio-chemical characteristics that may be attained, the utilization of fibers formed by molten basalt rock has attracted growing attention in recent years.[62, 63] In point of fact, basalt fibers display strong strength and stiffness capabilities even at high temperatures, long-term durability, high acid and solvent resistance, low water absorption, excellent heat and sound insulation properties, good processability, and their manufacturing process is often much less expensive than that of carbon and glass fibers.[63, 64]

Basalt is also a high-performance green inorganic material with a well-defined chemical and mineralogical composition, non-toxic interactions with air or water, non-combustible, explosion-proof, and high degrees of eco-compatibility and recyclability. [65] In contrast to other forms of fibers such as glass and carbon, basalt fibers and composite materials generated from them may be preserved to have a beneficial connection between quality and prices. For civil applications, a large selection of goods is also available. Basalt fibers realize new construction materials are employed. These materials are described as the proper mixing of a concrete matrix with short (staple) or cut (chopped) basalt fibers to improve the material's strength-to-weight ratio.[66, 67] Asbestos is being replaced in practically all of its uses by fiber-basalt-based composites. High-strength roving's for pultruded load-bearing sections and concrete-reinforcing bars; woven textiles for heat/sound insulation and fire protection; geogrids for road and land reinforcement; stucco nets for wall reinforcing and repair are all made using basalt filaments and fibers.[66]

3.1.1Basalt fibers Background

The term "basalt" comes from the Late Latin word "basalts," which is a misspelling of the Latin word "basanites," which means "tough stone." The term "basalt" was brought to Latin from Ancient Greek, while the term "bauhun" was first used in Egypt (namely, slate). The contemporary petrological word "basalt," which describes a specific composition of the lava-derived rock, stems from its introduction by Georgius Agricola in 1556 in his book of mining and mineralogy entitled "De re Metallica. Agricola called the volcanic black and hard rock of the Schloßberg (local castle hill) in Stolpen "basalt" in this book [68]. The most common igneous rock, basalt, is a mafic extrusive rock that is black. It is also the most common type of volcanic rock, accounting for more than 90 percent of all volcanic rocks [68].

When the rate of solidification of molten lava is high, an amorphous (uncrystallized) structure forms, as opposed to a basalt structure that displays an essentially regular atomic arrangement when the rate is low. Basalt has been used in architectural casting procedures to create tiles and slabs for many years. Basalt is used in industrial applications to make cast basalt liners for steel tubes because of its strong abrasion resistance. Basalt is used as aggregate in concrete when crushed. Furthermore, basalt has emerged as a feasible and competitive material for producing the reinforcing phase, primarily as fibers, in composite materials in the previous decade.[63, 64] The earliest efforts to extrude basalt rock into fibers were ascribed to the French Paul Dhè in the early 1920s, and a US Patent was awarded in 1922 [34].

Around 1960, the Soviet Union (USSR) started looking into basalt fiber applications, primarily for military and aeronautical needs and succeeded in developing the first continuous basalt fiber production method. Even though in the 1970s, market and industrial strategies in the United States shifted more towards the development of glass fibers than basalt fibers, research on basalt fiber production persisted in the United States [69] . Austin and Subramanian were granted a U.S. patent in 1979 for a technique of improving the tensile strength of basalt fibers by mixing ferrous and ferric oxides into natural molten lava. Subramanian and his colleagues at Washington State University linked the chemical composition of basalt to extrudability conditions and physicochemical properties of the resultant fibers. Continuing. In 1979 the U.S.[70] In more specific terms, they demonstrated that silane coupling agents have the potential to help increase the bond strength of basalt fibers in basalt fiber-polymer systems.[71, 72] Additionally, they demonstrated that the addition of alumina might produce an increase in fiber strength.[73]

The development of basalt fibers as structural materials in China's building and transportation fields between 2002 and 2008 is summarized here. The number of publications on this issue in these years, which increased by more than half from 2006 to 2008 (from 20 to 70), is discussed there. The growth in the mechanical characteristics of basalt fiber composites in terms of tensile strength and elastic stiffness is reflected in the trend of patents issued between 1997 and 2008, with a considerable number following the period 2006–2008. [70] The usage of basalt fibers for civil applications, which is the focus of this study, started in the 1990s, including strengthening and retrofitting civil structures, thermal and acoustic insulation, and the development of vibration dampening methods. Much research has also proven the viability of employing basalt fiber composite bars to replace steel bars in reinforced concrete (RC) constructions [70].

The mechanical characteristics of basalt fiber composites in terms of tensile strength and elastic stiffness have also been established[74]. Basalt fiber manufacturing is now widely available and improved, making the market more stable and competitive. According to statistics, the most common use of continuous basalt fibers is in the building and construction industry, accounting for around 37% of total demand in 2012. Due to intensive research efforts and substantial basalt reserves, the market is now controlled by Russian and Ukrainian firms, and the primary customers are North America, Asia Pacific, and Europe, in that order.[75]. Basalt material in rock form in below figure 3.1[64]

Figure 3. 1: Basalt material in rock form

3.2 Production technologies

Basalt is an appealing raw material for fiber formation due to its generally homogenous chemical composition, global availability, lack of contaminants, and capacity to produce fibers in the molten state.[76] After the raw material has been melted at a very high temperature (about 1200 °C–1500 °C), the basalt fibers may be extracted[64] .wever, in contrast to the manufacturing of glass fibers, the creation of basalt fibers does not need any specific prior operations, such as the dose of ingredients. Basalt composition is established by the rock itself, which simplifies the manufacturing process and lowers production costs. Two different technologies may be used to generate basalt fibers, the first of which is the Spinneret method.[76] as well as the Junkers. The first is utilized to make continuous fibers, while the second allows for the production of short strands.[77]

Regarding the Spinneret technology it is possible to spin basalt fibers in a manner quite similar to the method used for spinning glass fibers it shows in figure 3.2. Crushed basalt rock is meticulously cleaned before being placed into furnaces heated by an air-gas combination or electricity. Some electrodes are often submerged in the melting bath throughout the melting process. This helps to ensure that the bath is heated evenly and cuts down on the amount of time needed to reach a state of thermal equilibrium. When melting the basalt is finished, the molten basalt is deposited over platinum-rhodium heated bushings. From these bushings, filaments are extracted using hydrostatic pressure. Following the cooling phase, the filaments are gathered together to create a strand, which undergoes an initial lubrication step, ensuring the strand's integrity and chemical stability. The filament diameter, which may range from a few micrometers to a few millimeters, can be altered by adjusting both the drawing speed and the temperature of the melt.[78]

The major technical parameters of continuous-fiber manufacturing and the fundamental physical-chemical features of continuous basalt fibers are mainly independent of the origin of the initial raw material, as long as the SiO2 concentration is between 45 and 50 percent. A melt-blowing method is used in Junker's technology and it shows in figure 3.3. Three spinning cylinders with horizontal axes and a nozzle plate perpendicular to the cylinders make up the production system. On the top rotating cylinder, molten basalt is poured. Molten basalt is transferred beneath two cylinders due to the tangential speed (fibrillation shafts). Due to centrifugal forces, molten basalt meatus breaks apart into little droplets.

Compressed air jets from the nozzles behind the cylinders shape the droplets into thin and oblong forms, which lead to the short basalt fibers after cooling. It is worth noting that when air jets induce drop elongation, one or both ends of each thread may have a little round head.[64, 77] This phenomenon may have two negative impacts, as discussed in the literature [79], and two adverse effects. On the one hand, since fibers with heads are more difficult to pull out of the matrix, the mechanical characteristics of the resultant composites are typically improved. However, on the other hand, the presence of fiber heads may cause stress/strain localizations, resulting in the initiation and propagation of damage and, consequently, a probable loss of the mechanical characteristics of the fiber-reinforced composite material.

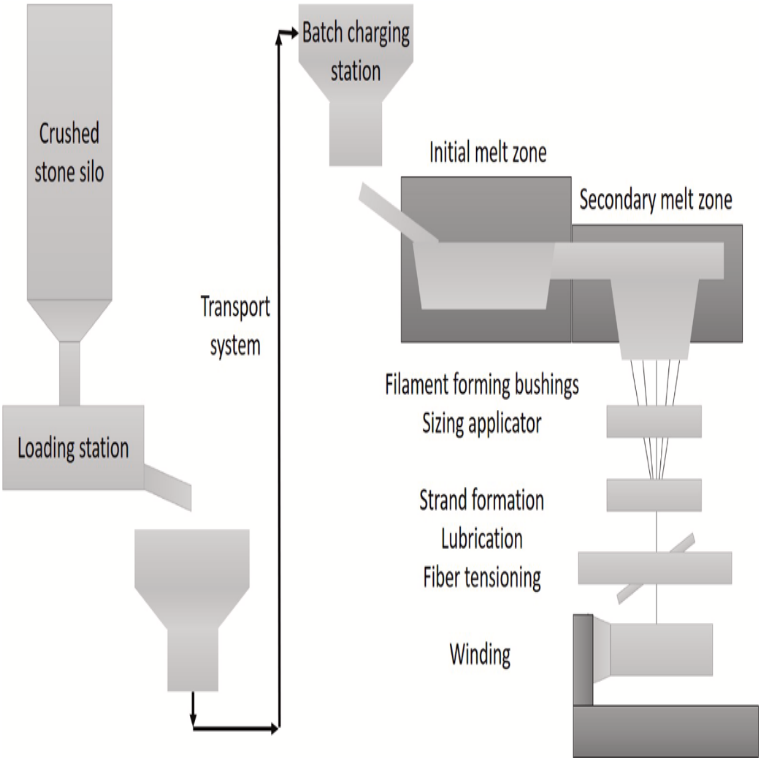

Figure 3. 2: Spinneret technology [65,81]

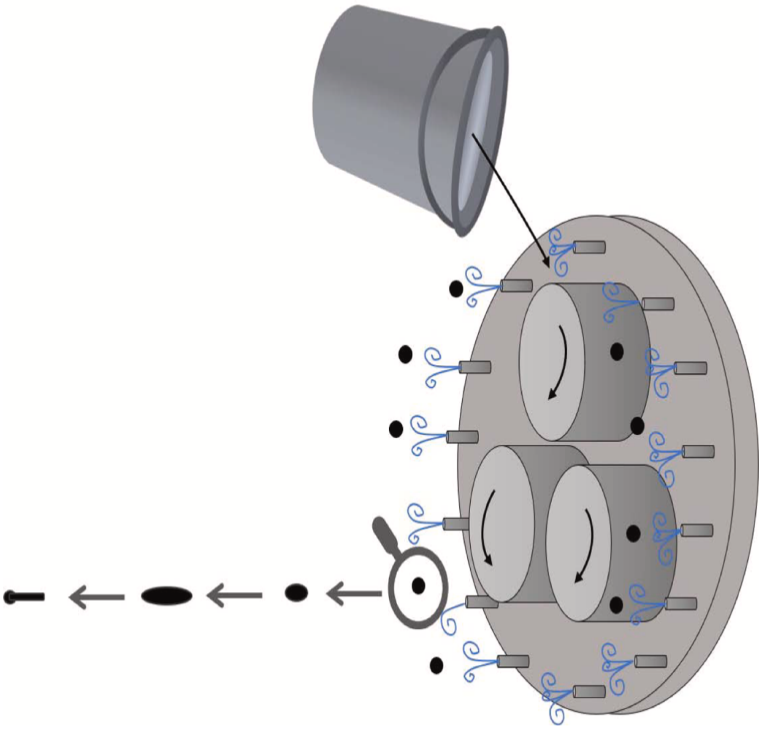

Figure 3. 3: Junker's technology [75,76]

3.3 Basalt fiber production

Basalt continuous fiber has a better affinity for other materials than other fiber materials, such as different resins and inorganic compounds [80]. This indicates that the composite is more effective. Continuous basalt fiber may create various composite materials with unique enhancing properties. Basalt fiber and epoxy resin have a superior bonding strength to E glass fiber, carbon fiber, and high silicon-oxygen fiber. This is the case whether the threads in question have been surface treated or treated with silicone[81, 82].

3.3.1 Principle and productions

3.3.1.1 Composite with matrix to enhance the properties of the material

Basalt fiber has a greater modulus of elasticity, better temperature resistance, impact resistance, and chemical stability than regular glass fiber, composite materials made up of different types of resins have optimal physical and chemical qualities and may be molded into complicated forms for long-term usage in high pressure, chemical, and thermal stress situations[83]. In many cases, basalt fiber reinforced composites may be compared to S glass fiber or Aramid fiber-reinforced composites. It costs about the same as or slightly less than glass fiber. Its key performance indices are much superior to typical silicon aluminum glass fiber, even approaching the more costly magnesium silicate fiber, and specific attributes are comparable to carbon fiber.

- *Basalt fiber reinforced composite bars*

Spinning, winding, surface coating, and compound molding create basalt fiber reinforced bar from high-strength basalt fiber and vinyl resin (epoxy resin). It is a novel construction material with high strength, good acid and alkali resistance, and extended durability[83]. It has three times the toughness of steel and just a quarter of the density. It may replace steel bars in various civil engineering sectors since it is a novel, green, environmentally friendly, and cost-effective material. It may be used to lay down reinforcement nets on the road) pavement, and all types of anchoring and reinforcement for special events (earthquake monitoring station, etc.) [83].

- *Short cut basalt fiber*

Basalt fiber with shortcuts Seamless basalt fiber is sliced into short-cut basalt fiber. Using this product, concrete and mortar's impact resistance, wear resistance, temperature shrinkage, and freeze-thaw resistance may be improved. It may be used to construct highways, bridges, airport runways, dams, and other structures.[83]

3.3.1.2 sound absorption and heat dissipation

When basalt fiber is manufactured to the appropriate fineness and density, the material may have a low heat conductivity. This basalt fiber may be utilized to make a composite material for thermal insulation [81, 84]. Because of its exceptional temperature range and tolerance to thermal shock, basalt fiber may simultaneously be used in high temperature and ultra-low temperature equipment, protective apparel for high-temperature operation, and low-temperature thermal insulation. These applications are all possible due to the fiber's versatility. The basalt fiber has a high capacity for sound absorption. This is due to the porous nature of the basalt fiber and its uneven arrangement. The absorbability of basalt fiber is improved by increasing the fiber layer thickness and decreasing the density. As a sound insulation material, basalt fiber may be produced into acoustic insulation composites for use in aircraft, ships, mechanical manufacturing, and building [84].

