A mini project report on

"GEOTECHNICAL INNOVATION FOR TRANSPORT INFRASTRUCTURE"

Submitted in Partial Fulfillment of the Requirement for the Award of the Degree of

MASTER OF TECHNOLOGY

IN

CIVIL ENGINEERING

(With specialization in Geotechnical Engineering)

Under

Assam Science & Technology University

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Submitted by

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DECLARATION

I hereby declare that the mini project "**GEOTECHNICAL INNOVATION FOR TRANSPORT INFRASTRUCTURE**" in partial fulfillment of the requirement for the award of the degree of " MASTER OF TECHNOLOGY" in Civil Engineering (With specialization in Geotechnical Engineering), submitted in the Department of Civil Engineering, Assam Engineering College, Jalukbari, Guwahati-13 under Assam Science & Technology University, is a real record of the work carried out in the said college for six months under the supervision of Dr. Sasanka Borah, Associate Professor, Department of Civil Engineering, Assam Engineering College, Jalukbari, Guwahati-13.

Do hereby declare that this project report is solemnly done by me and is my effort and that no part of it has been plagiarized without citation.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

This study is about transportation geotechnics. Transportation geotechnics integrates geotechnical engineering principles into planning, construction, and maintenance of transportation infrastructures such as roads, highways, railways, bridges, and tunnels, vital yet resource-intensive infrastructures that demand significant attention with respect to sustainable practices. Recently, there has been a growing emphasis on implementing sustainability approaches in transportation geotechnics. This shift holds promise for environmental, economic, and societal sustainability, with potential benefits that include reducing the construction industry's carbon footprint, conserving natural resources, minimizing harmful emissions, and lowering transportation infrastructure costs. This review explores diverse strategies for advancing sustainability in transportation geotechnics, encompassing innovative materials, ground improvement techniques, and use of geosynthetics.

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CHAPTER 1

INTRODUCTION

1.1 Transport Geotechnics

Transportation geotechnics is a crucial field that plays a pivotal role in ensuring safe and efficient movement of people and goods on our roadways, railways, and other transportation infrastructure. By studying the behavior of soils and rocks in the context of transportation projects, pavement/railroad engineers can design and construct stable and durable foundations, embankments, tunnels, and retaining walls. Understanding the properties of the underlying ground is essential for preventing failures, minimizing settlements, and ensuring adequate performance under traffic loading. By addressing geotechnical challenges appropriately, transportation infrastructure can become more resilient, cost-effective, and sustainable, thus improving the overall safety and connectivity of our global transportation networks.

Additionally, transportation geotechnics play a crucial role in environmental preservation and sustainability. With the growing emphasis on reducing carbon emissions and promoting eco-friendly practices, geotechnical engineers are tasked with developing transportation infrastructure that has minimal impact on the environment. By carefully selecting construction materials and designing solutions that minimize excavation and disturbance of natural landscapes, transportation projects can coexist harmoniously with their surroundings, preserving ecosystems and biodiversity. The geotechnical aspects are particularly important today, as longer pavement performance (analysis) periods are being used in design, and the axle loads for trains keep increasing with time. The maintenance and rehabilitation activities used for the transportation infrastructure require competent support from the underlying geo-materials.

1.2 Geotechnical Innovation

Geotechnical innovation is important for transportation geotechnics because it can help make transportation infrastructure safer, more sustainable, and more cost-effective. Geotechnical innovation towards a sustainable transport infrastructure could be in the form of materials, methodologies, technologies, practices etc.

1.3 Sustainable Transport Infrastructure

Transportation infrastructure supports a wide variety of industries and needs. From the passenger bus and train terminals commuters stand in every morning, to airports, freight terminals and busy shipping networks that power global trade—it's hard to imagine the world we live in without it. Sustainable transportation infrastructure helps structures and networks function at optimal levels so everyone and everything gets to where they are going with minimal impact on the environment. Sustainability of transport infrastructure could be evaluated in different ways such as lower fuel consumption, better compliance with environmental health and safety, more reliable and efficient maintenance procedure, better asset performance, management, maintenance and longer asset lifespan etc.

CHAPTER 2

LITERATURE REVIEW

2.1 Review of available literatures

A. Title: Utilization of Granular Wastes in Transportation Infrastructure (2024)
Authors: B. Indraratna, C. M. K. Arachchige, C. Rujikiatkamjorn, A. Heitor, and Y. Qi

This paper attributed to environmental preservation in urban infrastructure development, the recycling of waste materials produced in the coal and steel industry as well as the reusing of waste tires is a high priority in Australia. In this article, the practical applications of (i) coal wash (CW) and steel furnace slag mixtures, (ii) CW and fly ash mixtures, and (iii) rubber elements derived from recycled tires are discussed. In this regard, some examples of real-life applications are elucidated in relation to coastal reclamation as well as road and rail construction (e.g., Port Kembla, Kangaroo Valley highway, and Chullora Rail Precinct). The article outlines various aspects of site investigation, construction techniques, and the installation of instrumentation to evaluate the field performance of these waste materials in contrast to traditional (natural) quarried materials. The results from these case studies demonstrate that properly engineered granular waste mixtures can exhibit promising characteristics even to exceed the current technical standards, implying reduced intensity of maintenance. The research outcomes strongly support sustainable solutions to be embraced in the future development of transportation infrastructure, capable of withstanding increased freight loading and enhanced longevity.

B. Title : Innovative Approach in the Use of Geotextiles for Failures Prevention in Railway Embankments (2016)
Authors: Clemente Fuggini, Donato Zangani, Aleksander Wosniok, Katerina Krebber, Petra Franitza, Luciano Gabino, Frank Weigand.

This study gives an insight about the maintenance and renewal costs of a typical railway, track and substructure represents 50–60% of the total costs of such infrastructure over its entire service life. Innovations in track and substructure are therefore fundamental to achieve a significant impact on the overall cost reduction for the railways. Therefore, new solutions for track improvements that are effective and that can minimize the interruption of traffic are needed. Moreover, failures of railway embankments happened recently in different regions of the world. Such events, such as the one happened in UK in February 2013 (http://www.bbc.co.uk/news/uk-england-south-yorkshire-21441070), are showing the importance of monitoring track and infrastructure coupled with the use of numerical models for the localization of the critical areas and the design of appropriate countermeasures. Indeed embankment failures, landslides and uneven settlements and similar events are becoming much more common than in the past due to climate changes, and this requires the infrastructure managers to look from a different perspective infrastructure maintenance issues. What was previously consider as “extreme” is now “common” and thus actions need to be taken to be ready when such events will happen. The aim is to mitigate their effects on the infrastructure and to minimize disruptions to train services and reduce maintenance costs to restore the normal service conditions. If this mental change happens, then the need for solutions and techniques for global asset monitoring and ground stabilization will probably increase. Among the others, geotextiles and geogrids for soil reinforcement used in combination with condition monitoring techniques have the potential for minimizing catastrophic events, whilst at the same time providing a good balance among costs and benefits (i.e. sustainability)

C. Title: The evolving role of materials in geotechnical infrastructure systems (2017)
Authors: J. David Frost, M. Mahdi Roozbahani, Andres F. Peralta, Seth D. Mallett & Sangy S. Hanumasagar

This study is about increasing operational demands placed on geotechnical infrastructure systems, the need to achieve higher performance levels in the face of unprecedented engineering challenges continues to evolve. These new demands are due to the desire to increase maintenance intervals, the need to develop and adopt more sustainable materials and the need for increased hazard resilience. Many of these emerging demands are the result of climate change and other unprecedented associated natural phenomena. To address these challenges, materials are emerging at the core of some of the most innovative science and engineering developments. This paper presents several examples such as the development of multifunctional geosynthetic materials. The manner in which insights gleaned through the use of microscale experimental and numerical simulation tools, in conjunction with techniques such as 3D printing, can provide a robust basis for performance evaluation and prediction. The importance of innovating at field-scale is illustrated through the concept of inverted base pavements. Finally, the paper concludes by showing how new materials and systems innovations can be inspired by nature. The opportunity for humans to learn from and mimic the approaches developed and evolved by nature over millions of years is potentially transformational.

D. Title: Advances in innovative sustainable transportation geotechnics (2024)
Authors: Araz Hasheminezhad, Halil Ceylan, Sunghwan Kim

This article is about transportation geotechnics. Transportation geotechnics integrates geotechnical engineering principles into planning, construction, and maintenance of transportation infrastructures such as roads, highways, railways, bridges, and tunnels, vital yet resource-intensive infrastructures that demand significant attention with respect to sustainable practices. Recently, there has been a growing emphasis on implementing sustainability approaches in transportation geotechnics. This shift holds promise for environmental, economic, and societal sustainability, with potential benefits that include reducing the construction industry's carbon footprint, conserving natural resources, minimizing harmful emissions, and lowering transportation infrastructure costs. This review explores diverse strategies for advancing sustainability in transportation geotechnics, encompassing innovative materials, ground improvement techniques, and use of geosynthetics. Life-cycle assessments of sustainable transportation geotechnics in terms of environmental impacts have also been investigated. A case study is presented to illustrate the practical implementation of sustainable geosynthetics in the United States, offering practical insights into real world implementations. Challenges, opportunities, and future directions in integrating sustainability into transportation geotechnics are also discussed, offering a roadmap for advancing environmentally responsible and economically-viable infrastructure development.

E. Title: Geotechnical Innovation for Transport Infrastructures (2020)

Authors: Sanjay Nimbalkar, Prabir K. Kolay and Yifei Sun

The transportation and transit systems are crucial parts of a nation's economy playing major roles in efficiently managing the conveyance for passengers, mail, or freight. However, the service life performance of these systems is impeded by deterioration of key components including road/rail, base, and subgrade due to ever-growing traffic. Providing safe, efficient, and sustainable transport infrastructure is often challenging owing to complex geotechnical aspects of the ground. This Research Topic is designed to accommodate the interests of engineers and researchers in modelling and designing both geomaterials and geo structures that could improve performance, sustainability, and life cycle of transportation infrastructures. The topic involves a wide coverage of timely issues on technologies and innovations focusing on broad aspects of geotechnical innovations in order to address global grand challenges and UN's sustainable development goals with great social and economic importance. We are proud to present this topic containing 10 peer-reviewed contributions providing insights into geotechnical innovations crucial for sustainable transport in many continents, including Asia, Australia, Europe, and North America.

Pile foundations supporting high-rise buildings and transport infrastructures are often subjected to eccentric lateral cyclic load arising from the action of wind, waves, high speed traffic, ship impacts etc. Such lateral load can induce torsion in pile and lead to progressive degradation of the soil strength and the axial pile capacity as reported through boundary element modeling (BEM) approach by Nimbalkar et al.. The results from this study can be utilized for formulating the design criteria for pile subjected to axial and torsional cyclic loads relevant to transport environment. The granular soils including ballast usually experience dynamic loads in the field. The existing models are complex and can mainly be used to predict the monotonic stress-strain response of granular soils. However, the cyclic fractional constitutive model developed by Li et al. is simple and is able to capture the cyclic (repetitive) loading representative of traffic. By employing the discrete element modeling (DEM) approach in PFC 3D, Dahal and Mishra highlighted the significance of particle breakage in permanent deformation accumulation of ballast layer under cyclic loading. The gravel loss is a major limitation for unsealed roads and effects of three significant factors, material properties, traffic,

F. Title: A review of sustainable approaches in transport infrastructure geotechnics (2016)

Authors: A. Gomes Correia, M.G. Winter, A.J. Puppala

Transportation geotechnics associated with constructing and maintaining properly functioning transportation infrastructure is a very resource intensive activity. Large amounts of materials and natural resources are required, consuming proportionately large amounts of energy and fuel. Thus, the implementation of the principles of sustainability is important to reduce energy consumption, carbon footprint, greenhouse gas emissions, and to increase material reuse/recycling, for example. This paper focusses on some issues and activities relevant to sustainable earthwork construction aimed at minimising the use of energy and the production of CO2 while improving the in-situ ground to enable its use as a foundation without the consumption of large amounts of primary aggregate as additional foundation layers. The use of recycled materials is discussed, including steel slag and tyre bales, alongside a conceptual framework for evaluating the utility of applications for recycled materials in transportation infrastructure.

G. Title: Optimizing Geotechnical Parameters for Sustainable Road Embankments in Flood Disaster-Prone Areas of Bangladesh (2024)

Authors: Sree Pradip Kumer Sarker and Md. Maminul Islam

The vulnerability of transportation infrastructure to flood disasters in Bangladesh necessitates strategic interventions to optimize geotechnical parameters for sustainable road embankments. This study focuses on a flood disaster-prone region of Bangladesh, aiming to enhance the resilience and sustainability of road infrastructure in the face of recurring floods. The research is driven by the imperative to develop effective engineering strategies that mitigate the impact of floods on road embankments, ensuring safe and reliable transportation networks. The study area is characterized by a complex interplay of geographic and geological factors that contribute to its susceptibility to flooding. Understanding the local geology is crucial for tailoring geotechnical parameters to the specific conditions of the region. Detailed analyses of soil types, their composition, and formation processes provide the foundation for the subsequent optimization efforts. The methodology employed involves systematic sampling along a Road, incorporating both in-situ and laboratory testing. Geotechnical analyses include the evaluation of critical parameters such as California Bearing Ratio (CBR), shear strength, and soil composition. These analyses are instrumental in identifying key geotechnical characteristics that significantly influence the performance of road embankments during flood events. The optimization process encompasses the application of advanced techniques to enhance the resilience of road embankments. The results and subsequent discussions delve into the effectiveness of the optimization strategies in comparison to existing standards and guidelines for road construction. This involves a comprehensive assessment of soil properties, composition, and the outcomes of the optimization process. Finally, the study sheds light on the critical role of geotechnical parameters in developing sustainable road embankments in flood-prone areas. The findings not only contribute to the understanding of the study area but also offer valuable insights for broader applications in flood disaster mitigation in Bangladesh. The research emphasizes the need for a proactive approach to optimize geotechnical parameters, paving the way for resilient and sustainable road infrastructure that can withstand the challenges posed by recurrent floods.

