On the review of rigid pavement construction on the soft soil foundation

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Abstract

This comprehensive review examines the critical challenges and innovative solutions for constructing rigid pavements on soft peat soil foundations. Peatlands, characterized by high compressibility, low shear strength, and acidic conditions, necessitate specialized engineering approaches to ensure structural integrity. The analysis synthesizes findings from recent studies on elastic foundation models (e.g., Winkler's approach) and finite element simulations, revealing that deformation is governed by pavement thickness and load intensity. Key advancements include sustainable material innovations—such as geopolymer concrete, palm oil fuel ash, and foam concrete—which enhance durability in acidic environments. Stabilization techniques using industrial byproducts and biochar are highlighted for minimizing settlement, while lightweight materials and floating foundations offer subsidence mitigation. The review underscores the environmental and economic benefits of these strategies, advocating for integrated approaches to achieve resilient and sustainable infrastructure in peatland regions.

Keywords: Rigid pavement, Peat soil, Geopolymer concrete, Stabilization techniques, Sustainable infrastructure, Elastic foundation model

1. Introduction

Study by [1] investigated the effectiveness of pozzolanic materials in enhancing concrete canal blocks for tropical peatland recovery, focusing on strength and acid resistance. By replacing 10% of Ordinary Portland Cement (OPC) with Palm Oil Fuel Ash (OPC POFA) and testing Portland Composite Cement (PCC), they found that both materials outperformed OPC in compressive strength (increased by 15-20%), tensile strength, Young's Modulus, and porosity reduction after 150 days in acidic peat water. Results demonstrated that pozzolanic materials significantly improve durability and structural performance, making them ideal for canal blocks in highly acidic tropical peatlands [1].

Study by [2] investigated the early strength of various fly ash-based concretes in acidic peat environments, testing seven mixtures, including geopolymer hybrid (15% OPC), high-volume fly ash (25%, 50%, 75% replacement), and blended OPC-fly ash (15, 21, 29 MPa grades). Results revealed that concrete type, fly ash content, and grade significantly influenced early strength (7-28 days) and acid resistance. Geopolymer hybrid and blended cement performed best, with strength retention up to 20-25% higher than OPC, while high-volume fly ash showed moderate resistance and OPC was most vulnerable [2].

Study by [3] explored lightweight concrete using PET plastic as a coarse aggregate replacement (0%, 40%, 50%, 70%, 100%) for peatland construction in Riau Province, where weak soil conditions demand innovative solutions. Testing compressive strength and weight revealed that 70% and 100% PET mixtures produced lightweight concrete (6.4 kg and 5.81 kg, respectively). The 70% PET mix achieved K-193 quality, offering medium strength and suitability for peatland applications, balancing weight reduction and structural integrity [3].

Study by[4] reviewed the potential of hybrid geopolymer concrete, combining fly ash and Portland cement, for construction and conservation in peat environments. Activated by alkaline solutions, the hybrid forms a robust C-A-S-H structure, enhancing resistance to acidic peat conditions. Studies show it reduces heavy metal leaching by up to 50%, making it eco-friendly. With superior durability and environmental benefits, geopolymer hybrid concrete emerges as a sustainable, innovative material for peatland construction and ecosystem conservation such depicted in **Table 1** [4].

Study by [5] examined challenges and solutions for constructing infrastructure on peat, characterized by low shear strength, high compressibility, and water content. Solutions include avoiding peat using end-bearing piles or soil replacement, or constructing on peat with lightweight materials and dewatering techniques. Case studies from the IConCEES 2015 workshop highlighted innovative approaches, though many remain untested. The study emphasizes the need for further research to address technical issues and improve sustainable infrastructure development on peatlands [5].

Study by [6] evaluated the long-term durability of iron-rich geopolymer concrete (GC) in sulphate, acidic, and peat environments, comparing it to Portland cement (PC). GC exhibited strength increases of 8.9% in Na_2SO_4 at 12 months but declined by 19.8% in MgSO4 and 11.3% in peat at 18 months. In acidic conditions, GC showed minimal mass loss (2-3%) and strength reduction (1.2-4.5%), outperforming PC due to ongoing geopolymerization and pore-filling N-A-S-H gel, making it ideal for peatland infrastructure [6].

Study by [7] investigated the settlement behavior of Parit Nipah peat, characterized by high compressibility and moisture content (>500%), under static embankment loading. A 3.6 m x 3.6 m concrete slab (150 mm thick) was tested to reduce settlement. Results demonstrated that the slab significantly minimized peat settlement under load, offering a potential solution to mitigate long-term post-construction settlement in peatlands, enhancing sustainable infrastructure development on challenging peaty grounds [7].