- *Basalt fiber cloth*

Fabrics such as woven roving, twill, satin fabric, and plain cloth may be crafted from basalt fiber with 7 to 13 microns. Non-flammability, flame retardancy, smoke-free, high-temperature resistance, no poisonous gas discharge, good heat insulation, no melting or dropping, high strength, no heat shrinkage, and so on are all benefits of this fabric. Field welding, gas cutting protective equipment, fireproof cloth wall, textile, chemical, metallurgical, theatrical, military employees, other ventilated fireproof and protective supplies, and fire helmets and necked fabric may benefit [81].

- *Basalt fiber high-temperature filter bag*

Basalt fiber high heat filter bag with the tensile strength of basalt fiber, with power and thermal, acid-alkali corrosion, oxidation resistance, and regular size, can meet the challenging circumstances of the dedusting operation and enhance the efficiency of dust removal, and extend the life of the filter bag. Basalt fiber high heat filter bag with the high tensile strength of basalt fiber, high-temperature resistance, acid-alkali corrosion, oxidation resistance, and stable size. It has applications in the steel business, chemical industry, cement industry, black carbon industry, and food for collecting dust or goods [81].

3.3.1.3 Anti-friction

Steel fiber, glass fiber, aramid fiber, carbon fiber, and asbestos fiber are now utilized to produce fiber-reinforced composite materials the most often; nevertheless, each has both benefits and drawbacks. For instance, steel fiber has high strength and effectively maintains its temperature. Still, it also has a large density. As a result, it rusts readily and can be destroyed easily. Glass fiber is easy to melt at high temperatures, which leads to a loss in the material's qualities ann instability in the friction properties [81].

Despite its great strength and low price, glass fiber is difficult to work with. Asbestos materials offer outstanding features such as high strength, good surface activity, good friction and wear capabilities, and a dispersed and homogenous mixture; nonetheless, asbestos is a carcinogenic element that puts human health at risk, and asbestos dust pollution is very harmful. Aramid fiber and carbon fiber have excellent performance, but their prices are incredibly high. However, because of the basalt fiber's high strength, excellent thermal stability, not easily damaged dualism, low wear and tear, stable friction coefficient, and appropriate pricing, it will be the material of the first choice for non-asbestos fiber. Basalt fiber also has a low friction coefficient.[81]

3.3.1.4 Insulating materials and electromagnetic shielding materials

Compared to carbon fiber, basalt fiber has superior non-conductive and electromagnetic qualities. As a result, it finds widespread use in power and radar engineering and other military and civil engineering areas. Examples of basalt fiber applications are insulators, trolley wrists, and basalt fiber Radome [81, 84].

3.4 Properties of basalt

BFs have gained the attention of their users because of their qualities, even though they are tough to digest. BFs offer robust physical, chemical, and adhesive rates to metals, epoxies, and glues [76]. Compared to glass, carbon, and other fibers, BFs offer extremely excellent characteristics at a reasonable price. In terms of performance, BF falls between carbon fiber and glass fiber. BFs provide higher tensile strength than E-glass fibers, higher failure strain than carbon fibers, and strong resistance to chemical assault, impact load, and fire with fewer hazardous vapors. The advantages of BF include[85, 86]: good temperature range, considerable heat and acoustic damping capabilities, excellent vibration isolation, high tensile strength, strong resistance to alkalis and acids, good electromagnetic characteristics, resistance to corrosion, resistance to radiation and UV light, and non-toxic to the end-user and environmentally friendly [86].

3.4.1Physical and mechanical properties of basalt

The density of the basalt ranges from 2.6 to 2.8 g/cc, which is much lower than that of metal (steel) and more comparable to that of carbon and glass fibers, despite basalt being more affordable than carbon fiber and more robust than glass fiber. Basalt is exceptionally hard, with hardness levels ranging from 5 to 9 on the Mohr scale (for contrast, diamond = 10) and more extraordinary abrasion qualities and it illustrates in table 3.1. Even prolonged abrasion of the BF-woven textiles over the propeller-type abraders does not result in the generation of fine fibers or the splitting of fibers by fracture. Instead, it only breaks individual threads from the woven structure, which prevents the potential of generating dangers associated with breathing. Compared to eels, it has a specific strength that is 2.5 times greater. Glass fibers do not have the same sound insulating qualities as BF. As a result, an interior built on BF will make you feel more at ease. 80–95 percent soundproofing for 400–1800 Hz.[87-89]

Table 3. 1: Physical and mechanical properties. [91]

Properties	Basalt
Density (g/cm3)	2.63–2.8
Filament diameter (μm)	6–21
Tensile strength of single filament (MPa)	3000–4840
Elastic modulus (GPa)	93–110
Elongation at break (%)	3.1–6
Specific gravity	2.65–2.8
Sound absorption coefficient	0.95–0.99

3.4.2 Thermal properties of basalt

According to a recent study, they have excellent thermal/heat resistance and humidity absorption; BF moisture absorption for 24 hours is less than 0.02 percent, whereas glass is 1.7 percent. BFs recover 1% of their moisture. Industrial glass fiber, particularly those with a neutral composition, may absorb a lot of water from humid air. These harms physical and technical qualities and their durability ultimately result in the fibers being destroyed. able. 80–95 percent soundproofing for 400–1800 Hz [89].

As a result of its chemical makeup, BFs have a low hygroscopicity that does not change over time (0.2–0.3%). Hygroscopicity does not steadily increase with time [90]. And it shows in table 3.2, in the long term, BFs contribute to thermal stability via their features. They are resistant to the effects of high temperatures for short periods up to 750 °C. However, the working temperature during prolonged labor is 260 to 700 °C, with a single impact of temperatures up to 1000 °C. Under the same circumstances, BF glass loses just 20–25 percent of its original strength, while E glass loses more than 40–45 percent of its strength.[91, 92]

Table 3. 2: Thermal properties. [65]

Properties	Basalt
Temperature °C to withstand	−260/−200… +600/800
Max application temperature, °C	Approx. 700–720
Melting temperature, °C	1450
Thermal conductivity at 25+/−5	0.031–0.038 W/m K
Thermal expansion coefficient	8.0 ppm/ºC

3.4.3 Chemical properties

These fibers do not conduct electricity when subjected to RF radiation, and no fields are created. In addition, basalt's dielectric characteristics, particularly its volume resistance, are almost identical to those of glass fibers. As a result, moving from glass to basalt does not affect the construction's radar transparency. It describes in table 3.3.[92]

Table 3. 3: Chemical Properties [91]

Properties	Basalt
% wt. loss after 3 h, boiling in H2O	1.6
% wt. loss after 3 h, boiling in NaOH	2.75
% wt. loss after 3 h, boiling in HCl	2.2

Because BFs are not only harmless to the environment but also living organisms, this material is suitable for usage in hostile settings. In addition to being inherently resistant to ultraviolet (UV) and high-energy electromagnetic radiation, BFs can keep their characteristics even when exposed to low temperatures. The use of basalt as a lightweight, cost-effective, and durable composite material is possible. Moisture is reclaimed, and the moisture content of BFs is less than 1%. The materials made from basalt have a high level of resistance to the activity of fungus and other microorganisms [92].

3.5 Applications of BF

Its wide variety of desirable qualities results in an extensive range of potential applications. Fiber and composite material manufacturers have already shown interest in BF. [93]In recent years, advancements in technology and equipment for BF manufacturing have enabled production costs to approach those of E-fiber glass.[91] The qualities of thermal insulation, electrical insulation, and sound insulation of basalt are all above average. BF may be used as a polymer reinforcing material in polymer matrix composites instead of glass fiber for many applications. Threads are exceptionally well suited for composites applications because of their superior mechanical characteristics, ease of wetting the filament surface, and recyclability [93].

Outdoor BF reinforced. Composites have good weatherability due to UV resistance, improved acid resistance, somewhat better alkaline resistance, and deficient water absorption of fibers. This inherent quality of BF is particularly significant for various applications, such as corrosive containing multiple conveyor systems, waste energy filters, pavement reinforcement, and cementitious rebars. The fatigue behavior of BF laminates was shown to be superior to glass–fiber composites, with more muscular stiffness retention at low fatigue loads and improved damping qualities. As a result, the potential of BF as a substitute for conventional glass fiber for the manufacture of structural composites that combine strong mechanical performances and unique heat dissipation capabilities was brought to light.[94]

3.5.1 Areas of application of BF Civil and industrial construction

It is essential to have highly excellent hardness, high mechanical qualities, corrosion resistance, a wide temperature range, and outstanding insulating capabilities in this industry. Basalt may be used for a variety of applications as a building material, including tubes, bars, pipe fittings, internal heat and sound insulation of floors, walls, frame walls, boiler shells, tanks, chimneys, and other fire safety structures, wear-resistant paint coatings for bridges, tunnels, and other essential facilities and facilities, and watertight treatments for reinforced concrete structures. Applications requiring insulation and fire protection are perfect for using BFs. When not mechanically pressured, BF neither melts nor shrinks in the flame [75].

Due to the thermal insulating qualities that it has, it is already used as a type of fire protection in the form of textiles or tapes, such as fire curtains for hall partitioning and exterior emergency housing protection in case of wildfire, and fire-blocking inter liners for the seat coverings of mass transit. When it comes to heat resistance, basalt is an excellent fire barrier. Basalt materials are resistant to fire. Basalt melts around 1450 degrees Celsius. With a Bunsen burner aimed at it (1100–1200 °C), a basalt fabric gets as red hot as a metal cloth. This may go on for hours. The same flame pierces an E-glass material with the same surface density in seconds. Basalt's strong insulating properties have long been known, which is why it is a common insulation material in the building sector, processed as rock wool[75].

Concrete is frequently employed in structural engineering because of its great compressive strength, cheap cost, and abundant raw materials. However, typical concrete has several drawbacks that limit its uses, such as shrinkage and cracking, low tensile and flexural strength, poor toughness, excessive brittleness, low shock resistance, etc. Additional elements are added to increase the performance of concrete to overcome these flaws. Fiber-reinforced concrete is a new cement-based composite material that has just been created. BF is a relatively new material that has gained popularity in recent years. As a result, BF reinforced concrete is used for bridges and structures to provide reinforcement and fracture resistance. Compared to comparable goods, BFs are vibration-resistant due to the flexibility of the micro-and macrostructure. This characteristic is significant in mechanical and civil engineering.

Mineral and glass fiber vibration cushions are damaged and eventually dissolve when structures are built near roads, trains, and underground. Still, basalt slabs are vibration-resistant and hence more lasting. Also offered are concrete reinforcement, pultruded load-bearing sections and concrete-reinforcing bars, geogrids for road and land reinforcement, and stucco nets for wall reinforcing and rehabilitation. Because BFs do not react in alkaline settings or with corrosive substances, they provide high durability to the reinforced concrete. According to the business, one ton of basalt rods may give the same reinforcement as 9.4 tons of steel rods. Unlike glass fibers, oil and gas offshore platforms are very resistant to alkaline, acidic, and salt damage, making them an excellent choice for concrete, bridge, and coastal constructions. Corrosive elements and alkaline surroundings [89]. The shape of geogrid is shown in figure 3.4[75].

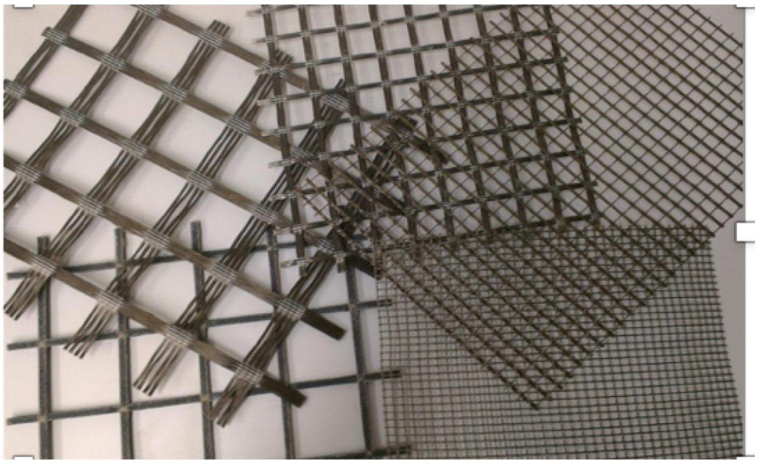

Figure 3. 4:different hole sizes of geogrid

Chapter 4

4. Materials and methodology

4.1 Introduction

This chapter aims to construct and create a numerical model to reinforce road embankment while using nature based material in geosynthetic geogrid. The result used in this study is taken from study carried out by Ethiopian road authorities (ERA's) in the region of Dukem in Ethiopia where the tests is carried out, and the results is related to the material parameters for the soil profile [9]. In addition, the material parameter for geogrid is supplied based on the standard. Develop models that reflect the behavior of both embankment material and soft soil materials, as well as geogrid.

The modeling procedure should involve a range of trials to construct a realistic model for a road embankment reinforced with geogrid placed on soft soil. These challenges should include the practical methodology for simulation, element of the model, mesh geometrical, boundary positions, choice of parameters used in the analysis, and the right choices again for the develop model that reflects the researched soil. Therefore, the modeling process should involve these challenges. In addition, since the finite element method, FEM is an acceptable method, it is required to carry out several preliminary tests, such as checking the sensitivity of the mesh and the distance to the boundary, to guarantee that the numerical analysis will be correct.

This chapter aims to go through the material parameters for road embankments required to run the PLAXIS 2D model. Geogrid material made of basalt fibers is utilized in the numerical analysis program in PLAXIS 2D. The rest of the sizes and measurements are based on the prior model. This chapter will address all embankment materials utilized in software. Furthermore, nature-based materials used for geogrid

4.2 Subgrade and embankment material

Study region of Dukem in Ethiopia where the soil sample were taken and carried out the tests in labs with assistant of ERA's and the results related to the material parameters for the soil profile. They did enormous investigation from 500m to 25000m [9] and it is illustrated in table

4.1. The given soil parameters from their research have been used again in this numerical analysis while using nature-based material geogrid model.