H. Title: Review of Application and Innovation of Geotextiles in Geotechnical Engineering (2020)

Authors: Hao Wu, Chongkai Yao, Chenghan Li, Miao Miao, Yujian Zhong, Yuquan Lu and Tong Liu

Most geotextiles consist of polymers of polyolefin, polyester or polyamide family, which involve environmental problems related to soil pollution. Geotextiles can be used for at least one of the following functions: Separation, reinforcement, filtration, drainage, stabilization, barrier, and erosion protection. Due to the characteristics of high strength, low cost, and easy to use, geotextiles are widely used in geotechnical engineering such as soft foundation reinforcement, slope protection, and drainage system. This paper reviews composition and function of geotextiles in geotechnical engineering. In addition, based on literatures including the most recent data, the discussion turns to recent development of geotextiles, with emphasis on green geotextiles, intelligent geotextiles, and high-performance geotextiles. The present situation of these new geotextiles and their application in geotechnical engineering are reviewed.

I. Title: Geosynthetic Solutions for Sustainable Transportation Infrastructure Development (2023)
Authors: Chungsik Yoo

Geosynthetic engineering has made significant advances during the past decade in the areas of manufacturing and practical applications. As a result, geosynthetics have become essential materials that facilitate construction, better improve short- and long-term performance, and reduce long-term maintenance costs in routine civil engineering projects. Geosynthetics are also being recognized as fundamental to sustainable infrastructure development as they reduce the carbon footprint generated by infrastructure development by minimizing the use of natural construction materials. Creative use of geosynthetics in geo-engineering practices is expected to continue to expand as innovative materials and products are becoming available. In this paper, we begin by discussing issues related to climate change. The sustainable benefits of geosynthetics are then presented by demonstrating the potential of geosynthetics to significantly reduce carbon footprints compared to traditional solutions. Finally, recent geosynthetic technologies have been introduced for use in transportation infrastructure. The pathway forward of the geosynthetic technology is also discussed from the view of sustainable infrastructure development.

CHAPTER 3

MATERIAL

3.1 General

Materials are a fundamental building block of all infrastructure systems. A common and long accepted base criteria used to assess both material and system performance is to ensure that capacity exceeds demand throughout the service life, and this is at the core of all planning, design, construction and maintenance activities. (David et al.) The transportation and transit systems are crucial parts of a nation's economy playing major roles in efficiently managing the conveyance for passengers, mail, or freight. However, the service life performance of these systems is impeded by deterioration of key components including road/rail, base, and subgrade due to ever-growing traffic. Providing safe, efficient, and sustainable transport infrastructure is often challenging owing to complex geotechnical aspects of the ground.(Sanjay et al.) Materials play a crucial role in sustainability because the choices we make about the materials we use impact resource consumption, environmental health, and waste generation. For example, renewable materials can be generated relatively quickly making them more sustainable than non-renewable options. On the other hand, recycled materials reduce the need for virgin sources and minimizes waste. Similarly biodegradable materials like compostable bioplastic or plant base alternatives break down naturally, reducing landfill waste. Energy efficiency, durability, longevity, environmental impact all these depend on the material used in the process.

3.2 Materials

Considering the sustainability aspect and the innovation in the field of geotechnical engineering towards transport infrastructure, there is a wide range of materials that is being used in practice as well as in the experimental phase. The findings from various literatures are –

3.2.1 Coal mining waste (Coal Wash, Fly Ash, Steel Furnace Slag)

The use of coal mining waste offers significant monetary benefits over the use of conventional (quarried) aggregates in substructure construction and land reclamation projects (Indraratna, Gasson, and Chowdhury 1994). Despite the favourable properties of coal mining wastes, such as adequate shear strength and permeability (drainage), Heitor et al. (2016) have shown that the breakage of CW is significant during initial compaction and subsequent shearing under live loading.

Fig1 : Coal Mining

Advantages:

1. **Cost Reduction**: Coal mining waste, like fly ash, slag, and other by-products, is often cheaper than traditional construction materials. Using waste products can lower the cost of construction, especially in areas near coal mines.
2. **Waste Disposal Solution**: Coal mining produces large amounts of waste, and finding beneficial uses for it can help reduce the environmental impact. By reusing mining waste in road construction, these materials are diverted from landfills or disposal sites, minimizing environmental pollution.
3. **Improved Strength and Durability**: Certain coal mining waste products, such as fly ash, can enhance the strength and durability of the road infrastructure. Fly ash, when mixed with other materials like cement or lime, can improve the overall performance of road pavement, increasing its resistance to cracking and wear.
4. **Environmental Benefits**: Recycling coal mining waste for construction purposes can reduce the need for natural aggregates, which can lead to reduced extraction of raw materials from the earth. Additionally, using waste materials like fly ash can help lower the carbon footprint of road construction, as it can replace a portion of cement in concrete, which is energy-intensive to produce.
5. **Improved Soil Stabilization**: Some coal mining waste materials, such as lime or fly ash, can be used for soil stabilization in road construction. This can improve the bearing capacity and compaction of soils, helping to create a stronger foundation for the road.
6. **Reduction of Acid Mine Drainage**: Coal mining waste, particularly from surface mines, can lead to acid mine drainage, which contaminates water sources. By incorporating this waste into road construction materials, it is effectively isolated from water systems, reducing the risk of environmental pollution.

7. **Energy Efficiency:** Utilizing coal mining waste in road construction can be more energy-efficient compared to traditional methods that rely on new materials. This can contribute to overall sustainability in the construction industry.

Disadvantages:

1. **Environmental Pollution Risks**: Coal mining waste may contain harmful heavy metals, such as arsenic, mercury, lead, and cadmium, which can leach into the environment, particularly groundwater. If not properly treated or managed, this could lead to contamination of surrounding ecosystems and public health risks.
2. **Uncertain Long-Term Performance**: The long-term durability and performance of roads built with coal mining waste materials can be uncertain. While materials like fly ash can improve strength and stability, the chemical composition of coal waste can vary, potentially affecting the consistency and quality of the road infrastructure over time.
3. **Health Hazards**: Some types of coal mining waste, especially fine particles, can pose health risks during handling and installation. Workers exposed to dust from coal waste may face respiratory issues, and prolonged exposure can contribute to conditions like silicosis or other lung diseases.
4. **Potential for Acid Mine Drainage**: Coal mining waste, particularly from surface mining, can lead to the creation of acid mine drainage (AMD), which is highly acidic and can harm aquatic ecosystems and soil quality. Although using coal waste in road construction can reduce exposure to water sources, improper management could still result in harmful environmental effects.
5. **Limited Availability of Suitable Waste**: Not all coal mining waste is suitable for use in road construction. Some waste materials may not meet the necessary engineering and environmental standards, requiring additional processing and treatment, which could negate some of the cost benefits.
6. **Public Perception and Acceptance**: The use of coal mining waste in infrastructure projects might face public opposition due to concerns about its potential environmental and health risks. People may be skeptical about using waste materials associated with coal extraction in critical infrastructure projects like roads, which could hinder its adoption.
7. **Regulatory Concerns**: The use of coal mining waste in construction is subject to strict environmental regulations. If these materials do not meet local or international standards for waste disposal and material safety, there could be legal challenges or the need for costly remediation.
8. **Potential for Leaching Contaminants**: If the waste is not properly processed or stabilized, there is a risk of contaminants leaching into surrounding soils or water sources. This can pose risks to both the environment and public health.
9. **Impact on Local Ecosystems**: Improper disposal or use of coal mining waste in construction can have detrimental effects on local ecosystems, including changes to soil chemistry, which can affect plant growth, soil fertility, and the overall health of nearby wildlife habitats.

3.2.2 Rubber Elements derived from recycled tires

Through extensive laboratory studies, it is proven that combinations of granular wastes including rubber tire segments, steel slag, and CW can offer adequate load-bearing properties to replace traditional (natural) road base, ballast, capping, and structural fill while ensuring enhanced longevity of transportation corridors. The application of CW (e.g., Leventhal 1996; Rujikiatkamjorn, Indraratna, and Chiaro 2013; Heitor et al. 2016) and mixtures of CW, steel furnace slag and rubber crumbs (Chiaro et al. 2015; Indraratna, Qi, and Heitor 2018; Qi et al. 2018) have demonstrated that marginal materials could be optimally engineered to attain acceptable mechanical and geotechnical characteristics, in relation to the required specifications of port reclamation fill (Indraratna, Heitor, and Rujikiatkamjorn 2015), capping or sub-ballast layers in rail tracks (Indraratna, Qi, and Heitor 2018). Wang et al. (2019) have proven the performance of CW mixture as an appropriate base or subbase material for pavements.

Fig 2: Rubber tyre

Advantages:

1. **Enhanced Durability and Flexibility**: Rubber-modified asphalt can significantly improve the flexibility and durability of road surfaces. The addition of rubber particles or crumb rubber from recycled tires helps create a more flexible road surface that can better resist cracking, especially in areas with temperature fluctuations. This leads to longer-lasting pavements and a reduction in the need for frequent repairs.
2. **Improved Noise Reduction**: Roads made with rubber-modified asphalt tend to absorb sound better than traditional asphalt, helping to reduce traffic noise. This is particularly beneficial in urban areas where noise pollution is a concern. The rubber in the asphalt creates a quieter, more comfortable driving experience for commuters.

3. **Increased Resistance to Wear and Tear**: Rubber can enhance the wear resistance of the road surface, leading to better performance under heavy traffic loads. This is especially advantageous in areas with high traffic volumes, where roads can degrade more quickly.
4. **Environmental Benefits**: By using rubber from recycled tires, it helps divert millions of waste tires from landfills, reducing environmental pollution. The reuse of tire rubber contributes to sustainability efforts and offers a way to repurpose materials that would otherwise be discarded. Additionally, using recycled tires can lower the environmental impact associated with producing new construction materials.
5. **Improved Traction and Safety**: Rubber-modified asphalt offers better skid resistance and traction for vehicles. This can improve road safety, especially in wet conditions, by reducing the likelihood of accidents caused by slippery surfaces.
6. **Cost-Effective**: While the initial cost of incorporating recycled rubber into road construction may be higher than traditional materials, it can be more cost-effective in the long term. The increased durability and reduced maintenance needs of rubberized roads result in savings over time, as they require fewer repairs and replacements.
7. **Better Resistance to Oxidation and Aging**: Rubberized asphalt is less prone to the oxidation and aging processes that can cause traditional asphalt to harden and crack over time. This helps maintain the quality and integrity of the road surface for longer periods, particularly in regions with extreme weather conditions.
8. **Energy Savings in Construction**: The incorporation of rubber into asphalt can reduce the amount of energy needed to produce and apply the material. Rubber-modified asphalt can be mixed at lower temperatures, which not only saves energy but also reduces greenhouse gas emissions during construction.
9. **Waste Tire Management**: Utilizing rubber from recycled tires in road construction offers an effective solution to the growing problem of waste tire disposal. Each year, millions of tires are discarded, and finding an eco-friendly use for them helps manage this waste stream while addressing the growing demand for construction materials.
10. **Potential for Reduced Carbon Footprint:** By reducing the need for new raw materials like aggregates and bitumen, the use of recycled rubber in road infrastructure can lower the carbon footprint associated with road construction. The overall environmental impact can be reduced through lower material extraction and energy use.

Disadvantages:

1. **High Initial Costs**: While rubberized asphalt can be cost-effective in the long term due to its durability, the initial cost of incorporating rubber into road construction can be higher than traditional materials. This includes the cost of processing the recycled tires and the specialized equipment needed for production and application.
2. **Potential for Environmental Contamination**: Rubber from recycled tires may contain chemicals like heavy metals, oils, and other additives that can leach into the environment over time. If the

rubber is not properly treated, these substances could potentially contaminate soil and groundwater, raising environmental and public health concerns.

3. **Inconsistent Quality of Recycled Rubber**: The quality of recycled rubber can vary depending on the source and processing method. Not all tire rubber is consistent in terms of size, shape, or chemical composition, which could affect the performance and longevity of the asphalt. This variability can make it more challenging to standardize and control the quality of the end product.

4. **Processing Challenges**: Recycling tires into usable rubber for road construction can be a complex and energy-intensive process. Shredding and processing tires into crumb rubber suitable for asphalt requires specialized technology and machinery, which can add to the overall cost and complexity of production.

5. **Durability Concerns in Extreme Weather**: While rubberized asphalt has improved resistance to cracking and wear, in some regions with extreme temperatures (very hot or very cold climates), the performance of rubber-modified materials can be less predictable. In some cases, the rubber may not behave as expected under certain temperature extremes, which could lead to premature deterioration or deformation of the road surface.

6. **Limited Availability of Recycled Rubber**: The supply of recycled rubber from tires may be limited in some regions, especially in areas where tire recycling infrastructure is not well-developed. This could make it difficult to meet demand for large-scale road construction projects or cause price volatility based on the availability of recycled tire material.

7. **Potential for Reduced Performance Over Time**: Some studies have suggested that while rubberized asphalt may perform well initially, over time, the rubber particles may degrade or lose their effectiveness. This could lead to reduced benefits, such as decreased durability, flexibility, and noise-reduction capabilities.

8. **Public Perception and Acceptance**: The use of recycled tire rubber in road construction may face public opposition due to concerns about the potential for environmental contamination or the use of non-traditional materials in critical infrastructure. There may be skepticism about the long-term safety and performance of roads made with recycled tire elements.

9. **Limited Research on Long-Term Effects**: Although rubberized asphalt has been used in road construction for some time, there is still ongoing research into the long-term effects of using recycled tire rubber. More data is needed to fully understand how these materials behave over extended periods and under varying environmental conditions.

10. **Potential for Increased Emissions**: Some processes used to manufacture rubber-modified asphalt, such as high-temperature mixing, could release harmful emissions into the atmosphere. While recycling tires for construction is an eco-friendly alternative to disposal, the production process itself might still contribute to air pollution.

3.2.3 Recycled Aggregates

Recycled aggregate applications was developed and was structured in terms of the environmental and economic utility (or value) of the application, and the utility relative to the original application. In the determination of utility, the factors considered included those related to production (energy consumption, financial cost, amount of pollution and waste generated) and those related to the market value of the product and the 'renewability' of the primary resource. Typically, three levels of applications are considered: low utility, intermediate utility and high utility. High utility and intermediate utility are more relevant in structural elements. The low utility applications for recycled aggregates are typically based upon their use as general fill. A study of the use of recycled aggregates in Scotland found that around 87% of spent oil shale, 100% of colliery spoil and 28% of PFA (pulverised fuel ash or fly ash) were recycled to low utility applications, predominantly as general fill. This is despite the fact that each material has been shown to be suitable for higher utility applications (Correia et al.)