Study by[8] explored glacial rock flour as a sustainable stabilizer for peat, which poses construction challenges due to high compressibility and low bearing capacity. By adding up to 15% rock flour, unconfined compressive strength (UCS) increased significantly, improving peat's mechanical properties. This cost-effective alternative to traditional excavate-and-replace methods offers a viable solution for foundation construction in peatlands, particularly in Scotland, where 25% of the land is peat-covered, promoting sustainable infrastructure development[8].

Study by [9] evaluated the performance of lightweight concrete piles (LCP), specifically palm oil clinker concrete (p-LCP) and foamed concrete (f-LCP), for floating foundations in soft soil. Field tests, including static and dynamic load tests, revealed that p-LCP and f-LCP exhibited higher compressive stress and driving resistance compared to normal concrete piles (NCP). Results demonstrated their suitability for deep foundations in soft soil, offering a sustainable and effective alternative for specific applications [9].

Study by [10] explored the use of palm oil fuel ash (POFA), an industrial byproduct, for sustainable peat stabilization. POFA improved peat's mechanical properties, increasing strength by up to 20% and transforming failure patterns from brittle to ductile. Microstructural analysis revealed the formation of cementitious compounds (CSH, CAH), enhancing inter-particle bonding. Environmental tests confirmed POFA's safety, with heavy metal leaching within EPA limits, except for Cr. This eco-friendly approach offers cost-effective solutions for peat reinforcement in construction [10].

Study by [11] investigated foam concrete as a sub-base layer for pavement, focusing on its low density and thermal insulation properties. Flexural strength tests on Poroflow 17-5 foam concrete, combined with geotextiles, were compared to traditional materials. Results showed foam concrete's suitability for pavement bases, with a homomorphic model developed to analyze stress distribution in structural layers. This innovative approach aligns with road design standards, offering a sustainable alternative for road infrastructure development [11].

Study by [12] critiqued the use of conventional consistency limits tests (liquid limit, plastic limit) for peat soils, arguing they lack meaningful results, especially for fibrous peats. Instead, they proposed focusing on natural water content, organic content, fiber content, and humification level as more reliable indicators of peat's geoengineering behavior. This approach, supported by prior research, offers a practical alternative to improve the assessment and stabilization of tropical peat soils in geotechnical engineering [12].

Study by [13] explored biochar as a sustainable alternative to cement for peat stabilization, using pyrolysis-produced biochar from wood and leaves. Biochar-amended peat (200 kg/m^3 biochar + 100 kg/m^3 cement) achieved comparable strength (63.3 kPa) to cement-only samples (63.2 kPa) but with a negative carbon footprint. Biochar reduced cement use by 50%, making stabilization climate-neutral at >27% biochar content. Future carbon prices (€85/t) could enhance biochar's economic viability, promoting sustainable peat stabilization in geotechnical engineering [13].

Study by [14] studied how gas diffusivity (Ds/D0) and water retention (SWRCs) affect O_2 profiles in drained peat layers, comparing sub-boreal and tropical peatlands. Tropical peat showed higher Ds/D0 but greater water retention, limiting aeration and promoting anaerobic layers. Numerical simulations revealed that tropical peat's high water retention inhibits O_2 diffusion, creating an "emission ceiling" for CO_2. These results highlight the trade-off between peat decomposition, gas transport, and water retention, crucial for understanding peatland carbon dynamics [14].

Study by [15] analyzed the physical characteristics of peat soils, focusing on water retention and hydraulic conductivity changes due to drainage and intensive use. Field and laboratory water retention curves aligned well, but wetting and drainage curves differed by up to 30 vol.-% due to wetting inhibition. Shrinkage from drainage caused errors in pore size distribution, especially in less altered peat. These findings highlight challenges in assessing peat soil properties for structural engineering and land use planning [15].

Study by [16] investigated the deformation behavior of peat soil using a physical model (200 cm x 50 cm x 90 cm) instrumented with displacement transducers, comparing it to sand. Peat, with high moisture (>100%), compressibility (0.9-1.5), and low shear strength (5-20 kPa), exhibited punching shear failure, while sand showed general bearing capacity failure. The study highlights peat's challenges for structural engineering due to its high organic content (>75%) and significant settlement, emphasizing the need for specialized foundation solutions [16].

Study by[17] analyzed the engineering properties and compressibility behavior of tropical peat soils (fibric, hemic, sapric) from Malaysia, with organic content ranging from 70% to 90%. Key parameters like loss on ignition correlated well with water content, liquid limit, and density. Compressibility tests (Rowe Cell, oedometer) identified C_c and C_α as critical for settlement estimation. Fibric peat showed the highest settlement under consolidation pressure, followed by hemic and sapric, highlighting structural engineering challenges [17].