Table 4. 1: Subgrade and embankment material [9]

Soil Parameter	Subgrade		Embankment	Unit
	Layer-1	Layer-2		
Material model	MC	MC	MC	[-]
Depth	0,00-2,50	2,50-5,00		[m]
Type of material behaviour	Undrained	Undrained	Drained	[-]
Bulk unit weight[γ]	18,4	19,1	20,2	[kN/m$^{3]}$
Saturated unit weigh [γsat]	18,4	19,1	20,2	[kN/m$^{3]}$
Over-consoilidation ratio	1	1	1	[-]
Poisson's ratio [v]	0,35	0,35	0,3	[-]
Young's modulus[E]	1000	2000	4000	[kN/m^2]
Cohesion [Cref]	13	17	1	[kN/m^2]
Dilatencey angle	0	0	4	[o]
Lateral earth coefficient	0,69	0,63	0,44	[-]
Friction angle [Ø]	18	22	34	[o]
Water Permeability Coefficient [K]			8,65E-06	[m/day]

4.3 Basalt fiber used in Geogrid

The below-mentioned properties of basalt material are received from Dakks Dutch company. They work specifically on basalt material and are also suppliers of the material to entire Europe. They work on promoting basalt material, since it is nature-based and environmentally friendly. Table 4.2 shows properties of geogrid basalt fiber used in PLAXIS 2D [appendix D]

Table 4. 2: Geogrid Basalt fiber Properties [appendix-D]

Geogrid type	Reference Name	Elastic Modulud [kPa]	Area [m]	EA [kN/m]
Geogrid Type I**	GGI	8,00E+07	0,07	6,24E+06
Geogrid Type II**	GGII	8,73E+07	0,07	6,80E+06
Geogrid Type III**	GGIII	9,17E+07	0,07	7,15E+06

4.5 Traffic loading

The numerical study of road embankment, in this case, live load that is traffic load considered in PLAXIS 2D along consider the dead load which are embankment and subbase layer in the software. The traffic load is considered approximate 50 kN/m [9].

4.6 Model development

4.6.1 Preliminary numerical analysis checks

The material model's complexity is simply one factor determining how accurate the finite element model will be. Other factors, such as the boundary condition of the domain, the number and type of elements used to discretize the field, and other modeling concerns, all play a role.

4.6.1.1 Influence of distance on the boundary

A finite element model's solution is defined by the real-world pressures, extensions, and circumstances represented by the outer bounds, which are artificial representations of these factors. Because it is not feasible to incorporate the genuine natural extension of a mass of soil or specific events that are applied to it, the finite element algorithm PLAXIS 2D allows the user to replace the response of these extensions and events as a constraint, displacements, and forces at the boundary[95]. Consequently, the user can quantify these impacts and attribute them to the researched model while having as little impact as possible on the correctness of the model.

The positioning of boundary restrictions can significantly impact the outcomes of a finite element simulation. Because the reaction forces that are created and the displacement that occurs in these boundaries might affect the effect that the applied forces have on the zones of interest. Therefore, to avoid any restrictions that could affect the accuracy of the finite element model, a user should select the location of these boundaries so that they are a sufficient distance away from any zone of interest. At the same time, the user should consider them not to be overly distant because this would require more time to analyze the data. The analysis was carried out on the side border since the bottom of the area depends on the soil profile, and it is sufficiently rigid at 5 meters deep. Therefore, the position of the footing center varied from 2B to 12B in terms of the distance to the border [96]. Model is shown in figure 4.1 [95].

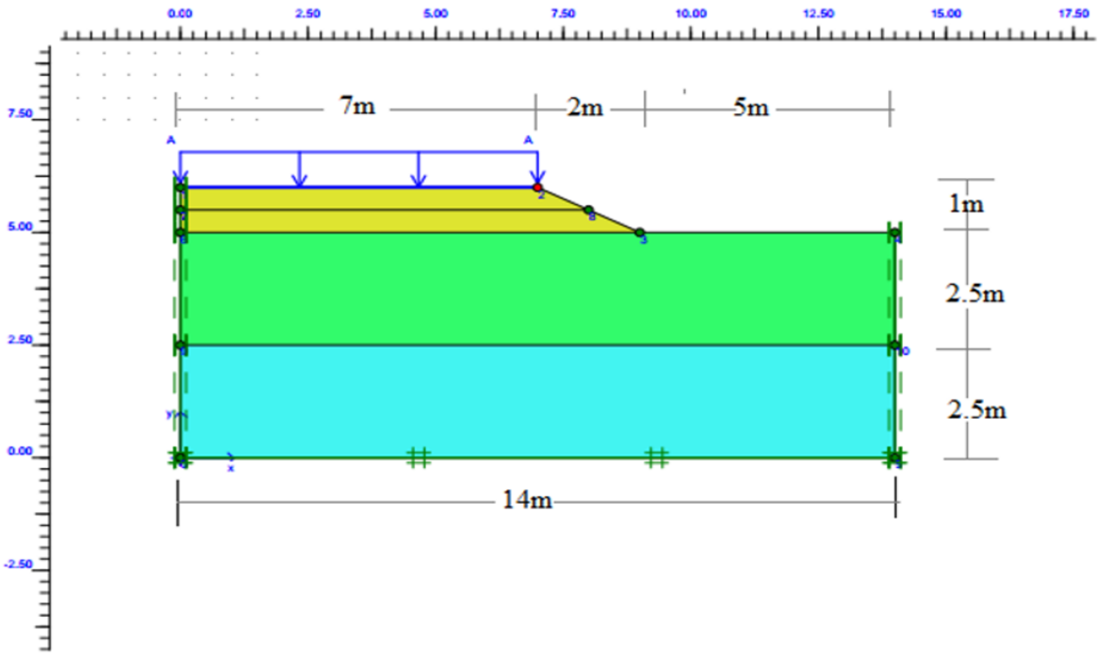

Figure 4. 1: Layout of soil profile

The sensitivity analysis was carried out on a chosen road cross-section that was 7 meters in length. The vertical displacement was measured at points A, B, and C, where A is located below the embankment. B is between soft clay and stiff clay, and C is located at the toe of the slope. The precision of the appropriate boundary distance may be ascertained by contrasting the normalized error for vertical displacement (uy) at a chosen position where the side boundary is situated at a distance xB with that of 12B. This allows one to identify which value is more accurate.

Normalized error for vertical displacement, $$\mathrm{u_y} = \left(\frac{u_{y\,(xB)} - u_{y\,(12B)}}{u_{y\,(12B)}}\right)$$

Where:u_y (xB) - denotes the vertical displacement at the chosen location for the scenario in which the side border is situated (xB) meters away from the geographic center of the route. U_y(12B) denotes the vertical displacement that occurred at the chosen position to represent the case of the side boundary and is situated (12B) meters out from the center of the highway.

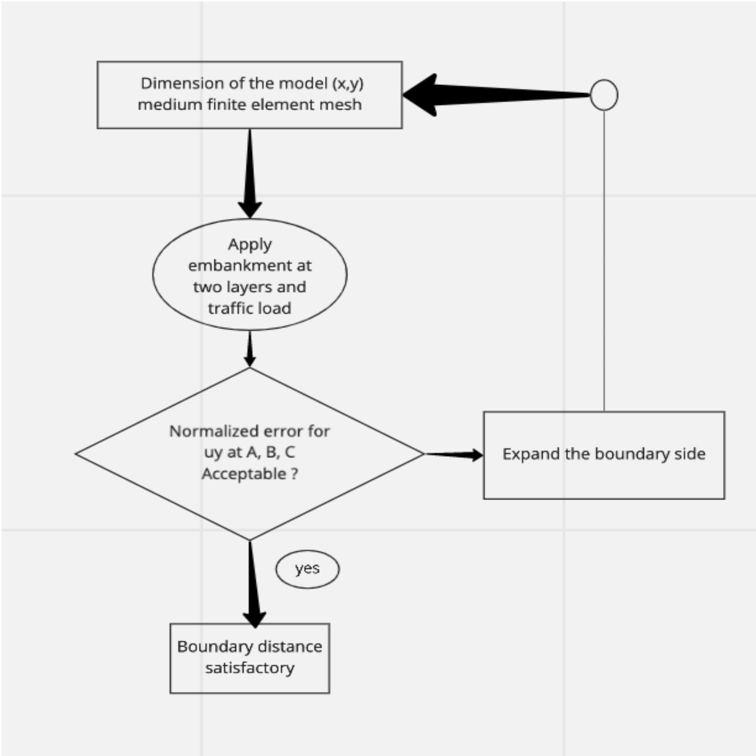

Figure 4. 2: Flow chart outlining preliminary analysis checks for boundary distance

Analysis of the relationship between the distance to the border and the vertical displacement of a road cross-section measuring 7 meters.

Table 4. 3:Influence of the distance to boundary upon the vertical displacement of 7m road cross-section [9]

Distance to boundry	**Vertical displacement u_y [mm]**				**Normalized error [%]**			
B=footing [width]	Point A	Point B	Point C	Extreme [u_y]	Point A	Point B	Point C	Extreme
2B	206,10	188,51	8,50	206,14	1,41	1,110	19,17	1,41
4B	205,80	188,60	10,00	205,80	1,56	1,080	4,93	1,56
6B	206,00	188,75	10,10	206,10	1,44	0,990	3,99	1,44
8B	209,70	191,04	10,70	209,70	0,29	0,210	1,90	0,29
10B	209,00	190,38	10,39	209,00	0,04	0,140	1,23	0,04
12B	201,10	190,64	10,52	209,00	0,00	0,000	0,00	0,00

Table 4. 4: Influence of the distance to boundary upon horizontal of 7m road cross-section [9]

Distance to boundry	**Horizantal displacement u_x [mm]**				**Normalized error [%]**			
B=footing [width]	Point A	Point B	Point C	Extreme [u_x]	Point A	Point B	Point C	Extreme
2B	0,00	0,00	37,90	56,37	0,00	0,00	2,95	2,18
4B	0,00	0,00	37,58	56,23	0,00	0,00	2,40	1,93
6B	0,00	0,00	37,19	56,13	0,00	0,00	1,34	1,74
8B	0,00	0,00	36,70	55,17	0,00	0,00	0,00	0,00
10B	0,00	0,00	36,70	55,45	0,00	0,00	0,00	0,00
12B	0,00	0,00	36,70	55,17	0,00	0,00	0,00	0,00

Table 4. 5: Influence of the distance to boundary upon the effective stress of 7m road cross-section [9]

Distance to boundary	**Effective stress,$Ó_{yy}$ [kN/m^2]**	**Normalized error [%]**
B= footing [width]	Extreme	Extreme
2B	163,59	1,08
4B	163,08	0,77
6B	163,02	0,73
8B	161,95	0,07
10B	161,80	0,03
12B	161,84	0,00

Moving the border closer to the middle of the footing than 2B causes higher vertical displacement (approximately 19%) in the road embankment. Therefore, for all following FEAs with modest vertical displacement, the overall distance to the border from the center of the footing is conservatively set at 4B. The maximum error is less than 5 percent, which is a minor normalized error. The results in the models are same as previous and current analysis.

4.6.1.2 Mesh sensitivity analysis

A mesh sensitivity analysis was performed to explore the effect of the number of elements on the accuracy of the finite element model. A mesh sensitivity study was conducted for an adequately chosen 4B boundary distance from the center, comparing the accuracy of medium and fine meshes to that of very fine meshes. As the settlement performance of the geogrid reinforced road embankment is the topic of this thesis, the vertical displacement (uy) was investigated for the mesh sensitivity analysis. Uy was measured at three locations: A, B, and C. A lies below the embankment, B is between soft and stiff clay, and C is near the slope's toe table 4.7. The accuracy of medium and fine meshes is assessed by measuring the normalization error for vertical displacement (uy) of medium and fine meshes to that of very fine meshes.

Normalized error for vertical displacement, $u_y = \left(\frac{u_{y,vf} - u_y}{u_{y,vf}}\right)$

Where: - for medium and fine-meshed components, vertical displacement at the given position - vertical displacement at the selected point for extremely fine-meshed elements. In addition to screening for discontinuities at inter-element borders, the mesh was examined for converging displacement with increasing features. Discontinuities are most common in areas with fast variations in stress and strain, such as under the edge of an embankment, and may be mitigated by refining the mesh.

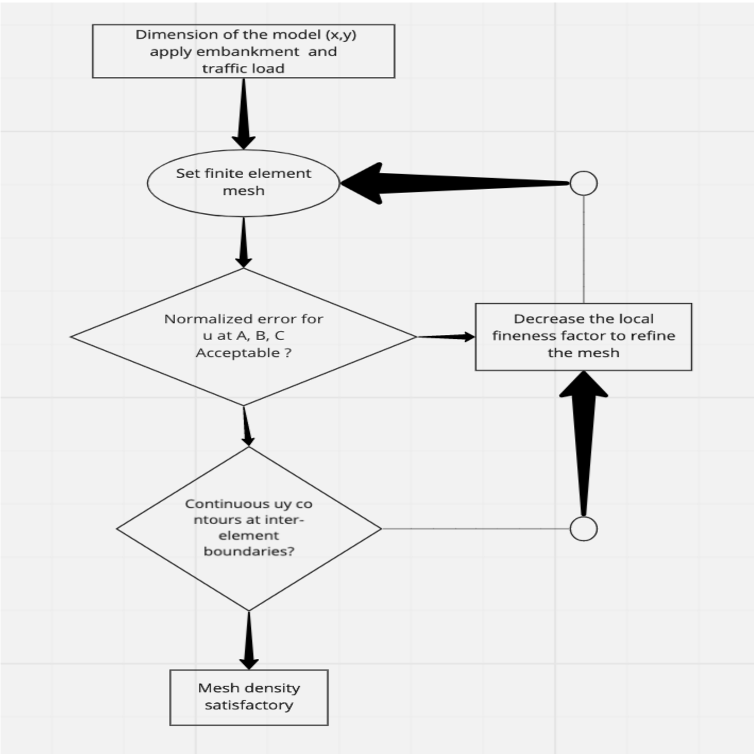

Figure 4. 3: Flow chart outlining preliminary analysis checks for mesh density

Table 4.3 outlines the number of elements used for each mesh and the normalized error for the vertical displacement. It is plain to see that the values for the medium and fine meshes are becoming closer and closer to those of the beautiful mesh. In addition, the average normalized error for the vertical displacement between the fine and very fine meshes is surprisingly low (the maximum error is no greater than 5 percent).