Fig 3: Recycled Aggregates

Advantages:

1. **Environmental Sustainability**: The use of recycled aggregates reduces the demand for natural resources like virgin sand, gravel, and crushed stone. This helps conserve natural habitats, reduces environmental degradation from extraction processes, and lowers the carbon footprint of road construction projects. By reusing construction and demolition waste, the need for landfilling these materials is minimized, contributing to waste reduction.
2. **Cost Savings**: Recycled aggregates are typically more affordable than new, virgin aggregates. The lower cost of obtaining and processing recycled materials can result in overall cost savings for road construction projects, particularly in urban areas where demolition waste is readily available.

3. **Waste Reduction**: Using recycled aggregates helps divert large quantities of construction and demolition waste from landfills. This contributes to waste management goals and reduces pressure on waste disposal systems, which is particularly important as the global construction industry generates significant waste.
4. **Conservation of Natural Resources**: By replacing virgin aggregates with recycled ones, the depletion of natural resources like quarries and mines can be reduced. This is especially important in areas where natural aggregate supplies are limited or in high demand.
5. **Improved Strength and Durability**: In some cases, recycled aggregates can offer comparable or even superior strength and durability to virgin aggregates, especially when processed and treated correctly. When used in road sub-bases or in combination with other materials like bitumen or cement, recycled aggregates can contribute to the long-term stability and durability of road surfaces.
6. **Reduced Transportation Costs and Carbon Emissions**: Using locally sourced recycled aggregates, especially in urban areas or near demolition sites, can significantly reduce transportation costs and emissions. This minimizes the environmental impact of hauling materials over long distances, which is often associated with the extraction of virgin aggregates.
7. **Support for Circular Economy**: The use of recycled aggregates supports a circular economy by promoting the reuse and recycling of construction materials. This contributes to a more sustainable construction industry by maximizing the life cycle of materials and reducing reliance on raw resources.
8. **Energy Savings**: Processing recycled aggregates generally requires less energy than producing new aggregates from raw materials. This results in lower energy consumption and fewer greenhouse gas emissions, contributing to overall energy efficiency in construction processes.
9. **Reduction in Landfill Usage**: By incorporating recycled aggregates into road construction, large amounts of construction and demolition waste are diverted from landfills, which can help address the growing problem of landfill overcapacity.
10. **Potential for Improved Drainage**: Recycled aggregates, particularly when used in road sub-bases, can offer improved drainage properties compared to certain virgin aggregates. The void space and porosity of some recycled materials can enhance water runoff and reduce issues with flooding or water accumulation on road surfaces.
11. **Innovative Material Properties**: Some recycled aggregates, especially those made from crushed concrete or asphalt, can contribute additional properties that benefit road infrastructure. For example, recycled asphalt can be used for creating high-performance asphalt pavements, offering durability, flexibility, and enhanced resistance to wear and tear.
12. **Regulatory and Incentive Benefits**: Many governments and regulatory bodies are encouraging or mandating the use of recycled materials in construction projects to promote sustainability. Using recycled aggregates may qualify projects for tax incentives, certification, or compliance with environmental regulations, contributing to green building standards.

Disadvantages:

1. **Variability in Quality**: Recycled aggregates can vary significantly in quality depending on the source material, the methods used for recycling, and the degree of contamination. This variability can affect the consistency and performance of the final construction material, making it difficult to achieve the same standards as virgin aggregates.
2. **Higher Processing Requirements**: Recycled aggregates often require more processing and treatment than virgin aggregates to ensure they meet the necessary standards for road construction. This may include crushing, screening, and washing to remove contaminants like soil, metals, or wood. The additional processing can increase the overall cost and energy consumption of the material.
3. **Limited Performance in Some Applications**: While recycled aggregates can be used in many parts of road construction, they may not perform as well in certain high-stress areas, such as the road surface or high-traffic zones. In these cases, virgin aggregates or specialized materials may be preferred to ensure durability and stability.
4. **Potential for Contamination**: If the source material is not properly sorted or cleaned, recycled aggregates may contain contaminants such as plastics, glass, or metals, which can affect the material's structural integrity and performance. The presence of contaminants can also lead to leaching of harmful substances into the surrounding environment.
5. **Reduced Durability**: Recycled aggregates may have lower durability compared to virgin aggregates, particularly if they come from low-quality or deteriorated source materials. Over time, the recycled material may break down more easily, which could lead to reduced longevity of the road infrastructure, particularly under heavy traffic or extreme weather conditions.
6. **Regulatory and Specification Challenges**: The use of recycled aggregates in road construction is often subject to specific regulatory standards and local codes, which can vary by region. Some jurisdictions may have stricter requirements for recycled materials, and meeting these standards could involve additional testing, certification, or approval processes, which may delay construction timelines.
7. **Reduced Workability**: The physical properties of recycled aggregates, such as particle shape, size, and texture, may differ from those of virgin aggregates. This can sometimes result in reduced workability when mixing recycled materials with asphalt or concrete, requiring adjustments to the construction process and potentially leading to more challenges in achieving the desired road surface quality.
8. **Limited Availability and Supply Issues**: The supply of high-quality recycled aggregates may be limited in certain regions, especially where demolition or construction waste is not collected or processed effectively. This can lead to shortages or inconsistent availability, which could disrupt construction projects.
9. **Higher Transportation Costs for Remote Areas**: While recycled aggregates can often be sourced locally, in some cases, they may need to be transported over long distances if local

recycling infrastructure is not available. This could negate some of the environmental and cost benefits associated with using recycled materials due to higher transportation costs and emissions.

10. **Potential for Higher Water Absorption**: Recycled aggregates, especially those from crushed concrete, may have higher water absorption rates than virgin aggregates. This can affect the mixing process and the strength of the road surface, requiring adjustments in the asphalt or concrete mix design to compensate for this property.
11. **Perception and Acceptance Issues**: There may be public or stakeholder concerns regarding the use of recycled aggregates in critical infrastructure projects. People may be skeptical about the long-term performance and safety of roads built with recycled materials, especially in high-traffic or important transportation corridors.
12. **Potential for Reduced Aesthetic Quality**: While not always a major concern in road infrastructure, recycled aggregates can have a different appearance compared to virgin materials, which may affect the aesthetic quality of the project. This could be a consideration for road construction projects in areas where visual appeal is important.

3.2.4 Natural Geomaterials

Earthworks seek to reuse and incorporate as much as possible of the geomaterial already existing on the construction site as is practicable. This will avoid the disposal of such materials and save on the consumption of natural resources, which include high quality and other quarried materials, as well as minimizing the demand for land and transport. Although not explored in detail, issues surrounding the acceptability of natural earthworks materials form an important part of the earthworks planning and implementation process and their correct application can have a fundamental effect on achieving sustainable earthworks construction. Similarly, where natural earthworks materials (including glacially deposited materials) incorporate large particle sizes (soil – rock fill mixtures), account must be made of differences between the limited particle size ranges of the samples tested at the planning (ground investigation) and construction stages and the materials that are actually placed. Failure to do so can lead to failure of the earthworks process and significant additional costs and energy consumption. Nevertheless, the first step in determining whether a material can be used is to evaluate whether the excavated geomaterial meets the specification(s) for the specific application. However, if it does not meet the specifications, mechanical and chemical treatments may be considered to render the material suitable. Amongst chemical treatments, lime is commonly used in many countries to allow the reuse of very wet or soft fine soils in the construction of embankments, road foundation capping layers, and other applications. An immediate improvement in the soil properties is expected and the treatment increases workability and assists compaction during earthworks. This technique has been common practice in Europe for several decades, but the long-term effects of lime treated soils have not been generally taken into account in design. Even mixing rather small amounts of lime with soils induces pozzolanic reactions that may continue over a period of years, resulting in a continuous increase of strength and stiffness. The results presented in Flores et al. show that for a silty soil treated with 3% quicklime only four days after construction (and thus four days of curing) the slope factor of safety increased from 1.5 for the untreated soil to 2.5 for the treated soil. This evolution continued with time and values of the factor of safety close to 4 and 10 were reached after 3 months and one year (in constant humidity and temperature conditions, 20^{o}C), respectively. Neglecting this long-term development resulting from pozzolanic reactions between lime, water, and the silica and alumina that exist in the clayey particles, has a direct impact on the costs of the earthworks, for example, as slope stability, erosion, bearing capacity will be underestimated. (Correia et al.)

(a) (b) (c) (d)

Fig 4: Natural Geomaterials (a) Rock (b) Clay (c) Soil (d) Sand

Advantages:

1. **Abundant Availability**: Natural geomaterials like sand, clay, and rock are commonly available in many regions, making them relatively easy to source. This widespread availability ensures a steady supply, which is critical for large-scale road construction projects.
2. **Cost-Effectiveness**: Natural materials are generally more affordable than manufactured alternatives. Since they require minimal processing, transportation, and labor to be used in road construction, the overall cost of using natural geomaterials tends to be lower compared to other high-tech materials.
3. **Strength and Durability**: Many natural geomaterials, especially rock and gravel, offer high strength and durability, which are essential qualities for road construction. These materials can withstand heavy traffic loads, weathering, and erosion over time, contributing to the longevity of the road infrastructure.

4. **Good Drainage Properties**: Sand and gravel are particularly valued for their excellent drainage properties. These materials allow water to pass through easily, helping to prevent water accumulation and reduce the risk of flooding or road damage due to waterlogging. Proper drainage is essential for maintaining road stability and longevity.

5. **Soil Stabilization**: Clay, when used in specific proportions, can help stabilize the subgrade in road construction. It can improve the compactness of the subgrade, reduce soil erosion, and enhance the overall strength of the road foundation. Properly stabilized soils help prevent road deformation and ensure a more solid roadbed.

6. **Flexibility and Versatility**: Natural geomaterials can be used in various forms and applications across different layers of road construction. For instance, sand and gravel are commonly used in the roadbase and subbase, while clay can be used for stabilizing or shaping embankments. The adaptability of these materials makes them versatile for use in different types of road infrastructure projects.

7. **Environmental Sustainability**: Natural geomaterials are renewable in the sense that they are replenished by natural processes over time. When extracted responsibly, they can be used in construction without causing long-term environmental harm. Unlike synthetic materials, they generally have a smaller carbon footprint, particularly if sourced locally, reducing the need for transportation and processing energy.

8. **Minimal Processing**: Unlike manufactured materials, natural geomaterials typically require less processing. For example, sand and gravel are often extracted and directly used in their natural form with minimal treatment. This not only reduces the environmental impact associated with production processes but also cuts down on costs and time needed for preparation.

9. **Favorable Mechanical Properties**: Many natural geomaterials like gravel and crushed stone offer excellent mechanical properties, such as high compressive strength, toughness, and abrasion resistance. These properties are critical for maintaining the integrity of road surfaces and foundations, especially under heavy traffic conditions.

10. **Long-Standing Proven Performance**: Natural geomaterials have been used in construction for centuries, and their performance is well-documented. Their reliability and predictability in various climate and traffic conditions make them trusted materials in road infrastructure, reducing the risk of unforeseen problems.

11. **Reduced Energy Consumption**: The production and processing of natural geomaterials typically consume less energy compared to synthetic or engineered alternatives. This contributes to the overall energy efficiency of road construction projects and helps to reduce the environmental impact associated with material production.

12. **Low Environmental Impact When Sourced Responsibly**: When mined and extracted responsibly, natural geomaterials such as sand and gravel have relatively low environmental impact. They do not involve the use of toxic chemicals or processes, and their use in road infrastructure does not release harmful emissions or pollutants, making them an environmentally friendly option when managed properly.

Disadvantages:

1. **Variability in Quality**: Natural geomaterials, especially sand and clay, can vary in quality depending on the source. The consistency of particle size, mineral composition, and moisture content may not always meet the specific requirements for road construction. This variability can lead to inconsistent performance and may require additional testing or sorting, which can increase costs and time.

2. **Limited Availability**: The availability of high-quality natural materials may be limited in certain regions, particularly for specific types of clay or high-strength aggregates like rock. The transportation costs of hauling materials over long distances can also negate some of the cost benefits associated with using natural materials. In some cases, extracting materials from local sources might not be feasible or could cause environmental concerns.

3. **Environmental Degradation from Extraction**: The extraction of natural geomaterials can lead to environmental degradation, especially if it is not done responsibly. For example, sand mining can lead to habitat destruction, soil erosion, and loss of biodiversity in riverbeds and coastal areas. Similarly, mining rock or clay can result in land degradation, deforestation, and disruption of ecosystems, particularly if done on a large scale.

4. **Erosion and Sedimentation**: While sand and gravel are valuable for their drainage properties, if improperly managed, they can contribute to erosion and sedimentation issues. Excessive use of these materials in the construction of roads or embankments can lead to instability, particularly in areas with high rainfall or poor drainage systems, which can damage the road structure over time.

5. **Clay's Limited Durability**: Clay, while useful for stabilizing the road foundation, can have issues related to its shrinkage and swelling characteristics. When exposed to moisture, clay can become soft and lose strength, leading to pavement cracking or subsidence. Conversely, when clay is dry, it can become too brittle, leading to roadbed cracking. These properties make clay less suitable for areas with fluctuating moisture conditions.

6. **Compression and Settlement**: Certain natural materials, particularly sands and soft clays, may experience settlement or compression under heavy loads or over time. This could lead to road deformation, causing uneven surfaces, ruts, or potholes. Special treatments such as soil stabilization may be required to mitigate these issues, which can increase project costs.

7. **High Dust and Compaction Issues**: Fine-grained materials like sand and silt can generate significant dust during transport and installation, which can cause air quality issues, particularly in urban or densely populated areas. In addition, natural materials like sand and gravel may require special compaction methods to achieve the desired strength, which can increase the complexity of the construction process.

8. **Limited Performance in Extreme Conditions**: Natural materials may not perform well under certain extreme weather conditions, such as freezing and thawing cycles or areas prone to flooding. For example, some sands and clays can become unstable when exposed to freeze-thaw cycles, leading to road surface deterioration. Similarly, excessive moisture can cause the road structure to weaken, particularly in areas with high water tables or poor drainage.