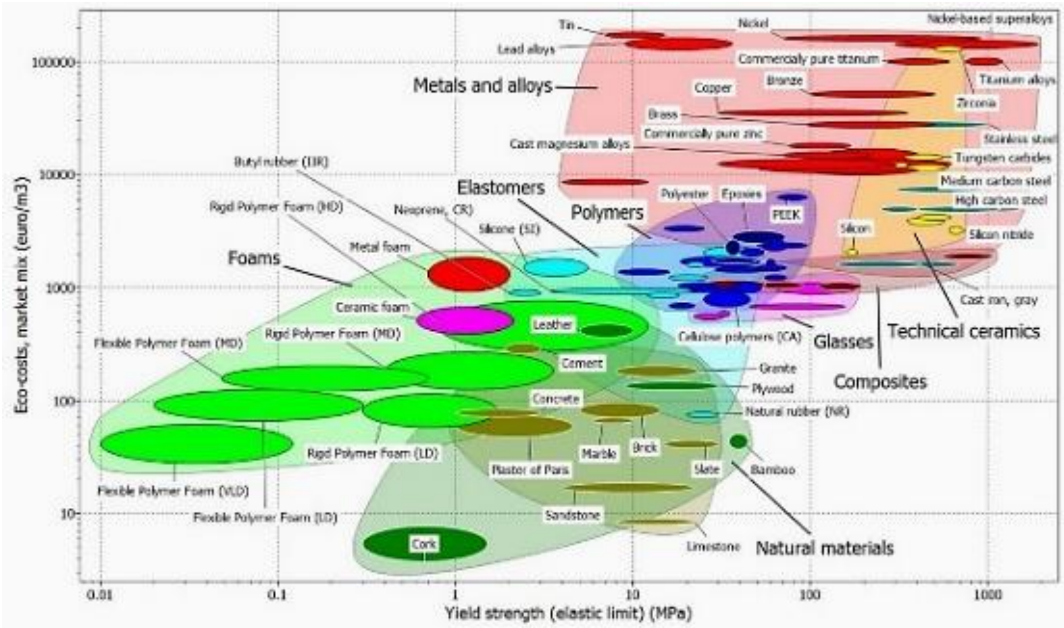

Fig. 1 .The the eco cost of various materials

The deformation of rigid pavements in soft soil foundations, especially in peatland environments, can be effectively analyzed using elastic foundation models, which highlight the importance of innovative materials such as geopolymer concrete and biochar to increase strength and minimize settlement in acidic conditions

2. Peat Soil

Peat soils present unique construction challenges due to their high moisture content (>100%), low shear strength (5-20 kPa), and high compressibility. Studies demonstrate that innovative solutions like geopolymer concrete (20-25% stronger than OPC in acidic conditions) and biochar stabilization can effectively address these issues. Lightweight materials and specialized foundation designs further help mitigate settlement problems in peatland infrastructure projects.

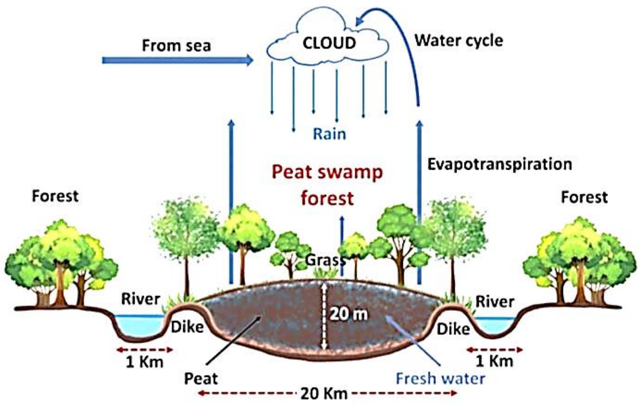

Fig. 2 . Concept Peatland [15]

Table 1. Key Factors Affecting Rigid Pavement on Peat Soil Foundations [4]

	Description	Impact on Rigid Pavement
Soil Type	Peat types : Fibric, Hemic, Sapric	Affects compressibility behavior and settlement
Compressive Strenght	Concrete strength under various conditions	Influences durability and load-bearing capacity
Settlement Index (Cc)	Compressibility index from consolidation tests	Essential for estimating settlement under load
Inovative Material	Use of geopolymer concrete, foam concrete, biochar	Enhances strength and durability in acidic environments
Stabilization Techniquea	Application of industrial by-products and biochar	Reduces settlement and improves soil properties
Environmental Consideration	Construction impact on peatland ecosystems	Promotes sustainable practices to minimize ecological disruption

3. Concrete Rigid Pavement

Concrete for Rigid Pavement: Ordinary Portland Cement (OPC) and geopolymer hybrid concrete (combining fly ash and OPC) were used to simulate rigid pavement. The geopolymer concrete was activated using alkaline solutions to enhance durability in acidic peat environments.