Table 4. 6: Influence of the mesh sensitivity on vertical displacement at points A, B and C.

Mesh	Vertical displacement u_y [mm]				Normalized error [%]			
	A	B	C	Extreme Uy, max	A	B	C	Extreme
Coarse	209,70	190,95	10,68	209,7	2,00	1,30	7,00	2,00
Medium	207,83	189,58	10,6	207,83	1,10	0,60	6,10	1,10
Fine	206,44	188,95	10,14	206,44	0,40	0,30	1,60	0,40
Very fine	205,57	188,48	9,98	205,57	0,00	0,00	0,00	0,00

Table 4. 7: Influence of the mesh sensitivity horizontal displacement point A, B and C.

Mesh	Horizantal displacement u_x [mm]				Normalized error [%]			
	A	B	C	Extreme Ux, max	A	B	C	Extreme
Coarse	0,00	0,00	37,69	56,46	0,00	0,00	0,70	0,60
Medium	0,00	0,00	37,58	56,23	0,00	0,00	0,40	0,20
Fine	0,00	0,00	37,41	56,02	0,00	0,00	0,00	0,00
Very fine	0,00	0,00	37,43	56,11	0,00	0,00	0,00	0,00

Table 4. 8: Influence of the mesh sensitivity on the extreme effective stress [9].

Mesh	Effective stress,Óyy [kN/m^2]	Normalized error [%]
	Extreme	Extreme
Coarse	161,87	1,12
Medium	163,08	0,39
Fine	163,52	0,12
Very fine	163,71	0,00

4.7 Numerical simulation of geogrid reinforced road embankment

A series of numerical simulations were carried out to determine the behavior of a road embankment after it was strengthened with geogrid of varying stiffness.

4.7.1 Geogrids in PLAXIS 2D

The soil reinforcement is another essential part of the reinforced soil bridge abutment. The 'geogrid' element included in PLAXIS 2D models the orthotropic behavior of soil reinforcement when subjected to loading conditions. 'EA1' and 'EA2' are the names of two parameters that need to be specified for the geogrid element. The parameter 'E' determines the material tension stiffness along with cross sections' A1' and 'A2' following the local axes of the geogrids[97].In equation. Geogrids, the formulation of the connection between tensile force and strain in geogrid, which is provided, is shown in [4.1]

$$\begin{bmatrix} N \\ H \end{bmatrix} = \begin{bmatrix} EA_1 & 0 \\ 0 & EA_2 \end{bmatrix} \begin{bmatrix} \varepsilon \\ \varepsilon_H \end{bmatrix} \qquad (4.1)$$

In equation 4.1, the symbols' N' and "indicate the tensile force and strain on the geogrid, respectively. The values denoted by "H" and "ε_H" respectively represent the hoop's force and strain. Since it is expected that the plain strain condition may be applied in the limit equilibrium design part, the expression 'H = ε_H = 0' applies to our situation. Considering this, the equation that describes the connection between tensile force and strain may be stated as follows:

$$\begin{bmatrix} N \\ 0 \end{bmatrix} = \begin{bmatrix} EA_1 & 0 \\ 0 & EA_2 \end{bmatrix} \begin{bmatrix} \varepsilon \\ 0 \end{bmatrix} \qquad (4.2)$$

It is assumed that the geogrid's cross-sectional area along both axes (A1 and A2) is the same in [4.2]. It leads to a single value being determined for the "EA" parameter, which governs the "stress-strain" behavior in the geogrids. In this scenario, the behavior of the "soil-geogrid" interface is modeled by simulating its "pullout resistance" using the parameters of the interface.

4.7.1.1 Geometric modeling

Layout of road embankment is shown in the profile in figure 4.1. This study uses the 1-meter height embankment and 7-meter wide road with slopes of 1:1.5, 1:2, and 1:3 are used for this study. The traffic loads of 50 kPa, were accepted for all future FEA calculations. The geogrid meant to strengthen the road embankment was embedded in many distinct levels. Parametric research was conducted to determine which reinforcement layer would be most effective.

4.8 The theoretical framework of numerical simulation

The planar strain model uses the finite element (FE) algorithm PLAXIS 2D version 8.6. Modeling apparent subgrade soil, embankment, and geogrid as 15-node wedge components using 2D plane strain code.

The early phase just activates soil clusters, not all structural sections. This step determines soil cluster stresses and deformations using gravity loading. In the early phase, the self-weight strains have been present for a long time, rendering the formation of excess pore water pressures meaningless. Initially, "ignore undrained behavior" is chosen. This option is not selected for other phases since extra pore water pressures must be considered throughout the construction and after all loading processes. The embankment comprises two 30-day segments. After the initial building phase, surplus pore pressures dissipated over 725 days. After the second phase, 725 days were added. There are two stages in plaxis, consolidation, and shearing. First, consolidation processes where water contents are dissipated from it, in case of drainage. When this stage is completed then next phase starts, shearing phase. Where sample deformation starts.

Chapter 5

5. Results of FEA and discussion

5.1 Introduction

To determine the vertical and horizontal displacement on soft soil in road embankment slope the help of PLAXIS 2D. According to what was said before, this research's primary objective is to determine the deformation of road embankment slopes while using two kinds of material in geosynthetic geogrid to reinforce road embankments. Compared results of both materials used in the model to obtain results from PLAXIS 2D to give a better understanding of how it behaves in soft clay soils.

Two different kinds of material have been usen to reinforce road embankment. One is nature-based material and second is synthetic-based material. Settlement parameters for both have been studies and compared. The focus has been on finding alternative materials placed instead of unnatured materials, which are commonly used in construction industry. This material is not environment friendly and to overcome the use of this material is necessary. Therefore, finding the strength parameters of basalt material, which is environment friendly, and compared to results of both materials where they are relevant to each other has been important in this research. This chapter discusses the findings of the results, including the confirmation of those conclusions using FEA, the effect of essential design factors, and the explanation of those results.

5.2 Detail Results of Finite Element Analysis

Following that, FEA was carried out with the help of the PLAXIS 2D algorithm to investigate the impact that key design factors had on the overall performance of the geogrid reinforced road embankment. Finite element studies analyzed the effect of different elements on strip footing performance on reinforced investigated soils were carried out on basalt material to reinforced embankment over placed on silty clay. The following variables were considered for this investigation: side slope, geogrid application layer, kind of geogrid, and several reinforcing layers. The load-deformation curve derived from the simulation of finite elements was used for each scenario to ascertain the road embankment's lateral deformation, vertical settlement, and effective stress.

5.2.2 Slope 1.1:5

Data and results

This section provides a summary of the results obtained from finite element studies using the PLAXIS 2D plain strain code for both materials, nature-based and unnatured based to reinforced road embankments with a slope ratio of 1:1.5. The extreme value of each model's horizontal displacement, vertical displacement, and effective stress are the outputs produced from the model. Both materials of, nature-based and unnatured based used in geosynthetic geogrid.

Table 5. 1: The results of FEA of a road embankment at slope 1:1.5 [9][appendix-A]

Slope V:H	Reinforcement	Reinforcement Layer		Geosynthetic Paramertric results			Basalt Paramertric results		
		Layer	at	Horizantal Displacement [mm]	Vertical Displacement [mm]	Effective mean stress [kN/m2]	Horizantal Displacement [mm]	Vertical Displacement [mm]	Effective mean stress [kN/m2]
1:1.5	Reinforcement with GG-1	Double	Bottom + Middle	32,53	135,66	142,2	33,71	14,11	69,02
			Bottom + Top	32,67	135,38	142,17	50,78	19,16	112
			MIddle + Top	37,75	140,69	142,13	54	21,13	112,9
	Reinforcement with GG-2	Double	Bottom + Middle	28,85	121,53	137,3	34,19	14,46	69,11
			Bottom + Top	28,93	121,21	137,29	50,74	19,12	105,6
			MIddle + Top	33,89	125,94	137,22	54,02	21,35	130,9
	Reinforcement with GG-3	Double	Bottom + Middle	25,15	109,7	132,54	33,51	14,21	68,99
			Bottom + Top	25,64	107,65	132,35	50,69	19	102
			MIddle + Top	30,19	111,46	132,33	54	21,3	110,2

Table (5.1) shows all calculated parameters by PLAXIS 2D of both materials, nature-based basalt material and polymer-based material, since these types of materials are used in geosynthetic geogrid. For example, two geogrid layers are used in the road's embankment to reinforce embankment slopes. The rest of all details are given in appendix A, and there are also calculated some other parameters which are not presented in the above information. Therefore, the primary purpose is to compare the results of both materials where they are relevant to compare side by side.

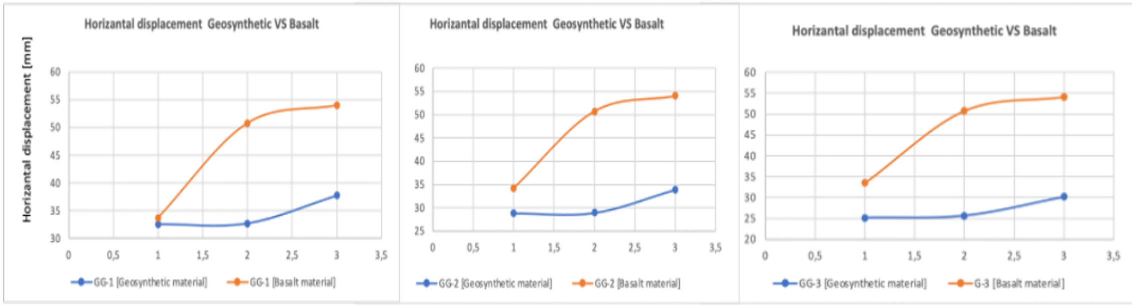

Figure 5. 1: Geogrid-1,2 and 3 horizontal displacement Nature based material Vs Un-nature material

In the figure (5.1) depicts some results given by numerical analysis. In the case of horizontal displacement, basalt material shows less resistance to polymer-based material. Still, it also depends on the arrangement of the layer to deploy in the reinforcement of embankment slopes. As mentioned in the table 5.1, there are three kinds of geogrid modeling: top and bottom, bottom and middle, and finally, the middle and bottom layer provided.

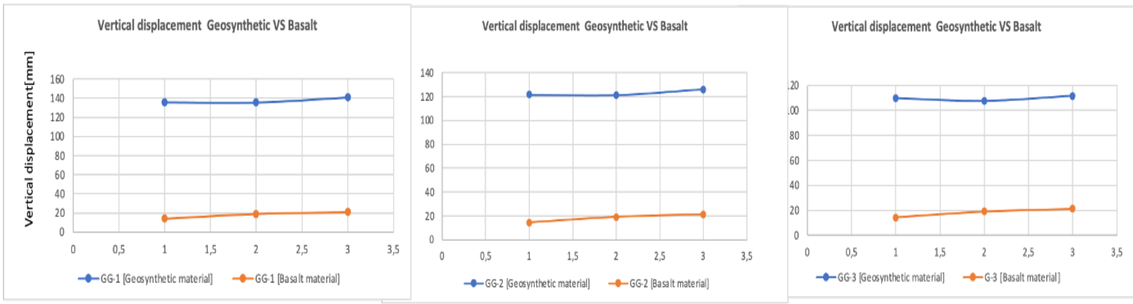

Figure 5. 2: Geogrid-1,2 and 3 Vertical displacement Nature based material Vs Un-nature material

Figure (5.2) describes that nature-based material provides more strength in vertical deformation. In addition, this case shows a pretty more minor settlement than other materials. Therefore, it gives more resistance against downward deflection of the embankment to control the settlement of roads, and it is environment-friendly material. Consequently, it is the best alternative to replace the polymer-based material used in geogrid.

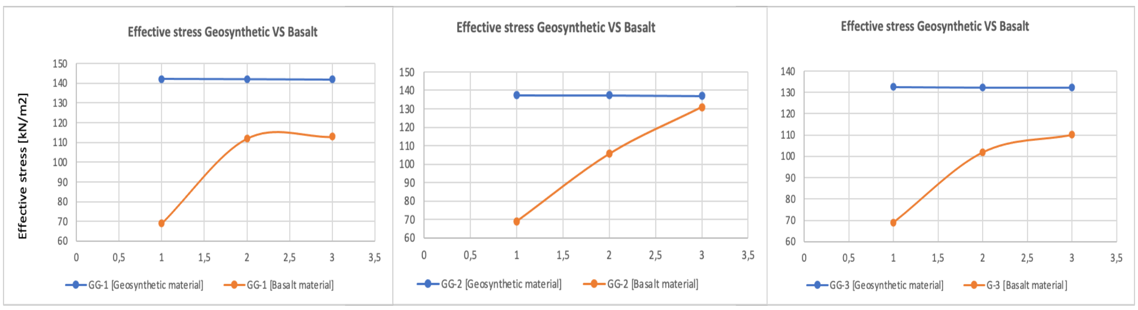

Figure 5. 3: Geogrid-1,2 and 3 Effective stress Nature based material Vs Un-nature material

Figure (5.3) shows results in the case of basalt materials that are effective stress vary through the graph, and it relies on an arrangement to the layer of geogrid in embankment while in the polymer-based material to show almost constant adequate pressure in three kinds of geogrid.

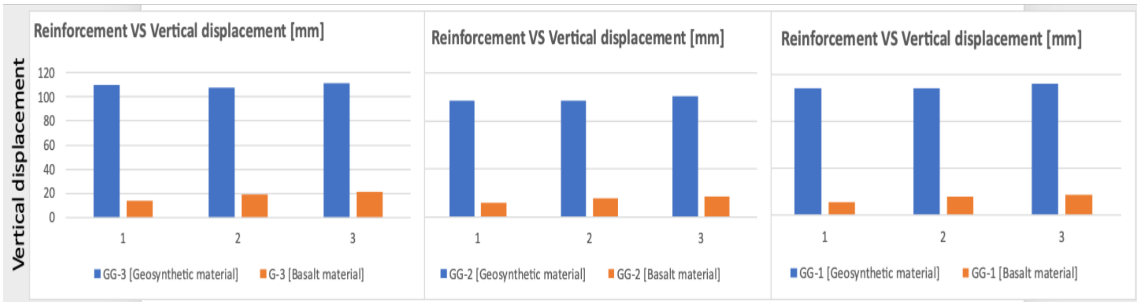

Figure 5. 4 :Geogrid-1,2 and 3 Vertical displacements Nature based material Vs Un-nature material

As illustrated above in the figure 5.4, the nature-based material of basalt fiber is solid concerning vertical settlement. It is more quietly resistant than polymer-based geogrid, so it is highly recommended for vertical deformation in road embankments. It makes stable road embankments slopes, and it is available material everywhere in the world.