9. **Inconsistent Drainage Characteristics**: While natural materials like sand and gravel have good drainage properties, not all sand or gravel deposits have the same permeability. Inconsistent drainage characteristics can lead to water pooling or suboptimal performance, resulting in long-term damage to the road structure. In such cases, additional drainage systems or material processing may be required to ensure proper water management.

10. **Limited Soil Stabilization Effectiveness:** In some regions, the natural soils may not have sufficient load-bearing capacity or stability, necessitating the use of soil stabilization methods such as the addition of cement, lime, or chemical stabilizers. Without stabilization, natural soils may not provide the necessary foundation for heavy traffic loads, leading to poor road performance and frequent repairs.

3.2.5 Geosynthetics made of non-biodegradable materials

The majority of geosynthetics are composed of non-biodegradable polymers such as Polypropylene (PP), Polyethylene terephthalate (PET), and Polyethylene (PE). Over time, extended usage can lead to the degradation of these synthetic polymers due to various external environmental elements such as wind, water, friction, and Ultraviolet (UV) radiation. This degradation process can contribute to the accumulation of microplastics in the surrounding environment. Additionally, the breakdown of the polymer may cause the additives present in the geosynthetics, especially in geotextiles, to leach out and contaminate the environment. There are several commonly used types of sustainable geosynthetics for civil and environmental engineering applications. Each type has its own unique benefits and applications, and the choice of which to use depends on the specific needs of the project. (Araz et al.)

Fig 5: Geosynthetics made of non-biodegradable materials

Advantages:

1. **Enhanced Strength and Load Distribution**: Geosynthetics, especially geogrids and geotextiles, improve the strength of road structures by distributing loads more evenly. This helps prevent rutting and deformation under heavy traffic loads, extending the lifespan of the road and reducing maintenance costs.
2. **Soil Stabilization**: Geosynthetics can be used to stabilize weak or soft soils. By reinforcing the soil beneath road structures, they improve its bearing capacity and reduce the risk of settlement, particularly in areas with poor or unstable subgrade soils. This leads to better road performance and a more stable foundation.
3. **Separation and Filtration**: Geosynthetics can be used to separate different layers of materials, such as the subgrade and aggregate base. This prevents the mixing of soil and aggregate, ensuring that the road structure maintains its integrity over time. Additionally, geosynthetics like geotextiles provide effective filtration, allowing water to pass through while preventing soil migration, which helps maintain the road's strength.
4. **Durability and Longevity**: Non-biodegradable geosynthetics are highly durable and resistant to biological degradation, making them suitable for long-term use in road infrastructure. They can withstand harsh environmental conditions such as moisture, UV radiation, and temperature fluctuations without breaking down, ensuring they perform well for many years.
5. **Cost-Effectiveness**: The use of geosynthetics can lead to significant cost savings in road construction. They can reduce the amount of expensive materials required, such as aggregates and

stabilization chemicals. Additionally, geosynthetics can decrease the need for deep excavation or expensive soil treatments, lowering overall construction costs.

6. **Improved Drainage**: Geosynthetics such as geocomposites and drainage nets can enhance the drainage capabilities of road infrastructure by directing water away from the road structure. Proper drainage is essential for preventing water accumulation that can cause erosion, cracking, or pavement failure. Geosynthetics improve the flow of water while protecting the road materials from damage.

7. **Erosion Control**: Geosynthetics, such as geomats and erosion control fabrics, are effective in controlling soil erosion along slopes, embankments, and roadside areas. They help stabilize soil and prevent the loss of material caused by wind and water erosion, maintaining the integrity of the road infrastructure.

8. **Quick and Easy Installation**: Geosynthetics are lightweight and easy to transport and install, which can speed up construction projects and reduce labor costs. Their ease of installation also reduces the need for heavy machinery and complex processes, making them a more efficient solution in certain road construction scenarios.

9. **Environmental Benefits**: While non-biodegradable geosynthetics do not decompose naturally, they contribute to sustainability by reducing the need for raw materials, like virgin soil and aggregates. Geosynthetics are often made from recycled plastics, which helps promote the circular economy and reduces waste. Furthermore, by improving the lifespan and reducing maintenance needs, they contribute to reducing the environmental impact of road infrastructure.

10. **Improved Performance in Extreme Conditions**: Geosynthetics are highly effective in road construction projects that need to withstand extreme conditions such as high traffic loads, freeze-thaw cycles, or wet climates. Their ability to resist chemical attack, physical damage, and biological degradation ensures they remain functional in harsh environments.

Disadvantages:

1. **Environmental Impact**: Non-biodegradable geosynthetics, typically made from plastics such as polypropylene, polyester, and polyethylene, do not decompose naturally over time. This can contribute to long-term environmental concerns, particularly in landfills, where they persist for hundreds of years. The accumulation of non-biodegradable materials in the environment is a growing issue, especially if they are not properly recycled or disposed of.

2. **Production and Disposal Issues**: The manufacturing process of non-biodegradable geosynthetics typically involves significant energy consumption and the use of petrochemical resources. This contributes to the carbon footprint of these materials. Additionally, if these materials are not recycled at the end of their life cycle, their disposal in landfills can contribute to pollution and environmental degradation.

3. **UV Degradation**: While geosynthetics are generally durable, exposure to ultraviolet (UV) radiation from the sun can cause the material to degrade over time. UV degradation can lead to a breakdown of the geosynthetic material’s mechanical properties, reducing its strength, flexibility,

and durability. However, certain additives and coatings can mitigate this effect, but they can add to the cost.

4. **Potential for Contamination**: Geosynthetics, particularly when used in soil stabilization, separation, or drainage applications, may become contaminated with chemicals or pollutants from surrounding environments. If these contaminants interact with the geosynthetic material, they may reduce its effectiveness or potentially leach harmful substances into the environment.
5. **Initial Cost**: Although geosynthetics can offer long-term savings through increased durability and reduced maintenance, their initial cost can be higher compared to traditional construction materials like soil or gravel. The cost of manufacturing, transporting, and installing geosynthetics can add up, which might be a barrier for some road construction projects.
6. **Limited Recycling Options**: While some geosynthetics are made from recycled materials, recycling them at the end of their life is often difficult. The recycling infrastructure for geosynthetics is not as developed as that for other materials, and not all geosynthetics can be easily processed for reuse. This lack of effective recycling options can contribute to waste accumulation and environmental concerns.
7. **Compatibility Issues with Soil and Other Materials**: Some geosynthetics may not be compatible with certain types of soil or other construction materials. For example, the use of geosynthetics in areas with highly acidic or alkaline soils can lead to degradation of the material. Additionally, not all geosynthetics may be suitable for specific road applications, such as those requiring high levels of filtration or drainage, unless carefully selected.
8. **Health and Safety Concerns during Manufacturing and Installation**: The manufacturing process of geosynthetics can release fumes or particles that may pose health risks to workers. Additionally, while geosynthetics are lightweight and easy to transport, improper handling during installation can lead to worker injuries or safety hazards, especially if the material is exposed to sharp objects or harsh environmental conditions.
9. **Lack of Long-Term Performance Data:** While geosynthetics have been used in road infrastructure for several decades, there is still a limited body of research on their long-term performance under various environmental conditions and heavy traffic loads. The effects of climate change, aging, and the long-term mechanical degradation of geosynthetics in road construction are still being studied.

3.2.6 Geosynthetics made of biodegradable materials

The Biodegradable thermoplastic polymers are in the range of biodegradable polymers that can be broken down by microorganisms and enzymes over time has expanded in response to environmental concerns and the need to address plastic waste. Biodegradable polymers can be derived from petrochemical or biological sources through either chemical synthesis or direct biosynthesis. Modifications can be made to adjust their mechanical properties, although this may affect their degradation rate. Incorporating biopolymers and bioplastics into geosynthetics requires meeting specific criteria involving evaluation of mechanical properties (modulus, strength, drapability) and hydraulic characteristics (permeability, porosity) based on the intended function. Material specifications such as density and weight also influence successful geosynthetic installation. The production of polymeric geotextile fibers typically involves melt spinning, necessitating thermoplastic behavior and melt processability. Price and production capacity of polymers play a significant role in determining material choices. When considering technical biopolymers and natural fiber geotextiles, their durability and degradation are influenced by environmental factors. To prevent the accumulation of polymer fragments and additives, it is crucial for these materials to undergo complete degradation, resulting in the production of CO2, water, and biomass. However, real-world conditions may differ due to variables such as soil composition, pH, moisture, UV light exposure, and mechanical stress. Among fully biodegradable polymers, poly lactic acid or polylactide emerges as the most promising option. Poly lactic acid or polylactide, a thermoplastic polymer, boasts remarkable strength and modulus properties. Derived from renewable agricultural resources, PLA (Poly lactic acid or polylactide) offers sustainability benefits and ecological compatibility. It decomposes into harmless substances like water, carbon dioxide, and humus. While its degradation rate is relatively slow, PLA is both recyclable and compostable. By introducing appropriate plasticizers and subjecting the starch to high temperature and shear, it can be made thermoplastically processable, resulting in a material known as thermoplastic starch (TPS) that can be processed using standard thermoplastic equipment. TPS has limitations in terms of processing, brittleness, and hydrolytic degradation, that restrict its potential application. Blending TPS with synthetic bio-polyesters such as PLA, polycaprolactone (PCL), and different co-polyesters has been accomplished with success using various ratios. To enhance compatibility, environmentally friendly coupling agents are frequently employed. Among the bio-polyesters, PLA has garnered significant attention as a preferred blending component for TPS. Blends of corn starch with ethylene vinyl alcohol, PCL, and PLA have been reported to be successfully converted into fibres through a melt-spinning process. Poly-hydroxyalkanoate (PHA) is a type of biodegradable polyester synthesized via bacterial fermentation, producing a variety of polymer behaviours ranging from thermoplastic to elastic. The structural versatility of PHAs enables the development of materials with diverse properties tailored for specific applications, but challenges including high costs and quality variation currently hinder the commercial utilization of PHAs, making them economically impractical for geotextile applications. In addition to commonly used biodegradable polyesters, there are several other options available for geosynthetics production as alternatives to non-biodegradable plastics. Some examples include polybutylene succinate (PBS), polycaprolactone (PCL), polyethylene oxide (PEO), polyglycolic acid (PGA), and polytrimethylene carbonate (PTMC) . (Araz et al.)

Fig 6: Geosynthetics made of biodegradable materials

Advantages:

1. Environmental Sustainability

- **Eco-Friendly**: Being biodegradable, these geosynthetics naturally decompose into harmless components (e.g., water, carbon dioxide) after their functional life, leaving no long-term environmental footprint.
- **Renewable Sources**: Many biodegradable geosynthetics are derived from natural, renewable resources such as jute, coir, or polylactic acid (PLA), reducing reliance on synthetic materials.
- **Reduced Waste**: Since they degrade over time, these materials do not contribute to landfill accumulation, unlike synthetic geosynthetics.

2. Soil and Ecosystem Support

- **Soil Stabilization and Vegetation Growth**: Biodegradable geosynthetics stabilize soil temporarily while vegetation establishes itself, eventually decomposing to enrich the soil with organic matter.
- **Erosion Control**: They are particularly effective in preventing soil erosion during the critical period when vegetation is growing on embankments or slopes.

- **Improved Drainage**: Biodegradable geosynthetics like coir mats can facilitate proper drainage, reducing waterlogging and the weakening of road bases.

3. Cost-Effectiveness

- **Low Initial Cost**: Materials like jute and coir are often cheaper than synthetic alternatives, particularly in regions where these natural fibers are locally available.
- **Reduced Maintenance Costs**: Since they decompose naturally after serving their purpose, there is no need for removal or disposal, saving on labor and disposal costs.

4. Versatility in Applications

- **Temporary Reinforcement**: Ideal for applications requiring temporary stabilization, such as during road construction phases, before permanent measures are implemented.
- **Erosion Control Mats**: Commonly used on slopes, embankments, and drainage channels, biodegradable geosynthetics prevent soil displacement while vegetation is established.

5. Adaptability to Different Environments

- **Flood-Prone Areas**: Biodegradable materials can perform well in temporary stabilization efforts, especially in areas prone to flooding or heavy rainfall.
- **Road Shoulders and Rural Roads**: These materials are highly suited for low-traffic or rural road applications, where long-term reinforcement is not always necessary.

6. Aesthetic and Functional Integration

- **Natural Look**: Biodegradable geosynthetics blend seamlessly into natural environments, making them ideal for projects in ecologically sensitive areas or landscapes.
- **Minimal Disruption**: Their decomposition avoids the need for removal, minimizing disruption to the surrounding environment and ecosystems.

7. Support for Local Economies

- **Job Creation**: Using natural fibers like jute, coir, or sisal supports local farmers and cottage industries, boosting rural economies.
- **Sustainable Practices**: Encourages the cultivation of plants that produce these fibers, promoting sustainable farming.

Disadvantages:

1. Limited Durability

- **Short Functional Life**: Biodegradable geosynthetics naturally decompose over time, making them unsuitable for applications requiring long-term or permanent reinforcement.
- **Accelerated Degradation in Moist Environments**: Exposure to high moisture levels, such as in flood-prone areas or regions with heavy rainfall, can cause them to degrade more quickly than expected.
- **UV Sensitivity**: Prolonged exposure to sunlight can weaken natural fibers like jute or coir, reducing their effectiveness.

2. Lower Strength Compared to Synthetic Geosynthetics

- **Weaker Mechanical Properties**: Biodegradable geosynthetics typically have lower tensile strength and load-bearing capacity, making them unsuitable for high-stress applications like heavily trafficked roads or large embankments.
- **Susceptibility to Breakage**: Under heavy loads or extreme conditions, biodegradable materials may break or tear more easily than synthetic alternatives.

3. Environmental Constraints

- **Climate Dependence**: The rate of decomposition depends on environmental factors like temperature, humidity, and microbial activity, which can lead to unpredictable performance in different climates.
- **Rot and Decay**: In humid or wet climates, these materials can decompose too quickly, leading to structural failure before vegetation or other reinforcements are established.