Research shows that fly ash-based concrete, particularly geopolymer hybrid and blended cement, demonstrates superior performance in acidic peat conditions. These materials exhibit significantly higher strength retention and acid resistance compared to ordinary Portland cement (OPC), making them suitable for long-term applications in such challenging environments.

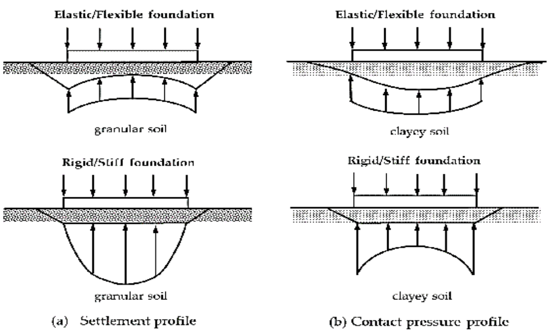

Fig. 3. Settlement and Subgrade Reaction [16]

3.1 Elastic Foundation Model

The peat soil was modeled as an elastic foundation using

Winkler's approach, where the soil is represented by a series of independent linear springs. This assumption allows for the analysis of pavement deformation under load.

A physical model of the pavement system was constructed, with dimensions of 200 cm (length) x 50 cm (width) x 90 cm (height). The model included a rigid pavement layer placed on a peat soil layer.

Displacement transducers were installed to measure deformation and settlement of the pavement under applied loads. Load tests were conducted to simulate traffic conditions, with incremental loads applied to the pavement surface. The deformation of the pavement and the corresponding settlement of the peat soil were recorded.

3.2 Testing Procedures:

Compression Tests: Unconfined compressive strength (UCS) tests were performed on peat samples to determine their load-bearing capacity.

Settlement Analysis: The settlement behavior of the peat under the pavement was analyzed using Rowe Cell consolidation tests and conventional oedometer tests. Key parameters such as compressibility index (Cc) and secondary compression index (Cα) were determined.

The comparison of concrete strength based on compressive strength and settlement rate at various curing conditions or material mixes among various researcher can be seen in **Fig. 5**. The excellent results of settlement achieved by compressive strength above 200 kPa.

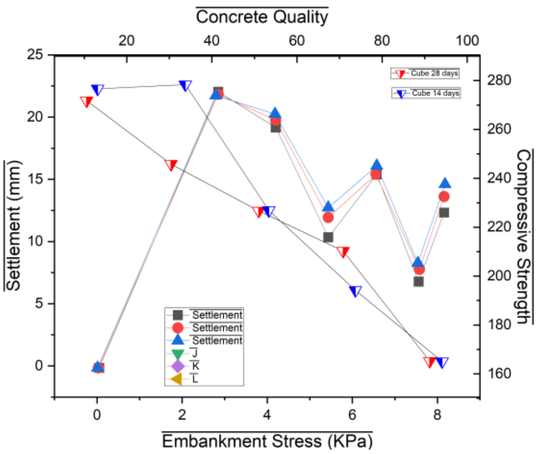

Fig. 5. The comparison on the concrete compressive strength's effect on the settlement among researchers [7].

Microstructural Analysis: Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) were used to examine the interaction between the pavement material and the peat soil, focusing on changes in pore structure and bonding.

4. Conclution

The construction of rigid pavement on soft soil presents significant challenges due to low bearing capacity, high compressibility, and potential differential settlement. If not properly addressed, these issues can lead to premature failure, increasing maintenance costs and reducing pavement lifespan. Several reinforcement techniques have been explored to mitigate these problems.

Soil stabilization using cement, lime, or chemical additives has proven effective in enhancing subgrade strength. Additionally, geosynthetics such as geotextiles and geogrids improve load distribution and prevent excessive settlement.

Layered foundation systems, including thickened subbase and base courses, further contribute to structural stability and durability.Material selection plays a crucial role in ensuring the long-term performance of rigid pavement on soft soil.

High-performance concrete, fiber-reinforced composites, and advanced subgrade treatment methods offer potential solutions to enhance pavement resilience.

To optimize rigid pavement construction in soft soil conditions, further research is necessary to explore innovative materials, advanced geotechnical techniques, and cost-effective construction practices.

Integrating modern engineering solutions with sustainable approaches will lead to more durable and resilient pavement structures, minimizing long-term maintenance needs and ensuring infrastructure reliability.

In conclusion, a comprehensive approach combining proper design, material selection, and reinforcement techniques is essential for achieving optimal rigid pavement performance on soft soil.

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