5.2.2 Slope 1:2

Provides a summary of the results obtained from finite element studies using the PLAXIS 2D plain strain code for both materials, nature-based and unnatured-based, to reinforce road embankments with a slope ratio of 1:2. The extreme value of each model's horizontal displacement, vertical displacement, and effective stress are the outputs produced from the model. Both materials, Nature-based and unnatured, based used in geosynthetic geogrid in the same kind model of PLAXIS 2D

Table 5. 2: The results of FEA of a road embankment at slope 1:2 [9][appendix-B]

Slope V:H	Reinforcement	Reinforcement Layer		Geosynthetic Paramertric results			Basalt Paramertric results		
		Layer	at	Horizantal Displacement [mm]	Vertical Displacement [mm]	Effective mean stress [kN/m2]	Horizantal Displacement [mm]	Vertical Displacement [mm]	Effective mean stress [kN/m2]
1:2	Reinforcement with GG-1	Double	Bottom + Middle	25,29	109,39	132,46	55,88	44,42	59,9
			Bottom + Top	25,4	109,12	132,43	48,7	44,7	50,88
			MIddle + Top	25,79	112,12	129,6	69	48,88	95,31
	Reinforcement with GG-2	Double	Bottom + Middle	22,72	95,04	129,6	44,42	44,42	50,92
			Bottom + Top	27,5	94,78	129,44	40,67	44,7	50,88
			MIddle + Top	29,41	96,14	129,11	69,07	48,88	92,47
	Reinforcement with GG-3	Double	Bottom + Middle	18,74	81,17	122,73	55,94	46,99	60
			Bottom + Top	18,78	80,94	122,71	45,49	45,42	50,83
			MIddle + Top	22,54	82,68	122,6	69,04	48,86	105,31

Table (5.2) shows all the calculated parameters by PLAXIS 2D of nature-based Basalt and polymer-based materials. These types of materials are used in geosynthetic geogrid. For example, two geogrid layers are used in the road's embankment to reinforce embankment slopes. The rest of all details are given in appendix A, and there are also calculated some other parameters which are not presented in the above information. Therefore, the primary purpose is to compare the results of both materials where they are relevant to compare side by side.

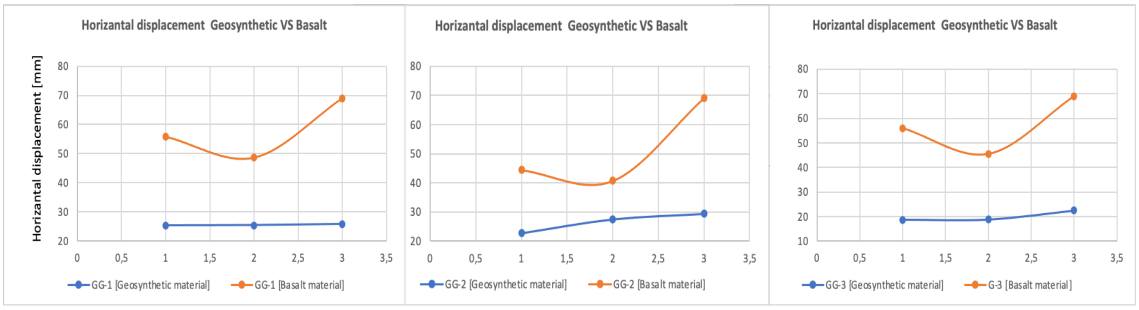

Figure 5. 5: Geogrid-1,2 and 3horizontal displacement Nature based material Vs Un-nature-based material

In the figure (5.5) depicts some results are given by numerical analysis, and in the case of horizontal displacement, basalt material shows the less resistance to polymer-based material, but it also depends on the arrangement of the layer to deploy in the reinforcement of embankment slopes, as it mentioned in the table 5.2 there are three kinds of geogrid modeling such as top and bottom, bottom and middle and finally middle and bottom layer provided

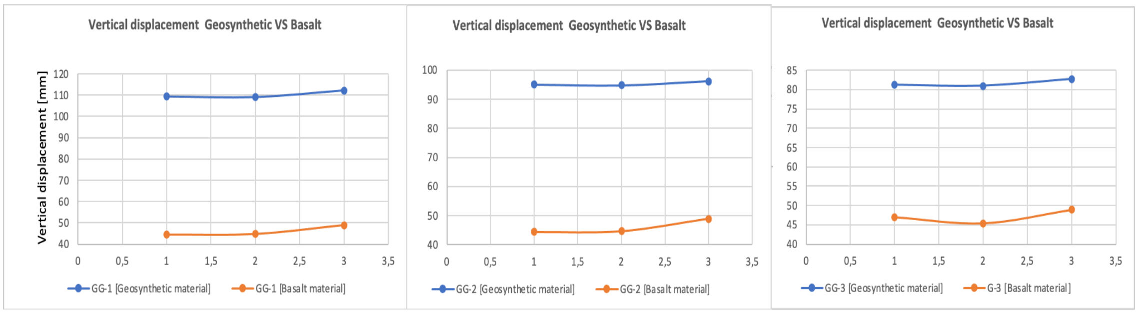

Figure 5. 6: Geogrid-1,2 and 3 Vertical displacements Naturel based material Vs Un-nature material

Figure (5.6) describes that Nature-based material provides more strength in vertical deformation. Furthermore, this case shows a pretty more minor settlement than other materials. Therefore, it gives more resistance against downward deflection of the embankment to control the settlement of roads, and it is environment-friendly material. Consequently, it is the best alternative to replace the polymer-based material used in geogrid.

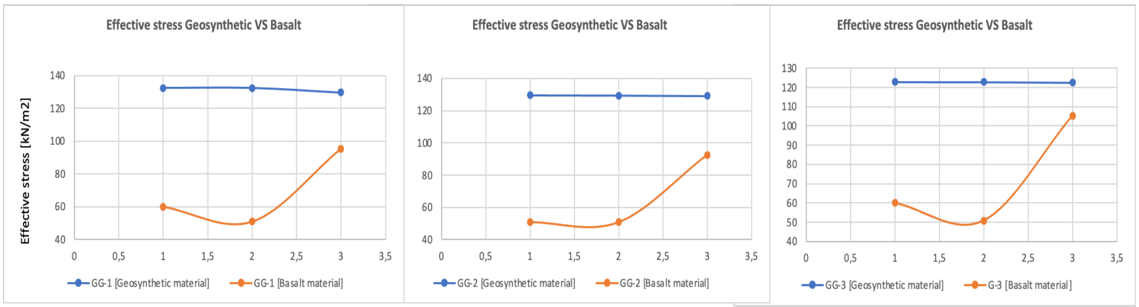

Figure 5. 7: Geogrid-1,2 and 3 Effective stress Nature based material Vs Un-nature material

In the figure (5.7) shows results in the case of basalt materials in which are effective stress vary through the graph, and it relies on the arrangement of the layer of geogrid in the embankment; meanwhile in, the polymer-based material shows almost constant effective stress in three kinds of geogrid

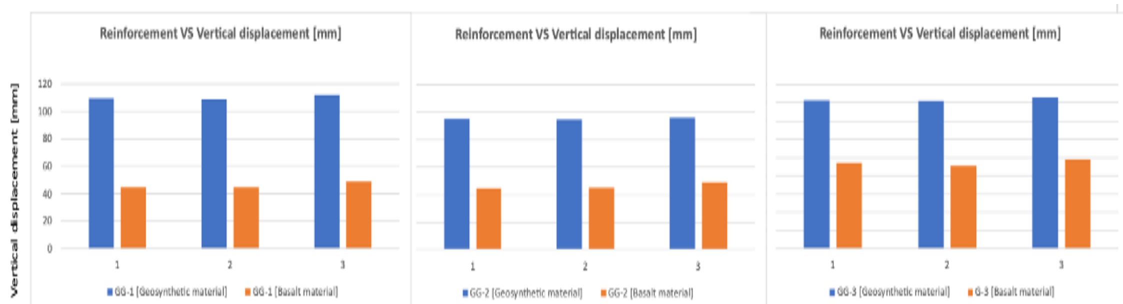

Figure 5. 8: Geogrid-1,2 and 3 Vertical displacements Nature based material Vs Un-nature material

As illustrated above in the figure (5.8), the nature-based material of basalt fiber is solid concerning vertical settlement. It is more quietly resistant than polymer-based geogrid, so it is highly recommended for vertical deformation in road embankments. It makes stable road embankments slopes, and it is available material everywhere in the world.

5.2.3 Slope 1:3

A summary of the results obtained from finite element studies using the PLAXIS 2D plain strain code for nature and polymer-based materials to reinforce road embankments with a slope ratio of 1:3. The extreme value of each model's horizontal displacement, vertical displacement, and effective stress are the outputs produced from the model. Both materials of nature-based and unnatured based used in geosynthetic geogrid in the same kind model of PLAXIS 2D

Table 5. 3: The results of FEA of a road embankment at slope 1:3 [9][appendix-C].

Slope V:H	Reinforcement	Reinforcement Layer		Geosynthetic Paramertric results			Basalt Paramertric results		
		Layer	at	Horizantal Displacement [mm]	Vertical Displacement [mm]	Effective mean stress [kN/m2]	Horizantal Displacement [mm]	Vertical Displacement [mm]	Effective mean stress [kN/m2]
1:3	Reinforcement with GG-1	Double	Bottom + Middle	23,82	109,53	132,51	46,58	27,57	57,72
			Bottom + Top	23,94	109,38	132,47	36	26	53
			MIddle + Top	28,47	112,29	132,49	35	28,69	51,87
	Reinforcement with GG-2	Double	Bottom + Middle	20,46	95,1	127,63	35,29	29,9	53,11
			Bottom + Top	20,53	94,78	127,6	38,37	24,48	53,13
			MIddle + Top	24,9	97,27	127,59	62,33	42,92	82,2
	Reinforcement with GG-3	Double	Bottom + Middle	17,6	81,08	122,77	34,54	29,54	52,82
			Bottom + Top	17,34	81,73	122,86	33,44	28,96	52,4
			MIddle + Top	21,52	82,46	122,69	62,17	57	91,38

Table (5.3) shows all calculated parameters by PLAXIS 2D of both materials, which are Nature-based Basalt and polymer-based materials, and these types of materials are used in geosynthetic geogrid. It is used two layers of geogrid in the road's embankment slopes. The rest of all details are given in appendix -A, and there are also calculated some other parameters which are not presented in the above-detailed information for the primary main purpose is to compare the results of both materials where they are relevant to compare side by side

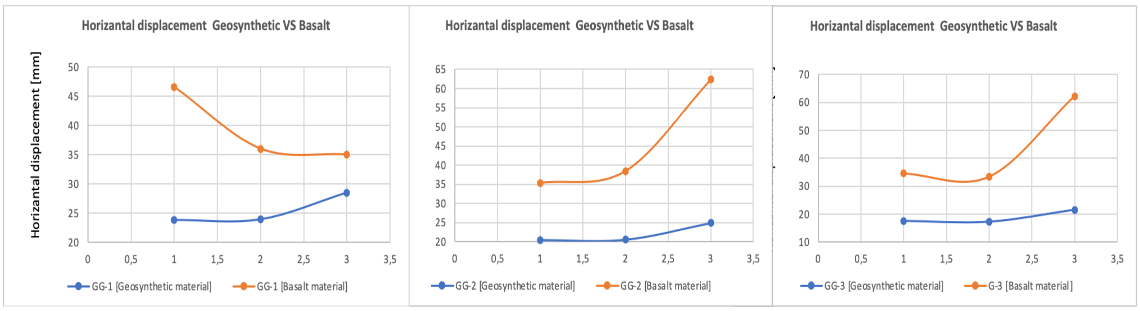

Figure 5. 9: Geogrid-1,2 and 3horizontal displacement Nature based material Vs Un-nature material

In the figure (5.9) depicts some results are given by numerical analysis, and in the case of horizontal displacement, basalt material shows the less resistance to polymer-based material, but it also depends on the arrangement of the layer to deploy in the reinforcement of embankment slopes. As mentioned in the table 5.3, there are three kinds of geogrid modeling such as top and bottom, bottom and middle and finally middle and bottom layer provided

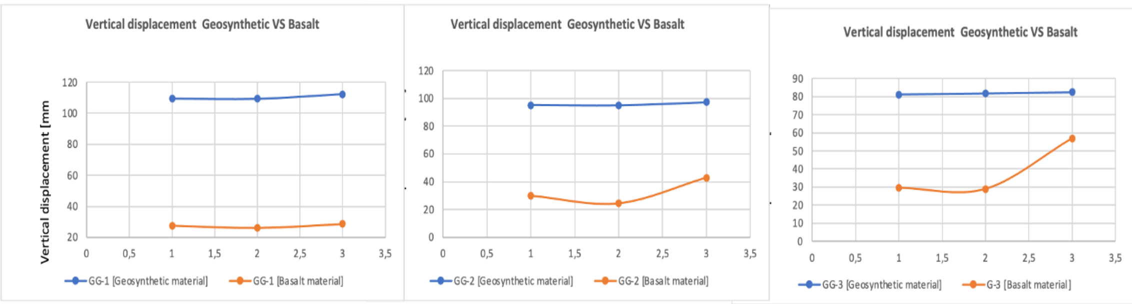

Figure 5. 10: Geogrid-1,2 and 3 Vertical displacements Nature based material VS Un-nature material

Figure (5.10) describes that nature-based material provides more strength in vertical deformation. In this case, it shows less settlement as compared to other materials. In addition, it gives more resistance against downward deflection of the embankment to control the settlement of roads, and it is environment-friendly material. Therefore, it is the best alternative to replace the polymer-based material used in geogrid.