4. Maintenance and Replacement

- **Temporary Nature**: Because of their biodegradability, these geosynthetics may require frequent replacement in applications where long-term stability is needed.
- **Potential for Erosion After Decomposition**: If vegetation has not fully established by the time the material degrades, the area may become vulnerable to erosion again.

5. Variability in Quality and Performance

- **Natural Material Variability**: The properties of biodegradable geosynthetics can vary significantly depending on factors like the type of fiber, processing techniques, and environmental conditions during use.
- **Inconsistent Degradation Rates**: Variability in how quickly the materials decompose can make it challenging to predict their performance and plan maintenance.

6. Cost and Availability

- **Higher Initial Cost in Some Cases**: While some biodegradable materials like jute or coir are cost-effective, others, such as polylactic acid (PLA)-based geosynthetics, can be expensive due to production and processing costs.
- **Limited Availability**: In regions without access to locally sourced natural fibers, transportation costs can increase the overall expense.

7. Susceptibility to Biological Attack

- **Pests and Microorganisms**: Biodegradable materials are more vulnerable to attack by insects, fungi, and bacteria, which can accelerate their degradation and compromise their performance.
- **Risk of Decay Before Use**: If not stored or transported properly, these materials can begin to decompose or rot before they are even installed.

8. Limited Applications

- **Not Suitable for Long-Term Projects**: Their temporary nature restricts their use to projects where short-term reinforcement is acceptable.
- **Unsuitable for Heavy Traffic Areas**: Roads with high traffic loads or significant stress require stronger and more durable reinforcement, making biodegradable geosynthetics impractical.

3.2.7 Recycled plastic

Increased availability of recycled materials has prompted a rise in the utilization of recycled fibres and plastics in the production of geosynthetics. Polypropylene (PP), Polyethylene (PE), and Polyethylene terephthalate (PET) are examples of common plastics that can be recycled efficiently using the current municipal processing facilities, potentially resulting in a significant percentage of plastics being reused after their product life has ended. The environmental effects of PP, PE, and PET products and processes can be significantly decreased by using municipal recycling channels, however, there are still issues with where these materials come from—petrochemicals—which has raised interest in plant-based substitutes, such PLA. Giving priority to recycling consumer waste, such PET bottles, for the production of plastic materials is a more environmentally friendly strategy that reduces the amount of plastic waste that ends up in the environment and the need for virgin resources. The adoption of recycled materials in geosynthetics offers several benefits. First, it reduces the demand for virgin plastic production, which requires the extraction of fossil fuels and contributes to greenhouse gas (GHG) emissions. By utilizing recycled plastics, natural resources can be conserved and the environmental impact associated with the extraction and manufacturing of new plastics can be mitigated. Recycling PET bottles into geosynthetics not only diverts waste from landfills but also reduces the environmental footprint of plastic waste. It offers a circular economy model whereby plastic waste is collected, recycled, and transformed into new products, thereby reducing the need for virgin materials. By incorporating recycled materials like PP, PE, and PET, the demand for virgin plastics is reduced, along with associated resource extraction and GHG emissions. (Araz et al.)

Fig 7: Recycled Plastic

Advantages:

1. **Environmental Benefits**

- **Waste Reduction**: Diverts non-biodegradable plastic waste from landfills and oceans, helping to address the global plastic pollution crisis.
- **Reduced Resource Extraction**: Minimizes the need for virgin materials like aggregates or bitumen, conserving natural resources.

- **Lower Carbon Footprint**: Recycling plastic emits fewer greenhouse gases compared to producing new plastic, contributing to reduced environmental impact.

2. Enhanced Road Performance

- **Increased Durability**: Recycled plastic enhances the strength, flexibility, and lifespan of roads, making them more resistant to cracking, potholes, and wear.
- **Improved Water Resistance**: Plastic-modified asphalt repels water, reducing the likelihood of water damage and erosion.
- **Thermal Stability**: Roads with recycled plastic exhibit better performance under extreme temperature variations, as the plastic helps resist melting and softening in high heat.

3. Cost-Effectiveness

- **Reduced Maintenance Costs**: More durable roads mean less frequent repairs and lower maintenance expenses over their lifecycle.
- **Cost Savings in Materials**: Replacing a portion of bitumen or aggregates with recycled plastic can lower overall material costs, especially in regions with abundant plastic waste.
- **Local Plastic Recycling Opportunities**: Utilizing locally sourced plastic waste reduces transportation costs and supports local recycling industries.

4. Lightweight Material

- **Easier Handling**: Plastic materials are lightweight compared to traditional aggregates, simplifying transportation and construction processes.
- **Reduced Pavement Weight**: This can be particularly advantageous in areas where the underlying soil has low load-bearing capacity.

5. Versatility in Applications

- **Modified Asphalt**: Recycled plastic is blended with asphalt to improve flexibility and strength.
- **Plastic Aggregates**: Shredded plastic can replace conventional aggregates in asphalt or concrete mixes.
- **Geotextiles and Liners**: Recycled plastic is used to create geosynthetic materials for soil stabilization, drainage, and erosion control.

6. Resilience to Weather and Traffic

- **Resistance to Rutting**: Plastic-modified roads handle heavy traffic loads without deforming.
- **Longevity in Harsh Conditions**: These roads are better suited to resist freeze-thaw cycles, making them ideal for regions with extreme climates.

7. Encourages Circular Economy

- **Recycling Incentives**: Promotes the collection, sorting, and recycling of plastic waste, creating new economic opportunities and fostering sustainability.
- **Waste Management**: Provides a practical and scalable solution for managing plastic waste, especially in urban areas.

8. Compatibility with Existing Infrastructure

- **Easy Integration**: Recycled plastic can be seamlessly incorporated into existing road construction processes with minimal modifications to equipment.
- **Adaptability**: Can be used in both urban and rural infrastructure projects, as well as for roads, sidewalks, parking lots, and more.

9. Social and Economic Impact

- **Job Creation**: Recycling initiatives and road construction projects using plastic create employment opportunities in collection, processing, and manufacturing.
- **Public Awareness:** Demonstrates innovative ways to address environmental challenges, raising public awareness about sustainability.

Disadvantages:

1.Environmental Concerns

- **Microplastics Risk**: Over time, recycled plastic in roads may degrade into microplastics, which could leach into soil and water, potentially harming ecosystems.
- **Non-Biodegradability**: While recycling plastic diverts waste from landfills, the material itself remains non-biodegradable and could persist in the environment if improperly managed.

2. Technical Challenges

- **Material Quality Variability**: The quality and properties of recycled plastic can vary based on the type of plastic and recycling process, which can impact road performance.
- **Compatibility Issues**: Some plastics may not blend well with bitumen or aggregates, leading to inconsistent mixtures and potential weaknesses.

- **Durability Under Certain Conditions**: Recycled plastic roads might not perform well in extremely cold conditions, where they can become brittle and prone to cracking.

3. Health and Safety Concerns

- **Toxic Emissions**: During processing and blending of recycled plastic with bitumen, toxic fumes or chemicals may be released, posing health risks to workers and nearby communities.
- **Fire Hazard**: Plastic is flammable, and roads containing large amounts of recycled plastic might have increased fire risks.

4. Cost and Processing Issues

- **Sorting and Cleaning**: Recycling plastic requires thorough sorting and cleaning to ensure only suitable plastics are used, which can increase processing costs and complexity.
- **Specialized Equipment**: Incorporating recycled plastic into road construction may require modifications to existing equipment or new machinery, leading to higher initial investment costs.
- **Transportation Costs**: If suitable plastic waste isn't available locally, transportation can add to the overall cost and environmental impact.

5. Limited Standards and Regulations

- **Lack of Standardization**: There are limited industry standards or guidelines for the use of recycled plastic in road construction, leading to inconsistent results and potential safety concerns.
- **Regulatory Challenges**: In some regions, the use of recycled materials in infrastructure may face regulatory hurdles or public skepticism.

6. Long-Term Performance Uncertainty

- **Insufficient Long-Term Data**: The use of recycled plastic in roads is a relatively new practice, and there is limited long-term data on durability, maintenance needs, and overall lifecycle performance.
- **Degradation Over Time**: Although recycled plastic improves certain properties of roads, its performance over extended periods, especially under heavy traffic and extreme weather conditions, is still being studied.

7. Potential Contamination

- **Hazardous Additives**: Recycled plastics may contain harmful additives, such as flame retardants or stabilizers, which could pose environmental and health risks if leached into the surroundings.
- **Impurities in Recycled Plastic**: Contaminants in the plastic, such as food residues or mixed materials, can compromise the quality of the final product.

8. Public Perception

- **Skepticism**: People may be hesitant to accept roads made from recycled materials, perceiving them as inferior or unsafe.
- **Aesthetic Concerns**: Roads made with recycled plastic may have different visual or tactile properties that some stakeholders might find undesirable.

3.2.8 Biodegradable Natural fibers

The three main categories of natural fibers are plant fibers, animal fibers, and mineral fibers. Among these, plant fibers have emerged as the preferred option for natural geosynthetics due to their abundance, ease of extraction, affordability, and excellent performance. Cotton, flax, coir, jute are examples of plant fibers, wool and silk are examples of animal fibers. The distribution and composition of the components in natural fibers define their characteristics. Natural fibers consist of various components, including cellulose, hemicellulose, lignin, and pectin, with the proportions of these components differing depending on the type of natural fiber. The physical properties of fibers, including their exceptional strength, are influenced by crucial constituents like cellulose, hemicellulose, and lignin. Among these, cellulose stands out as the toughest organic component found in fibers. The longevity of natural geosynthetics is influenced by the cellulose and lignin content in the fiber components, with higher amounts contributing to increased durability. Although the characteristics of natural fibers fluctuate depending on the variety, natural geosynthetics usually use superior mechanically performing natural fibers as their main source of raw materials. Because of their superior performance, jute and coir fibers have become the most studied materials for natural geosynthetics. More detailed information can be found in.

However, the primary challenge limiting the extended functionality of natural geosynthetics is their early biodegradation. To address this issue, extensive research has been conducted to enhance the durability of natural geosynthetics. Currently, the main approaches to improve the properties of natural geosynthetics involve incorporating a specific amount of synthetic fibers or implementing chemical modifications to the natural geosynthetic material. Natural fibers can also be made more durable by adding coatings to their surface or altering their chemical composition to target the hydroxyl groups in the cellulose polymer. One method is to blend natural geosynthetics with synthetic fibers to improve their mechanical and physical characteristics. In a variety of testing conditions, geosynthetics composed of natural fibers and polymers, such as jute/PP geotextiles, nettle/polylactic acid geotextiles, and jute/PET geotextiles, have demonstrated successful results. Furthermore, chemical modification techniques and the utilization of adhesion promoters present intriguing possibilities for enhancing the overall mechanical properties of natural geosynthetics.

Fig 8: Biodegradable Natural fibers

Advantages:

1.Environmental Sustainability

- **Reduced Carbon Footprint**: Natural fibers, such as jute, coir, flax, and hemp, are renewable and biodegradable, minimizing the environmental impact compared to synthetic fibers.
- **Waste Utilization**: Agricultural residues (e.g., coconut husks or straw) can be repurposed, reducing waste and promoting circular economy practices.
- **Biodegradability**: Once their functional life is over, these fibers decompose naturally, leaving no harmful residues.

2. Cost-Effectiveness

- **Lower Material Costs**: Natural fibers are often cheaper than synthetic alternatives, especially when sourced locally.
- **Reduced Transportation Costs**: Local availability of fibers like jute and coir can lower transportation expenses.
- **Job Creation**: Using locally sourced materials supports rural economies and creates jobs in farming and processing.

3. Improved Road Performance

- **Erosion Control**: Natural fibers help stabilize soil and prevent erosion, making them ideal for use in embankments and slopes.
- **Enhanced Pavement Durability**: Incorporating fibers into asphalt or concrete can improve tensile strength and resistance to cracking.
- **Water Drainage**: Fibers like coir mats facilitate proper drainage, reducing water accumulation that can weaken road structures.

4. Thermal and Acoustic Benefits

- **Thermal Insulation**: Natural fibers offer good thermal insulation properties, which can help in regions with extreme temperatures.
- **Noise Absorption**: They can reduce noise pollution when used as part of sound barriers or road layers.

5. Flexibility and Versatility

- **Soil Reinforcement**: Natural fibers can be woven into geotextiles to strengthen soil and improve load-bearing capacity.

- **Temporary Stabilization**: They are effective for short-term stabilization of unpaved roads or during construction phases, as they allow vegetation to grow over time.

6. Reduced Energy Consumption

- **Low Processing Requirements**: Producing natural fibers requires less energy compared to manufacturing synthetic fibers, contributing to energy savings.

Challenges to Address

While the advantages are significant, some challenges include:

- **Durability**: Natural fibers may degrade under prolonged exposure to moisture unless treated.
- **Strength Limitations**: May not match the strength of synthetic materials for heavy-duty applications.
- **Treatment Needs:** Biodegradability is an advantage, but it may require periodic replacement or protective coatings in certain scenarios.

Disadvantages:

1. Limited Durability

- **Moisture Sensitivity**: Natural fibers absorb water, which can lead to swelling, weakening, and accelerated degradation under wet conditions.
- **Biodegradability**: While this is an environmental advantage, it limits the long-term durability of natural fibers, especially in environments with high moisture or microbial activity.
- **UV Degradation**: Prolonged exposure to sunlight can weaken fibers like jute and coir, reducing their effectiveness over time.

2. Lower Strength Compared to Synthetic Materials

- **Mechanical Properties**: Natural fibers generally have lower tensile strength, impact resistance, and load-bearing capacity compared to synthetic alternatives like geosynthetics or polymer-based materials.
- **Structural Integrity**: In heavy-duty applications, they may not provide the same level of reinforcement as engineered materials.

3. Need for Treatment

- **Chemical Treatment**: To enhance properties like moisture resistance, fire retardance, and durability, natural fibers often require chemical or physical treatments. This adds to costs and may reduce their environmental benefits.
- **Maintenance Requirements**: Fibers may require periodic replacement or additional coatings to prevent premature degradation.

4. Variability in Quality

- **Inconsistency**: The quality of natural fibers can vary due to differences in plant growth, harvesting methods, and processing techniques.
- **Unpredictable Behavior**: Variability in fiber properties can lead to inconsistencies in performance, making standardization difficult.

5. Susceptibility to Biological Attack

- **Pests and Microorganisms**: Biodegradable materials are prone to attack by insects, fungi, and bacteria, especially in tropical and humid climates.
- **Rot and Decay**: Without proper treatment, natural fibers can decompose quickly in damp or soil-exposed environments.

6. Limited Availability and Scalability

- **Regional Constraints**: The availability of certain fibers, like jute or hemp, may be limited to specific regions, making widespread adoption challenging.
- **Production Challenges**: Scaling up the production of high-quality natural fibers to meet large-scale infrastructure needs can be difficult.

7. Environmental and Economic Trade-offs

- **Resource-Intensive Cultivation**: Growing natural fibers requires land, water, and fertilizers, which could compete with agricultural production for food.
- **Processing Costs**: Although natural fibers are initially cheaper, the costs of harvesting, processing, and treating them can offset their affordability.
- **Shorter Lifecycle**: The need for periodic replacement due to biodegradability can lead to higher maintenance costs over time.

8. Limited Knowledge and Acceptance

- **Lack of Awareness**: Engineers and contractors may have limited knowledge or experience in using natural fibers, leading to slower adoption.
- **Standards and Regulations**: Few established guidelines and standards exist for the use of natural fibers in road infrastructure, which can deter their integration into projects.

9. Climate and Environmental Constraints

- **Performance Variability**: Natural fibers may not perform well in extreme climates, such as areas with prolonged wet seasons or freezing temperatures.
- **Fire Risk**: Untreated fibers can be flammable, posing a risk in dry or fire-prone areas.

CHAPTER 4
METHODOLOGY

4.1 General

A methodology refers to a system of methods, principles, and rules used to guide a specific process or achieve a particular goal. In geotechnics, methodology plays a crucial role as it provides a systematic approach to investigating, analyzing, and solving problems related to the behavior of soil, rock, and other materials. Geotechnical engineering relies on methodology to ensure safe, efficient, and reliable designs for structures.

4.2 Methods

The following three methodologies are inspired by nature, sustainability and application of sensor driven assemblies into the field of geotechnical and transportation engineering.

4.2.1 Sensor integrated geotextiles

Geotextiles are permeable fabrics used in geotechnical engineering applications, such as soil stabilization, erosion control, and drainage. By integrating sensors, these geotextiles can provide continuous, real-time data about their surrounding environment. Sensor-integrated geotextiles are innovative materials that combine traditional geotextiles with embedded sensors to monitor and assess various environmental and structural conditions in real time.

Classical Use

The classical use of geotextiles in embankments on relatively soft soils is to reduce settlement and to increase the bearing capacity and slope stability. Geotextiles are normally placed at the bottom of the embankment, about 50 cm above the original ground surface in one or more layers. In recent years a new kind of foundation, the so-called "geosynthetic-reinforced and pile-supported embankment" has been developed and it is now in use in practice. Pile-like elements are placed in a regular pattern through the soft soil down to a load-bearing stratum above which a reinforcement of one or more layers of geosynthetic (mostly geogrids) is placed before the embankment is filled. The stress relief in the soft soil results from an arching effect in the reinforced embankment over the pile heads and a membrane effect of the geosynthetic reinforcement.

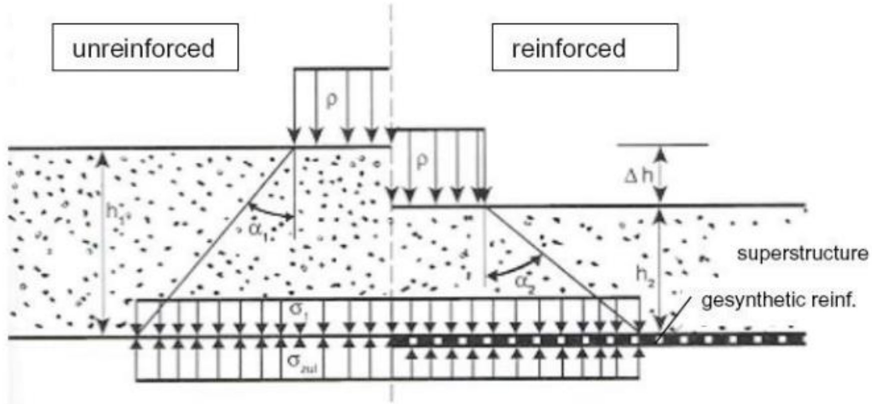


Fig 9: Use of geotextiles for soil reinforcement

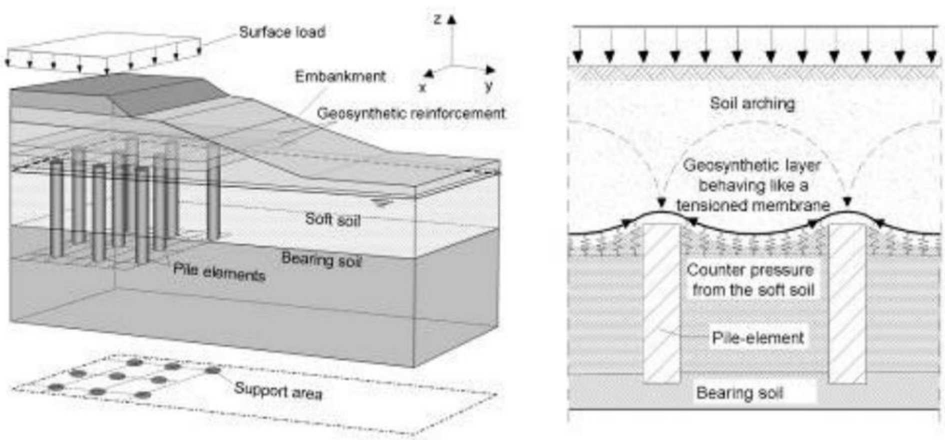


Fig 10: Geosynthetic-reinforced and pile supported structures

Innovative Use

Up to date design and construction standards require the installation of systems to monitor the stability and serviceability of geotechnical structures. New multifunctional geotextiles are nowadays introduced in geotechnical engineering practice since they provide, at the same time, both the stability and monitoring functions. The multifunctional geotextile includes protection of the railway substructure against the increased loads induced by heavier vehicles travelling at higher speed by strengthening and stabilisation of the existing structures and the monitoring of their performance with the possibility of the infrastructure owner being alerted by an alarm before structural failure occurs.

Among the others, Sensor Integrated Geotextiles (Zangani et al., 2015) have been developed to offer the chance to monitor the infrastructure where such materials are integrated in addition of the usual functions geotextiles perform (strengthening, filtration, stabilisation, separation, drainage). The Structural Health Monitoring (SHM) capacity of this system is the result of the integration with the structure of distributed Fiber Optics Sensors (FOS), whose response can be collected and processed almost continuously or can be carried out at predetermined time intervals. An efficient signal processing technique is used to process the raw sensor measurements and draw from them an estimate of the damage size and location, being able to distinguish the damage from other perturbations caused by environmental disturbances. The system automatically generates warning alarms when there is a structural risk, or when maintenance is required. The monitoring function is performed thanks to a distributed optical fiber embedded within the geogrid (figure below). The optical fiber itself is the sensing element which can be used as local sensing element or as distributed sensing cable, with sensing lengths up to several kilometres along a lowattenuation single-mode silica glass fiber.

To perform the above functions and in order to satisfy the demanding requirements of cost and resistance required for the intended applications, geotextiles are generically made from plastic materials and mostly polypropylene, and polyester, but fiberglass are used. Sewing thread for geotextiles is generally made from any of the above polymers. Using warp knitting technology to construct geotextiles makes it possible to provide reinforcement with easy sensor incorporation, thus opening up new design opportunities for multifunctional geotextiles (MFG).

Fig 11: Innovative Sensors Integrated Geotextiles

The benefits of using the proposed innovative Sensors Integrated Geotextiles within the railway substructure can encompass:

- Indicate impending failure and provide a warning

- Reveal unknowns
- Evaluate critical design assumptions
- Assess contractor's means and methods
- Minimize damage to adjacent structures
- Provide data to help select remedial methods to fix problems
- Document performance for assessing damages
- Inform stakeholders
- Satisfy regulators
- Reduce litigation
- Advance state-of-knowledge

It is important to recognize that this approach only provides an organized way to help make rational decisions based on quantified information. Geotechnical instrumentation by itself does not change the outcome but can minimise the impact of a particular event. Placing geotechnical instrumentation in an embankment to monitor stability does not alter the factor of safety of the embankment. It is only through the intelligent use of the data from the geotechnical instrumentation that engineers can better foresee potential outcomes and take appropriate actions to alter the events or reduce the consequences.

Testing the performance

Lab Test

The effectiveness of the proposed solution a series of laboratory tests have been carried out in order to verify their behaviour under different loading scenarios. A simple test rig has been prepared, as shown below, where a roll of the geotextile was used. The sensor type for the test is a distributed single-mode Glass Optical Fiber (GOF), with silicone-based sheet, produced by Fiberware. The Reading Unit produced by Luna Technologies uses the so called swept wavelength interferometry (SWI) to measure the Rayleigh backscatter as a function of length in optical fiber with high spatial resolution. Furthermore, external factors like temperature or strain changes cause temporal and local shifts in the Rayleigh backscatter pattern along the sensor fiber which can be measured and scaled giving a distributed temperature or strain measurement. Thereby, a temperature and strain resolution as fine as 1 µstrain and 0.1 °C is to achieve with sub-centimeter-scale spatial resolution up to 70 meters of the sensor fiber.

The test evaluated the strain measured by the sensor due to a load supported by the geotextile. First (figure 12) a single load was applied, whose effect is shown by peaks in the reading data; afterwards (figure 13) multiple loads have been applied to simulate more realistic conditions. The tests have been replicated with multiple loads and multiple positions of the load over the geotextile to identify the correlation among the measured data and the effective strain.

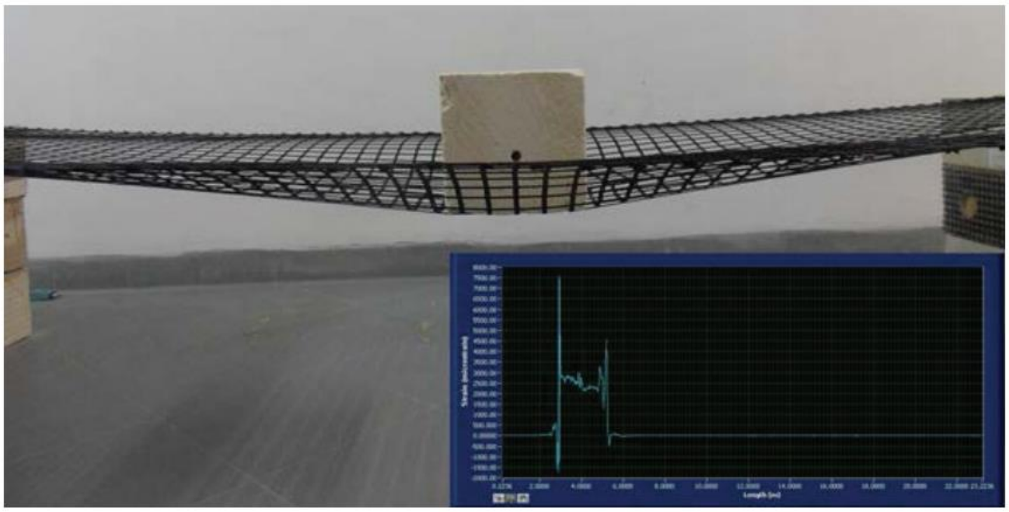


Fig 12: Acquisition of strain induced by an imposed load corresponding to single stone block

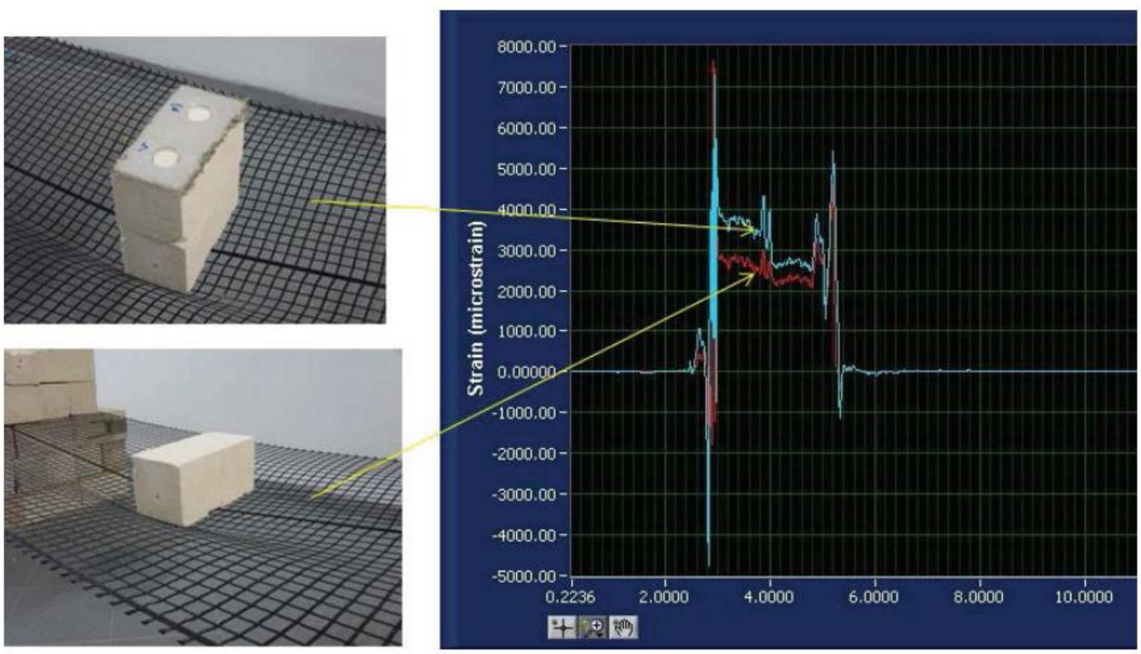


Fig 13: Acquisition of strain induced by an imposed load corresponding to double stone block

Field Test

Following the laboratory tests, field tests have been performed. The location of the test is in correspondence of a curve of a railroad near Chemnitz (Germany), as depicted in Figure 6. The traffic volume in the nearby rail track is very high. The portion of the embankment is more than 100 years old, reconstructed in 2007-2008.