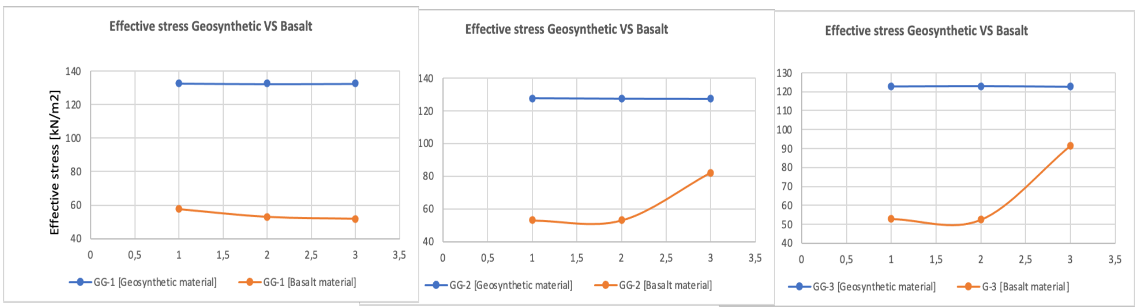

Figure 5. 11: Geogrid-1,2 and 3 Effective stress Nature based material Vs Un-nature material

Figure (5.11) shows results in the case of basalt materials with effective stress vary through the graph, and it relies on the arrangement of the layer of geogrid in the embankment. Meanwhile, the polymer-based material shows almost constant effective stress in three kinds of geogrid.

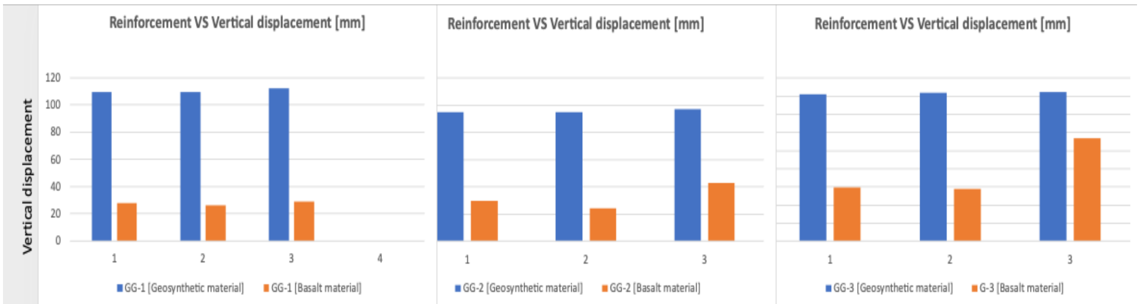

Figure 5. 12: Geogrid-1,2 and 3 Vertical displacements Nature based material Vs Un-nature material

As illustrated in the above figure (5.12), the nature-based material of basalt fiber is significantly strengthened concerning vertical settlement. It is more quietly resistant than polymer-based geogrid, so it is highly recommended for vertical deformation in road embankments. It makes stable road embankments slopes, and it is in a material available everywhere in the world.

5.3 Parametric study

The kind of geogrid utilized to support the road embankments and the side slope of the embankment are critical design characteristics that may impact the performance of the road embankment addressed in this work.

5.3.1 Effect of side slope

The slope of the embankments determines the lateral stability of a roadway structure. The influence of side slope choices for the road embankment model is 1:1.5, 1:2, and 1:3. In this FE modeling, vertical settlement, horizontal displacement, and effective stress are used to illustrate the impact of the side slope on the performance of the road embankment.

a) *Concerning horizontal displacement (lateral deformation)*

The impact on horizontal displacement for double-layered reinforcement is indicated in the relevant figures from (5.1,5.6 and 5.9). The finding suggests that horizontal displacement reduces as the side slope increases. Polymer-based material shows more strength in lateral deformation compared to nature-based material.

b) *Concerning vertical displacement (settlement)*

The figure above from (5.2, 5.7 and 5.10) illustrates the impact of the vertical displacement on the double-layered reinforcement. As seen in the graph, the result reveals that the vertical displacement reduces as the side slope increases. In the vertical settlement, nature-based material represents minor deformation downwards, making more stiffness soil properties.

*c) **Concerning effective stress***

The figure illustrates (5.3, 5.8 and 5.11) the effects of the effective stress for double-layered reinforcement. As seen in the graph, the result reveals that the effective stress reduces as the side slope increases. The slope's stability is an essential feature of embankment construction. The finding indicates that the gentler the slope, the minor deformation and settlement will occur. From the graph, the failure criteria often decrease when the ratio decreases from 1:1.5 to 1:2 and gradually from 1:2 to 1:3. Based on this conclusion, we may determine which side slopes are the most effective for designing a safe and cost-effective geogrid-reinforced road embankment. Therefore, nature-based basalt material shows relatively less effective stress than polymer-based material used in geosynthetic geogrid.

5.3.2 Effect of location of geogrid material

The influence on the effective stress for double-layered reinforcement considering the effects of geogrid reinforcement concerning the location of the road embankments is shown in the figures from (5.1 to 5.11). In this FE model, vertical settlement, horizontal displacement, and effective stress are used to illustrate the influence of a geogrid-reinforced layer on the performance of a road embankment and strengthened roadway bank. Furthermore, the arrangement of geogrid layers is affected by what kind of deformation occurs more so that location and what type of material is used also shows effects.

a) with respect to horizontal displacement

As shown in the figure above from (5.1, 5.6 and 5.9), the effect of the reinforcing position is applied at the "bottom," "middle," and "top" of the embankment for the single-layered reinforcement and at the "bottom + middle," "bottom + top," and "middle + top" for the double-layered reinforcement. The figures depicts the influence of reinforcing location on horizontal displacement for single- and double-layered reinforcement. The result suggests that bottom-layered reinforcement may minimize horizontal displacement more than middle- and top-layered reinforcement. Both materials are showings different values in lateral displacement.

b) With respect to vertical displacement

Figure (5.2, 5.7 and 5.10) depicts the influence of reinforcing position on vertical displacement for single- and double-layered reinforcements at their respective application layers. As shown in the figures, the result indicates that bottom-layered reinforcement may reduce vertical displacement slightly more than middle- and top-layered reinforcements. In addition, nature-based material shows less displacement in vertical displacement while used in geogrid than polymer-based material.

c) With respect to effective stress

Figure (5.3, 5.8 and 5.11) represents the impact of reinforcing location on the effective stress for single- and double-layered reinforcements at their respective application layers. As seen in the figures, the results indicate that the effectiveness of the bottom-layer reinforcement may be somewhat less than that of the middle-layer and top-layer reinforcement. This demonstrates that when the geogrid is deployed at the base of the embankment (i.e., above the soft soil), it may significantly affect the performance of road embankment materials. There is also respect to effective stresses polymer-based material while placed in the geosynthetic geogrid to provide poor results compared to basalt fiber.

5.3.3 Effect of Geogrid Type and Number of Reinforcement Layers

The impact of geogrid reinforcing type and number of layers applied to a road embankment was determined below. In this investigation, classes I (GG-I), II (GG-II), and III (GG-III) geogrids were used (GG-III). In addition, the number of reinforcement layers employed in road embankments and a double reinforcement layer. In this FE model, vertical settlement, horizontal displacement, and effective stress are used to illustrate the influence of a geogrid-reinforced layer on the performance of a road embankment.

a) With respect to horizontal displacement

The figures illustrates in (5.1, 5.6 and 5.9) the effect of geogrid type concerning layer. Although polymer-based material minimizes lateral stresses, whereas the basalt fiber shows more lateral displacement, the type III (GG-III) geogrid reinforcement is more advantageous than the other two.

b) With respect to vertical displacement

Figures from (5.2, 5.7 and 5.10) illustrate the effect of reinforcing location on vertical displacement for single- and double-layered reinforcement at their respective application layer. As shown in the figure, the result suggests that the bottom-layered reinforcement may minimize vertical displacement somewhat more than the middle- and top-layered reinforcement. In both conditions, nature-based and unnurtured-based material uses in geogrid.

c) With respect to effective stress

Figures from (5.3, 5.8 and 5.11) illustrate the impact of reinforcing location on the effective stress for single- and double-layered reinforcements at their respective application layers. As seen in the graph, the result demonstrates that the effective stress reduces as the side slope increases. This indicates that when geogrid is laid at the bottom of the embankment (i.e., above the soft soil), it might significantly impact the performance of the road embankment. Both materials improve the stability of the embankments of roads, but basalt fiber provides more stability to the road embankments than polymer-based geogrid.

5.4 Validation of finite element analysis

The FEM is a solid investigative tool that outperforms laboratory trials and large-scale field testing in many ways. The FEM, on the other hand, is still an approximation approach that idealizes real-life circumstances into a series of continuum components and uses constitutive models to predict soil behavior. Therefore, validation of the FEM output is required to guarantee that the real-world scenario is appropriately simulated.

Finite element studies were initially compared to laboratory model experiments for geogrid reinforced road embankment on silty clay subgrade soil published [98] to evaluate the adequacy of the selected material models for the soil geogrids interaction. Steel plates with dimensions of 150 mm x 150 mm x 25 mm (length, breadth, and height) were employed in the laboratory, and the model tests were carried out in a 1.5 m long, 0.9 m wide, and 0.9 m deep steel box. Figure 5.13 show a comparison of finite element studies and laboratory model testing for one-layer geogrid reinforced road embankments on silty clay subgrade soil.

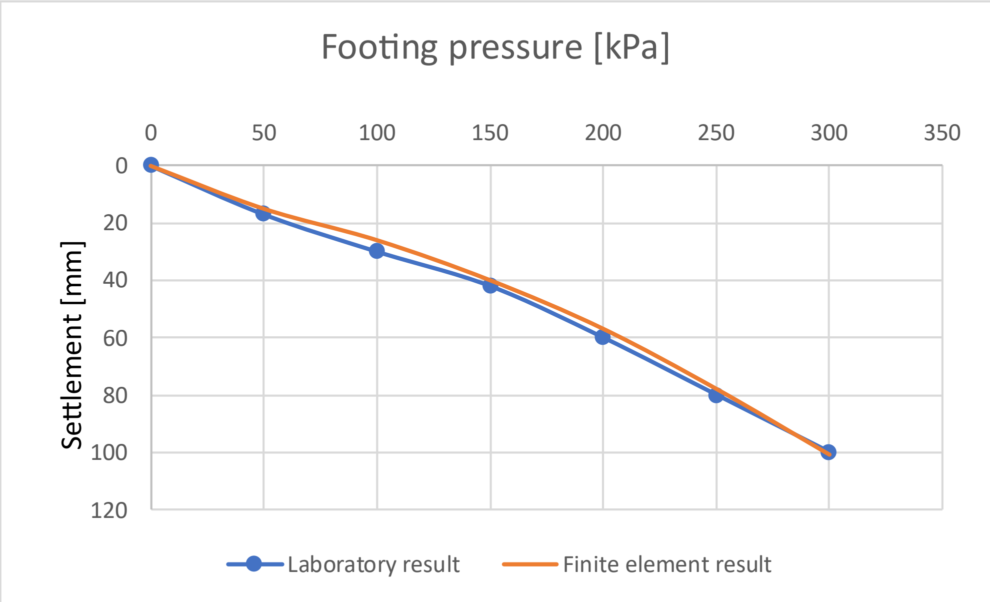

Figure 5. 13: Laboratory result vs Finite element method

With reinforcement in the embankment, the effect depth may greatly minimize to produce vertical stresses. Therefore, the soil's consolidation settling will be reduced. The stiffer geogrids reduce center stresses better than the less stiff geogrids because of their higher stiffness and geometric shape. In addition, reinforcement may provide a "surcharge effect," which prevents soil from sliding higher and improves clay's bearing capability. A series of two-dimensional finite element analyses were conducted to investigate the effect of critical design factors on the performance of geogrid-reinforced road embankments. The road embankment modeled in a 2D FEA simulation with varying side slope, geogrid layer arrangement, and the geogrid standard was analyzed in terms of lateral deformation (horizontal displacement), settlement (vertical displacement), and effective stress.

Due to its high compressibility, the design of foundations on poor soils is often driven by settlement scenarios rather than bearing capacity standards. The emphasis of this work was on the deformation performance of road embankments. Consequently, the performance of a geogrid-reinforced road embankment under operating loads is of the utmost significance. Based on parametric analysis of the geogrid-reinforced road embankment with a side slope of 1:2, a double layer of type III geogrid positioned at the base of the embankment is chosen and suggested as the most practical combination of the remaining alternatives.

In the comparison, two types of materials are used in geosynthetic geogrid. Nature-based material is better for strengthening properties to control vertical settlement and effective stress to improve stiffness properties of the embankment of roads. Therefore, it is preferred use to make geogrid instead of polymer-based material. However, there is still required to work more on nature-based material, especially in the laboratory side, to judge the actual material behavior of geogrid while used to stabilize the road's embankment. Therefore, they compared both materials in different ways as much as possible to reach where they are relevant.

Chapter 6

6. Summary and Conclusions

A variety of preliminary checks for analysis and subsequent FEA were performed in this work. The most extreme values of horizontal displacement (Ux), vertical displacement (Uy), and effective stress (Ó) of each model were obtained and compared to two distinct materials used in geosynthetic geogrid. One of which is a nature-based material called Basalt and the other being a synthetic material. Consequently, the outcomes in both scenarios varied depending on the slopes and the material utilized in the geogrid. When multiple results were compared, each showed a different effect material. Two other materials were used in the geogrid and the same model. However, the results were inconsistent. As in this project, alternative and environmentally acceptable materials were sought to substitute synthetic materials while stabilizing the embankment of a smooth road using geogrids.