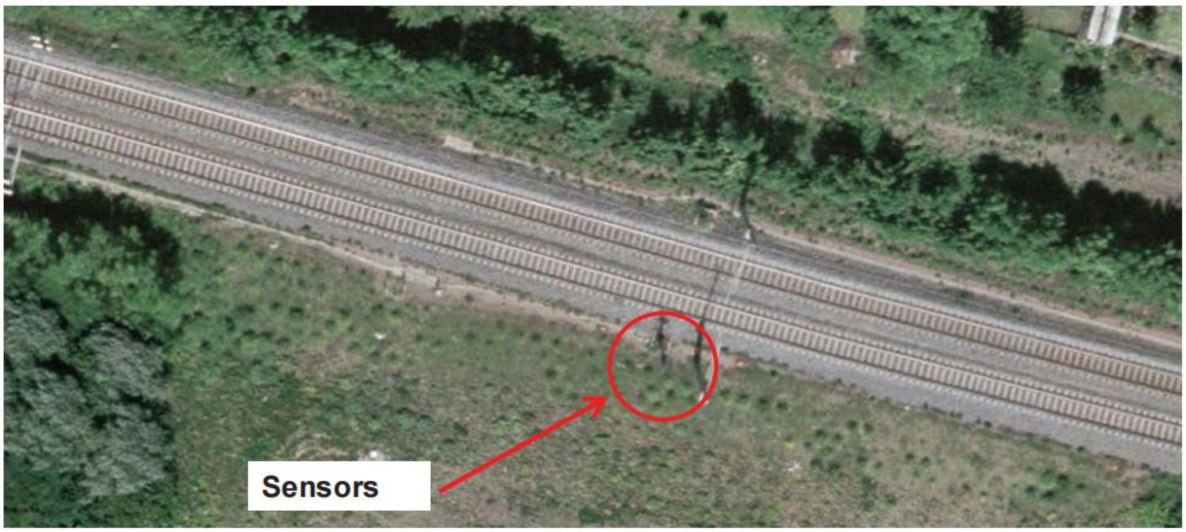
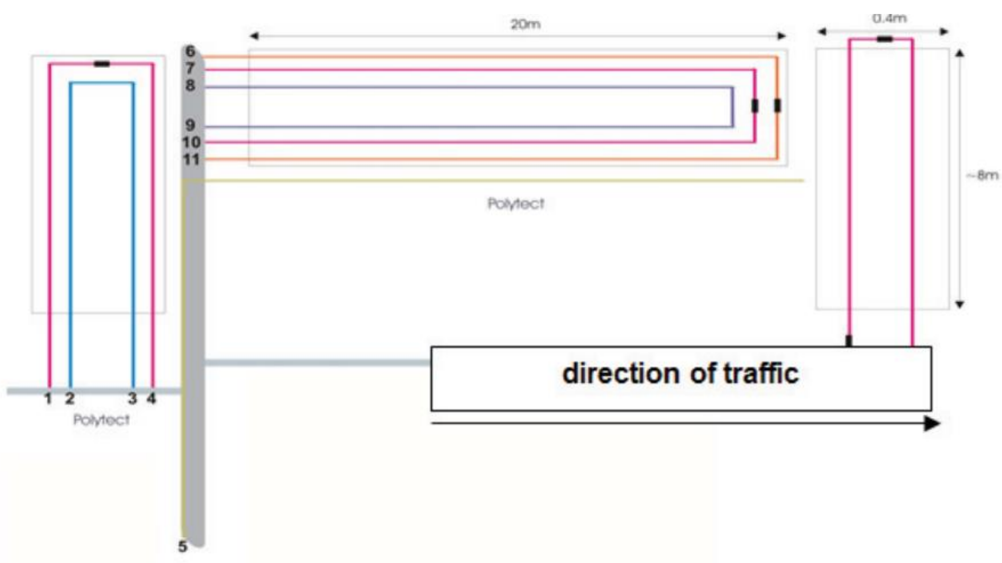


Fig 14: View of test site with sensors location

The placement of the sensors is as depicted below



1 – 4, 12 - 13	installed transversally (90° to the tracks)
5	installed for measurements partly in transversal and longitudinal direction
6 – 11	installed parallel to the tracks (longitudinal measurement)

Fig 15: Positions of the sensors in the test site

How the sensors and the acquisition unit look like is shown in the next picture

Fig 16: Sensors and acquisition unit at the site

Tests have been periodically realized from 2007 up to 2014, being the sensors still in use.Summary results are provided in the following pictures for sensors 1-4 installed transversally to traffic direction on the railway line (Figure 17) and for sensors 6 and 11 installed parallel to the direction of the traffic (Figure 18). Main finding of this long-term testing campaigns are:

- no negative influence of moisture on sensor fibers (no increase in optical attenuation observed)
- "recovery" of sensor fibers due to relaxation processes in polymer optical fibers (lower optical attenuation in comparison to previous measurements)
- damaging event can be detected for the sensor in position one

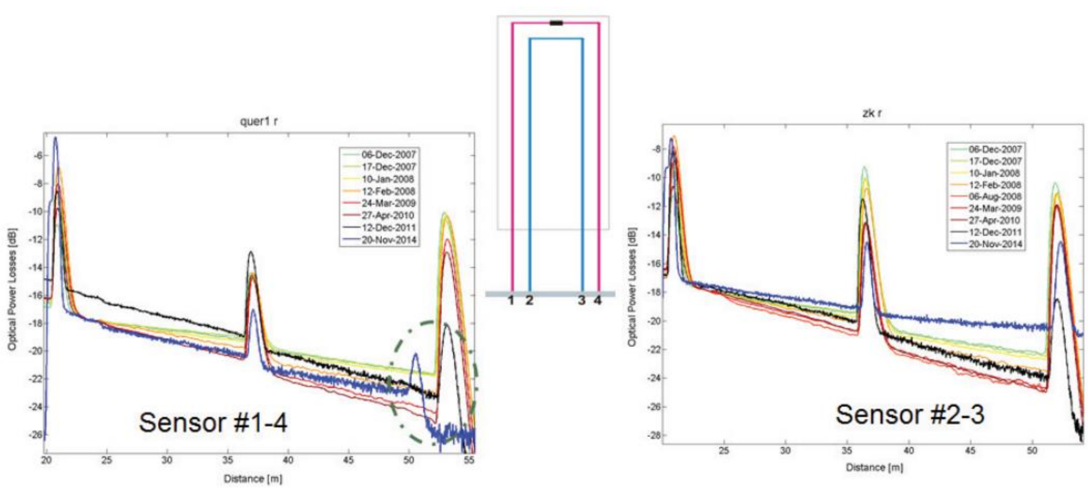


Fig17: Results from sensor 1-4

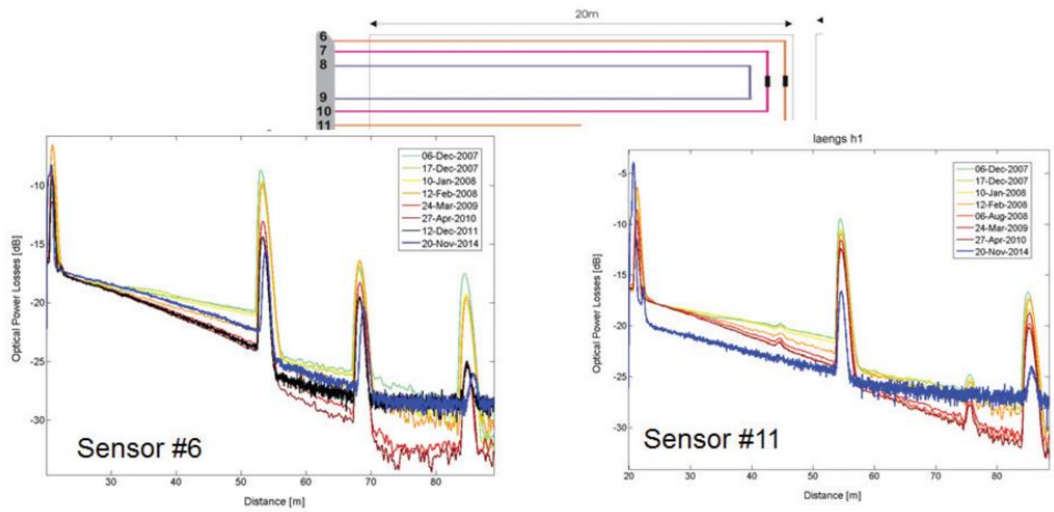


Fig 18: Results from sensor 6,11

4.2.2 Bio Inspired Innovations

With no more than a couple of thousand years of experience, humans have developed innovative techniques to leverage the subsurface for a variety of beneficial functions. In contrast, nature has had the benefit of several billion years to initially design and subsequently evolve the manner in which flora and fauna practice subsurface engineering. This paper presents two examples of how nature has evolved its solutions in contrast to what humans have done and identifies potential enhancements that humans could better exploit, in the future, through a deliberate mimicking of what nature has done. In particular, a comparison of selected aspects of ant–soil interaction and root–soil interaction are used to illustrate where significant potential exists in the emerging field of bio-geotechnics. The paper describes some salient characteristics of the framework by which nature designs its technology, and in turn, how this approach can be used to augment how humans conceive and design new materials and processes. As a measure of the interest in and potential for this approach, the U.S. National Science Foundation funded four U.S. universities (Arizona State University, Georgia Institute of Technology, New Mexico State University and the University of California Davis) through an $18.5M cooperative agreement to establish the Center for bio-mediated and bio-inspired geotechnics (CBBG) to develop bio-geotechnical engineering processes and solutions inspired by nature to transform the design, construction, operation and maintenance of resilient and sustainable civil infrastructure and resource development systems. While CBBG is the first civil infrastructure focused initiative of this scale, bio-inspiration and bio-mimicry have periodically emerged as sources of solutions to human challenges, particularly in the past few decades. Well-known examples of bio-mimicry include "Velcro" or hook and loop which was inspired by how plant burrs attached to animal hair. Others include the shape of the leading engines of high-speed "Bullet" trains which were inspired by the shape of the Kingfisher's beak and the directional adhesive on the feet of Gecko's which enables robots such as the "Stickybot" to climb vertical smooth surfaces. A comparison of the interface between a plant burr and a textile and the hook and loop structure of "Velcro" is shown in Figure 14 (Hebeler, Frost, & Myers, 2005).

4.2.3 Ants and soil mechanics

It has been estimated that ants use less than 0.1% of the energy that the most advanced human tunnelling machines do to excavate the same volume of soil (Iai, 2011). It is believed that ants are able to do so since they perform their tunnelling activities using a variety of approaches which seem to minimize the amount of energy expended at each step, including tunnelling around obstacles, not removing particles that are deemed critical to supporting the surrounding soil particles (e.g. particles that are part of primary force chains) and creating clumps of several smaller particles as appropriate before removing them from the subsurface (Espinoza & Santamarina, 2010; Monaenkova et al., 2015; Sudd, 1970). These insights have been gleaned from both observing their behaviour while tunnelling as well as studying the characteristics of castings of the ant hill structures they create. An image with a harvester ant nest casting is shown in Figure 15. As part of ongoing studies, DEM simulations using PFC2D software (Itasca, Inc.) were employed to simulate and examine soil arching effects on the stability of cavities within granular media. Simulations were implemented according to a linear model (Cundall & Strack, 1979). To initiate the simulation, 10,000 particles were randomly generated and poured inside a rectangular container. Particles size varied between 0.004 and 0.01 (particle size/container width). Once the simulation reached a state of equilibrium after the pouring process, fixed parallel bonds were set up at particle contacts in order to imitate capillary forces that allowed for the formation of stable cavities of different sizes. On-going studies are investigating the topology

of the structure and in particular, the geometrical configuration of the larger open structures which appear to be spaced apart by equal distances in the ant nest casting. Initial indications from DEM simulations are that the presence of multiple cavities reduces the size of force chains in the vicinity of the openings and that more stable structures exist when multiple large cavities are present. A comparison of force chain plots for a single versus double cavity is shown in Figure 11 (Frost et al., in press). The stability of cavities was examined in 15 different cases including cavities of different sizes and in different locations within the assembly (Figure 12). The width of cavities was varied in proportion to the maximum particle size (MPS) in multiples
of 10, while their height was fixed at 10*MPS. For the multiple cavity simulations, the upper cavities had a constant width of 40*MPS, and the vertical distance from the centre of the upper cavity to the centre of the lower cavity was fixed at 40*MPS. As shown in Figure 12, the upper cavity collapsed when it reached a width of 50*MPS, while the lower cavity collapsed when it reached a width of 40*MPS. The higher instability of the lower cavity as compared to the upper one is a result of the higher overburden stress acting at the cavity ceiling. In Figure 12, both the lower and upper cavities showed a more stable structure when they were combined. In fact, the upper cavity for the combined case was stable at a width of 50*MPS, and the lower cavity collapsed only when its width was enlarged to 50*MPS. The presence of the combined cavities altered the state of stresses in their vicinity, orienting the principal stresses towards a more horizontal direction around the rectangular cavities. It should be mentioned that circular cavities were also created in the assembly. A symmetric geometry of circles did not effectively change the force chain orientation, and circular cavities revealed an independent behaviour of each other in the combined case. Therefore, an improvement in stability was not observed in the circular cavities. This is a compelling argument that can explain the reason why the chambers in ant nests have flat and elongated shapes instead of spherical shapes.

Fig19: Harvester ant nest casting after removal of soil

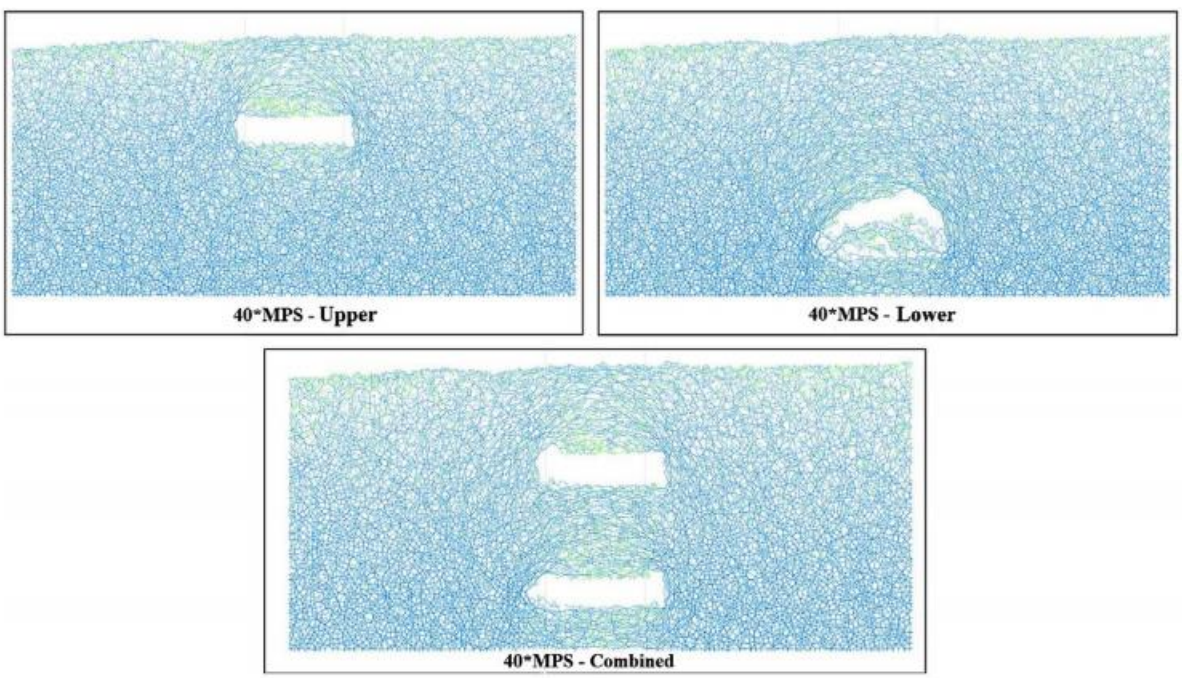


Fig 20: Force chain for single and double cavities

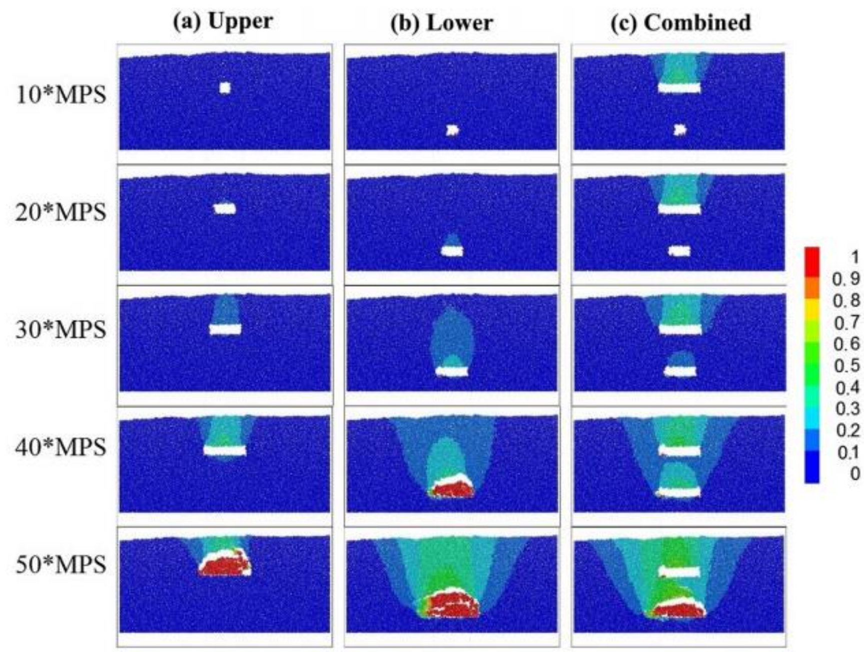


Fig 21: Particle displacements as a result of the presence of cavities at different locations

CHAPTER 5
PRACTICE

6.1 General

The primary objective of sustainable geotechnics is to comprehensively characterize the geotechnical properties of soil, so as to have detail information about the ground on which the infrastructure is actually being build or constructed. This involves conducting detailed field investigations, collecting soil samples and performing laboratory tests to assess parameters such as California Bearing Ratio (CBR), particle size distribution, Atterberg limits, compaction characteristics etc. The objective is to gain a thorough understanding of the soil's engineering behavior, enabling the formulation of targeted recommendations for sustainable design and construction.

6.2 Case Study

6.2.1 Study Area

The study was carried out at Sayedpur, which is located in Sirajdikhan Upazila on the fourth kilometer of the Sayedpur-Hasara Road. Situated roughly 37 kilometers southeast of Dhaka City is Sirajdikhan Upazila. Munshiganj District includes the upazila of Sirajdikhan. It is one of the six Upazilas in the Munshiganj district. The upazila's borders are as follows: on the north and east, Keraniganj Upazila of the Dhaka district and Narayanganj Sadar Upazila; on the south, Louhjong and Srinagar Upazilas; and on the west, Nawabganj and Srinagar Upazilas. The land area of the Upazila is 172.51 sq km, while the river area is 7.54 sq km, totalling 180.19 sq km. There are 288107 people in total, with 143559 men and 144547 women.

The Sayedpur-Hashara Road was chosen as the case study due to its vulnerability to flooding, a prevalent issue in the region. The selection aimed to assess the geotechnical properties of soils in a flood-prone area and formulate recommendations for sustainable road embankment construction.

Fig 22: Map of Study Area

6.2.2 Materials and Method

The study employed a comprehensive approach to investigate and optimize geotechnical parameters for sustainable road embankments in flood disaster-prone areas, focusing on the Sayedpur-Hashara Road in Munshiganj District, Bangladesh. The research methodology includes the given steps: Identify the Problem Statement, Objective, Literature Review, Visit Study Area, Data Collection, Data Analysis, Result Discussion, Conclusion & Recommendations.

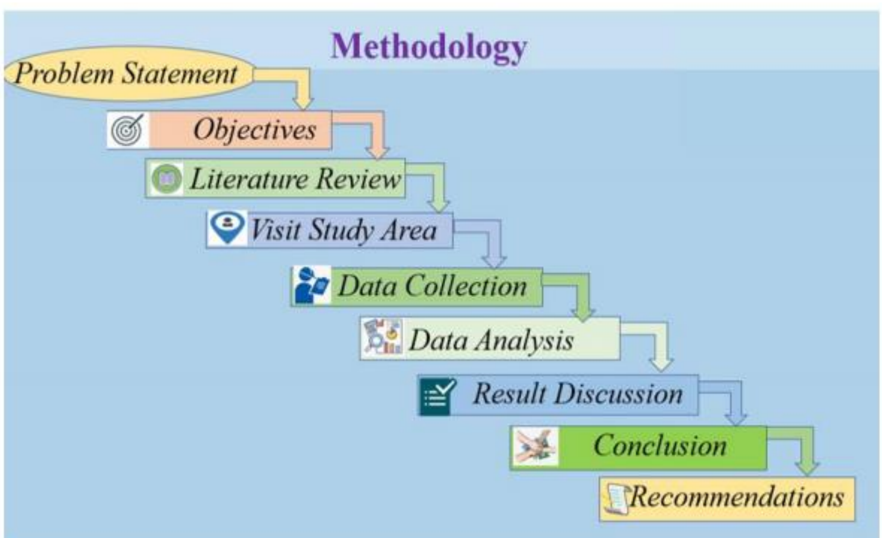


Fig 23: Methodology

6.2.3 Findings

The geotechnical investigations conducted along the Sayedpur-Hashara Road in Munshiganj District have provided insightful findings that are crucial for optimizing parameters in the construction of sustainable road embankments, particularly in flood-prone areas. The key findings are summarized below:

California Bearing Ratio (CBR) Distribution

The analysis of CBR values at different depths revealed variations in soil strength. The highest CBR value was observed at a depth of 3-4 meters, indicating a layer with optimal strength. This finding is pivotal for designing road embankments with varying load-bearing capacities, ensuring resilience against potential disasters.

Particle Size Distribution

The particle size distribution analysis indicated a well-balanced soil composition. The predominant presence of sand contributes to good drainage potential, reducing the risk of waterlogging. The combination of sand, silt, and clay provides a favourable environment for constructing embankments with enhanced cohesion and stability.

Atterberg Limits and Plasticity

The determination of Atterberg limits highlighted variations in liquid limit (LL), plastic limit (PL), and plasticity index (PI) among different soil samples. Soils with higher plasticity indices may require special considerations during construction to mitigate potential challenges arising from their behaviours, especially in flood-prone areas.

Compaction Characteristics

The compaction characteristics, represented by moisture content, dry density, and optimum moisture content, underscore the importance of achieving the right balance during construction. The findings help guide the compaction process, ensuring the embankment reaches the desired density for optimal performance under varying conditions.

Table 1. California Bearing Ratio (CBR) values for various soil layers

Depth (m)	CBR (%)	Remarks
0-1	6.8	Low strength, suboptimal
1-2	12.5	Moderate strength
2-3	18.2	Adequate strength
3-4	25.6	High strength, optimal

Table 2. Particle size distribution of soil samples

Soil Type	Percentage Passing Sieves
Gravel (>4.75mm)	10%
Sand (0.075-4.75mm)	45%
Silt (0.002-0.075mm)	30%
Clay (<0.002mm)	15%

Table 3. Atterberg limits of soil

Soil Sample	Liquid Limit (LL) (%)	Plastic Limit (PL) (%)	Plasticity Index (PI)
S1	35	20	15
S2	28	18	10
S3	40	25	15

Table 4. Compaction characteristics

Moisture Content (%)	Dry Density (kg/m³)	Optimum Moisture Content (%)
10	1850	12
12	1900	14
14	1750	16

The findings from these geotechnical analyses hold significant implications for the construction of road embankments in flood-prone areas. Understanding the soil's strength, composition, plasticity, and compaction characteristics is paramount for designing resilient infrastructure. The data-driven insights provided by this study offer a foundation for formulating engineering strategies that optimize geotechnical parameters, contributing to the development of sustainable road embankments capable of withstanding the challenges posed by floods in the Munshiganj District and similar regions in Bangladesh.

6.2.4 Recommendations

By implementing the following recommendations, stakeholders can contribute to the development of road embankments that not only withstand the challenges of flood-prone areas in Munshiganj District but also serve as a model for sustainable infrastructure development in similar regions of Bangladesh.

i. Site-Specific Design: Tailor road embankment designs based on the site specific geotechnical properties identified in the study. Consider variations in CBR, particle size distribution, and plasticity to enhance the embankment's resilience against flood-induced stresses.

ii. Continuous Monitoring: Implement a comprehensive monitoring program during and after construction to assess the long-term performance of the road embankment. Regular checks on CBR values, settlement patterns, and soil moisture content will aid in identifying potential issues and implementing timely remedial measures.

iii. Adaptive Construction Practices: Adopt adaptive construction practices that respond to the variability in soil properties. For areas with higher plasticity indices, incorporate engineering solutions to mitigate potential challenges such as excessive settlement during flood events.

iv. Awareness: Raise awareness among stakeholders and authorities about the importance of sustainable road construction practices. Engage in community-based disaster risk reduction initiatives to enhance overall resilience and preparedness.

v. Further Research: Encourage further research in geotechnical engineering, specifically focusing on the dynamic behaviours of embankments under flood conditions. Investigate innovative construction techniques and materials that can contribute to the overall sustainability and disaster resilience of road infrastructure.

CHAPTER 6
CONCLUSION

7.1 Discussion

Geotechnical planning, design, construction and rehabilitation in the early phases of an infrastructure project can significantly contribute to the overall sustainability of that particular development by making appropriate choices related to several aspects of the project. Geotechnical engineering in transportation infrastructure works highlights the transformation that has taken place in the industry in the last two decades from a traditional, low technology base to a much more sophisticated higher technology industry that fully takes account of sustainability issues. Sustainability can be improved by reducing energy consumption, greenhouse gas emissions, natural resource consumption, by increasing service life and by implementing more cost-effective solutions. However, it is not always easy to implement non-traditional practices, and it requires the dedication and perseverance of the entire project team including designers, builders and owners to select sustainable systems. Such practices will lead to the better use of sustainable systems in transportation infrastructure. However, in order to gain widespread acceptance, specifications must be developed to enable such techniques to be used on a regular basis.

The comprehensive geotechnical analysis conducted on the Sayedpur-Hashara Road in Munshiganj District provides valuable insights for optimizing parameters in the construction of sustainable road embankments, especially in flood disaster-prone areas. The study's findings underscore the significance of understanding soil properties, including California Bearing Ratio (CBR), particle size distribution, Atterberg limits, and compaction characteristics, in ensuring the resilience of road infrastructure. The variation in CBR values at different depths highlights the importance of tailored embankment designs to accommodate the diverse loadbearing capacities of the soil layers. The balanced particle size distribution, coupled with insights into Atterberg limits and plasticity, guides construction practices to address the challenges posed by different soil compositions. The compaction characteristics emphasize the need for meticulous control during the construction process to achieve the desired density for optimal embankment performance.

7.2 Future Scope

Following research areas will contribute to the development of sustainability and effective solutions for geotechnics and environmental assessment:

Unique Geotextile Design

In recent decades, geotextiles have been widely used in geotechnical engineering, and the global market demand is growing steadily. Geotextiles are mostly composed of polyolefin, polyester, or polyamide series polymers, and additives are usually added to enhance the performance of geotextiles. In the future, it is possible to design geotextiles with unique and excellent properties by applying nanofibers to geotextiles.

Cost Benefit Analysis of different materials

Conducting comprehensive economic analyses and cost-benefit assessments will be crucial for the wider adoption of materials used in the construction industry. Evaluating the overall financial implications and return on investment can guide decision-making for various stakeholders.

Sustainability assessment

As the field of geotechnics is application of principles of geotechnical engineering to the transport infrastructure, addressing these research areas will contribute to the development of sustainable and effective solutions for material and technology also environmental conservation.

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