Based on the results of the numerical modeling analysis of nature-based material to use in geogrid to reinforce road embankments, the following conclusion can be drawn

- The geogrid comparing the parametric study was reinforced while using two types of material in geogrid in stabilizing road embankment slope 1:1.5, when a double layer of geogrid to the reinforced embankment of the road. Meanwhile, nature-based material shows minor deformation in vertical displacement than polymer-based material. Furthermore, basalt material is provided more strength than synthetic material.
- Slopes 1:2 and 1:3 has happened, the same as slope 1:1.5 because, in the case of vertical displacement, basalt material is provided more strength than synthetic material compared to both materials' results. Still, in the horizontal deformation case, the basalt material provided less power than geosynthetic material.
- The effective stress values are increased significantly while using geosynthetic material in geogrid; meanwhile, the effective stresses values is started to decrease in basalt material used in geogrid on all slopes.
- Basalt fiber reinforced under an embankment can reduce vertical and horizontal displacement, but it is generally more effective in reducing vertical displacement. The reduction in displacements obtained is a function of the shear strength and depth of the soft clay layer.

Chapter 7

7. Recommendations and Further Works

Based on the present study's findings, it is evident that further research in this field can yield practical and valuable results. Hence, future studies should focus on:

- Laboratory-scale and full-scale model tests are unavailable using nature-based basalt material geogrid for soil reinforcement. They are strongly recommended to be carried out to get a real validation of material properties and their performance in geotechnical uses.
- They use the finite element model for reinforced road embankments to simulate a full-scale geogrid reinforced approach in the lab and compare the finite element results with field measurement from monitoring instrument embankments.
- The basalt material has limited study and searches material, so there is a need to use basalt fiber in geogrid. They should perform some tests to analyze all strength parameters of Basalt fiber-based geogrid and then compare numerical analysis with laboratory results.
- Basalt nature-based material should be used alternative material in geosynthetic geogrid. It gives more resistance to vertical deformation in road embankments, so they need to work more on it to elaborate its properties and uses.

References

1. Shukla, S.K. and J.-H. Yin, *Fundamentals of geosynthetic engineering*. 2006: CRC Press.
2. Jones, C.J., *Earth reinforcement and soil structures*. 2013: Elsevier.
3. Quinteros, V.S., *Observations on the mobilization of strength in reinforced soil structures*. 2014, University of British Columbia.
4. Koerner, R., *Designing with Geosynthetics. Prentice Hall, Upper Saddle River.* 2005.
5. Bieliatynskyi, A., et al., *Basalt Fiber Geomats–Modern Material for Reinforcing the Motor Road Embankment Slopes.* Transportation Research Procedia, 2021. **54**: p. 744-757.
6. Othman, B.A., *Performance of embankment on Bamboo-geotextile composite reinforced soft clay*. 2012, Universiti Teknologi Malaysia.
7. Khan, S.A. and S.M. Abbas, *Numerical modelling of highway embankment by different ground improvement techniques.* International Journal of Innovative Research in Advance Engineering, 2014. **1**(10): p. 350-356.
8. Datye, K., *Simpler technique for ground improvements.* Fourth IGS Annual Lectures, IGJ, 1982. **12**: p. 1-82.
9. Hausmann, M.R., *Engineering principles of ground modification*. 1990.
10. Liu, J., *Compensation grouting to reduce settlement of buildings during an adjacent deep excavation*, in *Grouting and Ground Treatment*. 2003. p. 837-844.
11. Binquet, J. and K.L. Lee, *Bearing capacity tests on reinforced earth slabs.* Journal of the geotechnical Engineering Division, 1975. **101**(12): p. 1241-1255.
12. Morsy, A.M. and J.G. Zornberg, *Soil-reinforcement interaction: Stress regime evolution in geosynthetic-reinforced soils.* Geotextiles and Geomembranes, 2021. **49**(1): p. 323-342.
13. Sharma, R., et al., *Analytical modeling of geogrid reinforced soil foundation.* Geotextiles and Geomembranes, 2009. **27**(1): p. 63-72.
14. Rajak, D.K., et al., *Recent progress of reinforcement materials: a comprehensive overview of composite materials.* Journal of Materials Research and Technology, 2019. **8**(6): p. 6354-6374.
15. Kaware, A., U. Awari, and M. Wakchaure, *Review of bamboo as reinforcement material in concrete structure.* International Journal of Innovative Research in Science, Engineering and Technology, 2013. **2**(6): p. 2461-2464.
16. Shukla, S.K., *Geosynthetics and ground engineering: sustainability considerations*. 2021, Springer. p. 1-3.
17. Look, B.G., *Handbook of geotechnical investigation and design tables*. 2007: Taylor & Francis.
18. Moayedi, H., et al., *Effect of geogrid reinforcement location in paved road improvement.* Electronic Journal of Geotechnical Engineering, 2009. **14**: p. 1-11.
19. Wu, P., A. Molenaar, and I. Houben, *Cement-bound road base materials.* Delft University of Technology, PowerCem Technologies: Delft, The Netherlands, 2011.
20. Abramson, L.W., et al., *Slope stability and stabilization methods.. John Wiley&Sons.* Inc, New York, USA, 2002.
21. Abramson, L.W., et al., *Slope stability and stabilization methods*. 2001: John Wiley & Sons.

22. Authority, E.R. and E.R. AUTHORIT, *Pavement Design Manual.* Addis Ababa, 2002.
23. Riad, H.L., et al. *Design of lightweight fills for road embankments on Boston's central artery/tunnel project*. in *Proceedings: Fifth international conference on case histories in geotechnical engineering*. 2004.
24. Balic, A., E. Hadzalic, and S. Dolarevic, *Numerical analysis of embankment primary consolidation with porosity-dependent and strain-dependent coefficient of permeability.* Coupled systems mechanics, 2022. **11**(2): p. 93-106.
25. Mamat, R.C., et al., *Artificial neural networks in slope of road embankment stability applications: a review and future perspectives.* International Journal of Advanced Technology and Engineering Exploration, 2021. **8**(75): p. 304.
26. Mamat, R.C., A. Kasa, and S.F.M. Razali, *A review of road embankment stability on soft ground: problems and future perspective.* IIUM Engineering Journal, 2019. **20**(2): p. 32-56.
27. Hearn, G., *The ERA Route Selection Manual.* 2013.
28. Wulandari, P.S. and D. Tjandra, *Analysis of geotextile reinforced road embankment using PLAXIS 2D.* Procedia Engineering, 2015. **125**: p. 358-362.
29. Alimohammadi, H., et al., *Evaluation of geogrid reinforcement of flexible pavement performance: A review of large-scale laboratory studies.* Transportation Geotechnics, 2021. **27**: p. 100471.
30. Kwon, J. and E. Tutumluer, *Geogrid base reinforcement with aggregate interlock and modeling of associated stiffness enhancement in mechanistic pavement analysis.* Transportation research record, 2009. **2116**(1): p. 85-95.
31. Dennis, A.R. and S.T. Kinney, *Testing media richness theory in the new media: The effects of cues, feedback, and task equivocality.* Information systems research, 1998. **9**(3): p. 256-274.
32. Nazzal, M.D., *Laboratory characterization and numerical modeling of geogrid reinforced bases in flexible pavements.* 2007.
33. Berg, B., *Litter decomposition and organic matter turnover in northern forest soils.* Forest ecology and Management, 2000. **133**(1-2): p. 13-22.
34. Al-Qadi, I.L., et al., *Laboratory evaluation of geosynthetic-reinforced pavement sections.* Transportation research record, 1994(1439): p. 25-31.
35. Cancelli, A. and F. Montanelli, *In-ground test for geosynthetic reinforced flexible paved roads*. 1999.
36. Moghaddas-Nejad, F. and J.C. Small, *Effect of geogrid reinforcement in model track tests on pavements.* Journal of transportation engineering, 1996. **122**(6): p. 468-474.
37. ZORNbERG, J.G. *Advances in the use of geosynthetics in pavement design*. in *Second National Conference on Geosynthetics*. 2011.
38. Koerner, R.M., *Designing with geosynthetics-Vol. 1*. Vol. 1. 2012: Xlibris Corporation.
39. Wasage, T., et al., *Laboratory evaluation of rutting resistance of geosynthetics reinforced asphalt pavement.* Journal of the Institution of Engineers, 2004. **44**(2): p. 29-44.
40. Al-Qadi, I.L., et al., *Dynamic analysis and in situ validation of perpetual pavement response to vehicular loading.* Transportation research record, 2008. **2087**(1): p. 29-39.
41. Anderson, P. and M. Killeavy. *Geotextiles and Geogrids: cost effective alternate materials for pavement design and construction*. in *Geosynthetics, Conference, 1989, San diego, California, USA*. 1989.

42. Chan, F., R.D. Barksdale, and S.F. Brown, *Aggregate base reinforcement of surfaced pavements.* Geotextiles and Geomembranes, 1989. **8**(3): p. 165-189.
43. Perkins, S., *Mechanical response of geosynthetic-reinforced flexible pavements.* Geosynthetics international, 1999. **6**(5): p. 347-382.
44. Bender, D.A. and E.J. Barenberg, *Design and behavior of soil-fabric-aggregate systems.* Transportation Research Record, 1978(671).
45. Nanni, A., M.S. Norris, and N. Bradford, *Lateral confinement of concrete using FRP reinforcement.* Special Publication, 1993. **138**: p. 193-210.
46. Perkins, S.W., *Mechanistic-empirical Modeling and Design Model Development of Geosynthetic Reinforced Flexible Pavements: Appendix C--DARWin Output*. 2001, Western Transportation Institute, Department of Civil Engineering, Montana ….
47. Namdar, A., *Forecasting bearing capacity of the mixed soil using artificial neural networking.* Frattura Ed Integrità Strutturale, 2020. **14**(53): p. 285-294.
48. Giroud, J.-P. and L. Noiray, *Geotextile-reinforced unpaved road design.* Journal of the Geotechnical Engineering Division, 1981. **107**(9): p. 1233-1254.
49. Subaida, E., S. Chandrakaran, and N. Sankar, *Laboratory performance of unpaved roads reinforced with woven coir geotextiles.* Geotextiles and geomembranes, 2009. **27**(3): p. 204-210.
50. O'Connor, P.J., et al., *Mood state and salivary cortisol levels following overtraining in female swimmers.* Psychoneuroendocrinology, 1989. **14**(4): p. 303-310.
51. Dafalias, Y. and E. Popov, *A model of nonlinearly hardening materials for complex loading.* Acta mechanica, 1975. **21**(3): p. 173-192.
52. McVay, M. and Y. Taesiri, *Cyclic behavior of pavement base materials.* Journal of Geotechnical Engineering, 1985. **111**(1): p. 1-17.
53. Bathe, K.J., *Finite element method.* Wiley encyclopedia of computer science and engineering, 2007: p. 1-12.
54. Perkins, C.E., et al., *Performance comparison of two on-demand routing protocols for ad hoc networks.* IEEE Personal communications, 2001. **8**(1): p. 16-28.
55. Tao, M., et al., *Application of shakedown theory in characterizing traditional and recycled pavement base materials.* Journal of Transportation Engineering, 2010. **136**(3): p. 214-222.
56. Leng, J. and M.A. Gabr, *Numerical analysis of stress–deformation response in reinforced unpaved road sections.* Geosynthetics International, 2005. **12**(2): p. 111-119.
57. Miura, N., et al., *Polymer grid reinforced pavement on soft clay grounds.* geotextiles and geomembranes, 1990. **9**(1): p. 99-123.
58. Andrii Bieliatynskyia, Kateryna Krayushkinab, Vera Breskichc,d, Mikhail Lunyakovd, *Basalt Fiber Geomats – Modern Material for Reinforcing the Motor Road Embankment Slopes.* 2021.
59. Gamelak, I., V. Kostritsky, and L. Artemenko, *Problems of using geosynthetic materials in road construction and ways of solving them.* KNUDT Bull, 2009. **6**: p. 17-27.
60. Codispoti, R., et al., *Mechanical performance of natural fiber-reinforced composites for the strengthening of masonry.* Composites Part B: Engineering, 2015. **77**: p. 74-83.
61. Rao, J., et al., *Plasma surface modification and bonding enhancement for bamboo composites.* Composites Part B: Engineering, 2018. **138**: p. 157-167.

62. Ross, A., *Basalt fibers: alternative to glass?* Composites Technology, 2006. **12**(4).
63. Dhand, V., et al., *A short review on basalt fiber reinforced polymer composites.* Composites Part B: Engineering, 2015. **73**: p. 166-180.
64. Singha, K., *A short review on basalt fiber.* International Journal of Textile Science, 2012. **1**(4): p. 19-28.
65. Perevozchikova, B.V., et al., *Quality Evaluation of the Kuluevskaya Basalt Outcrop for the Production of Mineral Fiber, Southern Urals, Russia.* Energy Procedia, 2014. **59**: p. 309-314.
66. Fangueiro, R., *Fibrous and composite materials for civil engineering applications*. 2011: Elsevier.
67. Brandt, A.M., *Fibre reinforced cement-based (FRC) composites after over 40 years of development in building and civil engineering.* Composite Structures, 2008. **86**(1): p. 3-9.
68. Rapp, G., *Archaeomineralogy*. 2009: Springer Science & Business Media.
69. Dhé, P., *Filament composed of basalt.* Google Patents, 1922.
70. Monaldo, E., F. Nerilli, and G. Vairo, *Basalt-based fiber-reinforced materials and structural applications in civil engineering.* Composite Structures, 2019. **214**: p. 246-263.
71. Lee, J.J., I. Nam, and H. Kim, *Thermal stability and physical properties of epoxy composite reinforced with silane treated basalt fiber.* Fibers and Polymers, 2017. **18**(1): p. 140-147.
72. Jung, T. and R.V. Subramanian, *Strengthening of basalt fiber by alumina addition.* Scripta Metallurgica et Materialia, 1993. **28**(4): p. 527-532.
73. Subramanian, R. and K.-H.H. Shu, *Silane coupling agents for basalt fiber reinforced polymer composites*, in *Molecular characterization of composite interfaces*. 1985, Springer. p. 205-236.
74. Brik, V., *Performance evaluation of basalt fibers and composite rebars as concrete reinforcement.* Tech Res submitted to NCHRP-IDEA, 1999: p. 1-97.
75. Industry, M.I.S.M.G., *Analysis, Size, Share, Growth, Trends & Forecast 2013–2019. Transparency Market Research. Albany (NY)*. 2014, Tech. Rept.
76. Jamshaid, H. and R. Mishra, *A green material from rock: basalt fiber–a review.* The Journal of The Textile Institute, 2016. **107**(7): p. 923-937.
77. Czigány, T., J. Vad, and K. Pölöskei, *Basalt fiber as a reinforcement of polymer composites.* Periodica Polytechnica Mechanical Engineering, 2005. **49**(1): p. 3-14.
78. Novitskii, A.G. and M.V. Efremov, *Technological aspects of the suitability of rocks from different deposits for the production of continuous basalt fiber.* Glass and Ceramics, 2013. **69**(11): p. 409-412.
79. Vas, L., et al., *Theoretical and experimental study of the effect of fiber heads on the mechanical properties of non-continuous basalt fiber reinforced composites.* Express Polymer Letters, 2007. **1**(2): p. 109-121.
80. Sim, J. and C. Park, *Characteristics of basalt fiber as a strengthening material for concrete structures.* Composites Part B: Engineering, 2005. **36**(6-7): p. 504-512.
81. Li, Z., et al. *Properties and applications of basalt fiber and its composites*. in *IOP Conference Series: Earth and Environmental Science*. 2018. IOP Publishing.
82. Zoltan, K., S. Sandor, and C. Tibor, *Production and investigation of biologically degradable matrix polymer composites reinforced with basalt fiber.* Muanyag Es Gumi/Plastics and Rubber, 2004. **41**(7): p. 285.

83. Hao, Y. and J. Xiao, *High-performance composite materials science.* Chemical Industry and Engineering Press, Beijing. Li, X., Marasteanu, M., Williams, RC and Clyne, TR (2008).“Effect of Reclaimed Asphalt Pavmeent (Proportion and Type) and Binder Grade on Asphalt Mixtures.” Journal of the Transportation Research Board, 2004. **2051**: p. 90-97.
84. Tatarintseva, O., T. Uglova, and G. Igonin, *J. Determination of operation times of basalt-fiber thermal insulating materials.* Stroitel’nye Materialy, 2004.
85. Sezemanas, G., et al., *The alkali and temperature resistance of some fibres.* Mater Sci, 2005. **11**(1): p. 29-35.
86. Toropina, L., et al., *New cloth from basalt fibres.* Fibre Chemistry, 1995. **27**(1): p. 67-68.
87. Haeberle, D., et al. *Performance and interfacial stresses in the polymer wear surface/FRP deck bond due to thermal loading*. in *Advanced Composite Materials in Bridges and Structures: 3rd International Conference*. 2000.
88. Ólafsson, H. and E. Þórhallsson, *Basalt fiber bar reinforcement of concrete structures.* Reykjavík University, 2009: p. 5-12.
89. Sergeev, V., Y.N. Chuvashov, and O. Galushchak, *Basalt fibers-a reinforcing filler for composites.* Powder Metallurgy and Metal Ceramics, 1995. **33**(9-10).
90. Wei, B., H. Cao, and S. Song, *Tensile behavior contrast of basalt and glass fibers after chemical treatment.* Materials & Design, 2010. **31**(9): p. 4244-4250.
91. Swink, M. *Continuous filament basalt*. in *Techtextil North America Symposium Atlanta, GA, USA*. 2002.
92. Czigány, T., *Discontinuous basalt fiber-reinforced hybrid composites*, in *Polymer composites*. 2005, Springer. p. 309-328.
93. Dorigato, A. and A. Pegoretti, *Fatigue resistance of basalt fibers-reinforced laminates.* Journal of Composite Materials, 2012. **46**(15): p. 1773-1785.
94. Dias, D.P. and C. Thaumaturgo, *Fracture toughness of geopolymeric concretes reinforced with basalt fibers.* Cement and concrete composites, 2005. **27**(1): p. 49-54.
95. Al Ammari, K. and B. Clarke. *Predicting the effect of vibro stone column installation on performance of reinforced foundations*. in *International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering*. 2016. World Academy of Science, Engineering and Technology.
96. Killeen, M., *Numerical modelling of small groups of stone columns.* National University of Ireland, Galway, 2012.
97. Chiang, J., et al., *Finite element analysis and design method of geosynthetic-reinforced soil foundation subjected to normal fault movement.* Computers and Geotechnics, 2021. **139**: p. 104412.
98. Chen, Q., et al., *Laboratory investigation of behavior of foundations on geosynthetic-reinforced clayey soil.* Transportation research record, 2007. **2004**(1): p. 28-38.

APPENDIX-A: Slope 1:1.5 Numerical Analysis

Table A 1: Reinforcement Vs Horizontal displacement [m]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	0.05078	0.05074	0.05069
[Top + Middle]	0.05405	0.05402	0.05405
[Middle + Bottom]	0.03371	0.03419	0.03351
[Top + Middle + Bottom]	0.051	0.051	0.051

Table A 2: Reinforcement Vs Deformed mesh[m]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	0.07932	0.07935	0.07920
[Top + Middle]	0.09389	0.09385	0.09391
[Middle + Bottom]	0.05433	0.05506	0.05394

Table A 3: Reinforcement Vs Total displacement [m]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	0.07932	0.07935	0.0720
[Top + Middle]	0.09389	0.09385	0.09391
[Middle + Bottom]	0.05433	0.05506	0.05394
[Top + Middle + Bottom]	0.79	0.79	0.78

Table A 4 : Reinforcement Vs Effective stress [kN/m^2]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	112.3	105.6	102.1
[Top + Middle]	112.9	130.9	110.2
[Middle + Bottom]	69.02	69.11	68.99
[Top + Middle + Bottom]	91.00	91.00	95.00

Table A 5: Reinforced Vs Effective stress [$ó_{XX}$][kN/m^2]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	57.19	54.33	48.88
[Top + Middle]	61.93	68.01	68.38
[Middle + Bottom]	46.97	46.96	46.96
[Top + Middle + Bottom]	47	51	50

Table A 6: Reinforcement Vs Effective stress [$ó_{yy}$][kN/m2]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	91.77	89.04	92.61
[Top + Middle]	96.49	95.67	93.81
[Middle + Bottom]	69.12	69.15	69.11
[Top + Middle + Bottom]	79	93	89

Table A 7: Reinforcement Vs Total displacement [m]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	0.01916	0.01916	0.0190
[Top + Middle]	0.0213	0.0213	0.0213
[Middle + Bottom]	0.014	0.0144	0.0142
[Top + Middle + Bottom]	0.01833	0.01833	0.01833

APPENDIX-B: Slope 1:2 Numerical Analysis

Table B 1:Reinforcement Vs Vertical displacement [m]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	0.03172		0.01993
[Top+ Middle]	0.06515	0.06491	0.06493
[Middle + Bottom]	0.03962	0.01003	0.03971
[Top + Middle + Bottom]	0.043	0,0447	0.044

Table B 2: Reinforcement Vs Horizontal displacement [m]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	0.04847		0.04549
[Top + Middle]	0.06907	0.06902	0.06904
[Middle + Bottom]	0.05588	0.03899	0.05549
[Top + Middle + Bottom]	0.0377	0.0388	0.0388

Table B 3:Reinforcement Vs Deformed mesh[m]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	0.06145	0.061	0.05906
[Top + Middle]	0.07888	0.05470	0.07884
[Middle + Bottom]	0.06742	0.07882	0.06745
[Top + Middle + Bottom]	0.05364	0.05432	0.05379

Table B 4:Reinforcement Vs Total displacement [m]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	0.06145	0.061	0.05906
[Top + Middle]	0.07888	0.05470	0.07884
[Middle + Bottom]	0.06742	0.07882	0.06745
[Top + Middle + Bottom]	0.05364	0.532	0.05379

Table B 5: Reinforcement Vs Effective stress [kN/m2]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	50.88	63.81	50.83
[Top + Middle]	95.31	50.92	105.3
[Middle + Bottom]	59.90	92.47	60
[Top + Middle + Bottom]	50.61	50.85	50.63

Table B 6:Reinforcement Vs Effective Stress [ó$_{XX}$][kN/m^2]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	26.99	44.19	25.86
[Top + Middle]	44.61	25.70	46.61
[Middle + Bottom]	30.57	45.29	30.58
[Top + Middle + Bottom]	25.56	25.66	25.56

Table B 7:Reinforcement Vs Effective stress [óyy][kN/m2]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	50.51	63.95	48.12
[Top + Middle]	85.95	48.18	99.19
[Middle + Bottom]	59.91	82.67	60.02
[Top + Middle + Bottom]	48.16	48.19	48.17

APPENDIX-C: Slope 1:3 Numerical Analysis

Table C 1:Reinforcement Vs Vertical displacement [m]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	0.02630	0.01991	0.02896
[Top + Middle]	0.02869	0.06061	0.05705
(Middle + Bottom]	0.03052	0.02990	0.02954
[Top + Middle + Bottom]	0,027	0,027	0,027

Table C 2:Reinforcement Vs Horizontal displacement [m]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	0.03601	0.03837	0.03344
[Top + Middle]	0.03502	0.06233	0.06217
[Middle + Bottom]	0.04658	0.03529	0.03454
[Top + Middle + Bottom]	0,0315	0,036	0,03

Table C 3:Reinforcement Vs Deformed mesh[m]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	0.04449	0.04546	0.04249
[Top + Middle]	0.04517	0.06791	0.06778
[Middle + Bottom]	0.05361	0.0441	0.04346
[Top + Middle + Bottom]	0.04099	0.04529	0.04028

Table C 4:Reinforcement Vs Total displacement [m]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	0.04449	0.04546	0.04249
[Top + Middle]	0.04517	0.06791	0.06778
[Middle + Bottom]	0.05361	0.0441	0.04346
[Top + Middle + Bottom]	0.04099	0.04529	0.04028

Table C 5:Reinforcement Vs Effective stress [kN/m2]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	53.13	53.13	52.40
[Top + Middle]	51.87	82.20	91.38
[Middle + Bottom]	57.72	53.11	52.82
[Top + Middle + Bottom]	52,83	52.84	51.35

Table C 6:Reinforcement Vs Effective Stress [ó$_{XX}$][kN/m2]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	34.73	34.72	34.76
[Top + Middle]	34.64	47.92	
[Middle + Bottom]	34.86	34.71	34.77
[Top + Middle + Bottom]	34.732	34.72	34.71

Table C 7:Reinforcement Vs Effective stress [óyy][kN/m2]

Type of material	Basalt	Basalt	Basalt
Reinforcement	GG-1	GG-11	GG-111
[Top + Bottom]	49.15	48.20	48.61
[Top + Middle]	46.41	77.32	
[Middle + Bottom]	57.82	49.02	48.76
[Top + Middle + Bottom]	48.52	48.12	48.11

APPENDIX-D: Basal fiber material Properties for geogrid

DAkkS Deutsche Akkreditierungsstelle D-PL-11239-01-00

Sächsisches Textilforschungsinstitut e. V.
Prüfstelle
23.03.16

stfi SÄCHSISCHES TEXTIL FORSCHUNGS INSTITUT e.V.

Prüfnorm	: DIN EN ISO 10319	Prüfdatum	: 27.10.2014
Auftragsnummer	: i20145266 T704_14	Prüfer	: 203
Probennr.	: 02 MD	Prüfmaschine	: Zwick TC-FR250SN.A4K
Artikel	: 550 M-A	Spannzeuge	: Hydr. Klemme M 250 HY-ME-2XL
Material	: Basaltgitter	Kraftsensor	: GTM Serie K, 250kN
		Wegsensor	: Videoextensometer

Feinheit	: 67200	tex	Prüflingsbreite	: 224	mm
Dichte des Probenmaterials	: 2,8	g/cm³	Beginn E-Modulermittlung	: 0,5	%
Vorkraft	: 290	N	Ende E-Modulermittlung	: 1	%
Einspannlänge bei Startposition	: 100	mm	Bemerkung	:	
Prüfgeschwindigkeit	: 70	mm/min	Einlagen	: Stahl glatt + CSG beidseitig	

Ergebnisse:

Nr	F_M N	F_M N/cm	R_H cN/tex	σ_M MPa	ε_M %	E_t GPa	$t_{Prüfung}$ s	S_0 mm²	Anmerkung
1	28283,15	1262,64	42,09	1178,46	1,45	90,6	4,64	24,00	Anzahl tragender Stränge: 7
2	32537,45	1452,56	48,42	1355,73	1,57	91,7	5,05	24,00	Anzahl tragender Stränge: 7
3	29168,12	1302,15	43,40	1215,34	1,48	87,3	4,90	24,00	Anzahl tragender Stränge: 7
4	28375,29	1266,75	42,23	1182,30	1,54	80,0	5,36	24,00	Anzahl tragender Stränge: 7
5	27848,35	1243,23	41,44	1160,35	1,47	89,0	5,16	24,00	Anzahl tragender Stränge: 7

Statistik:

Serie n = 5	F_M N	F_M N/cm	R_H cN/tex	σ_M MPa	ε_M %	E_t GPa	$t_{Prüfung}$ s	S_0 mm²
x	29242,47	1305,47	43,52	1218,44	1,50	87,7	5,02	24,00
s	1902,52	84,93	2,83	79,27	0,05	4,64	0,27	0,00
ν	6,51	6,51	6,51	6,51	3,43	5,29	5,44	0,00

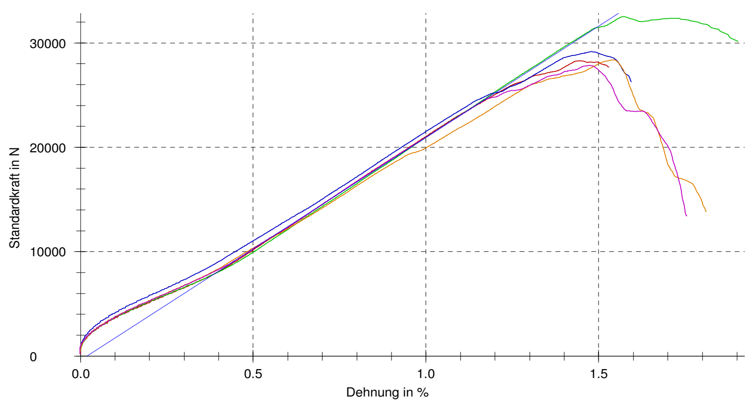

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Figure D 1.1: Basalt material result in Laboratory

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Science and Technology