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PROCEEDINGS OF 3rd NISE (NATURE-INSPIRED SOLUTIONS FOR BUILT ENVIRONMENT)

Regenerative Ground

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A collection of original articles, reviews, and extended abstracts is edited and presented across four thematic chapters to highlight the latest advances in nature-inspired ground engineering solutions. While the primary focus is on Northern Cyprus, the contributions have global relevance and reflect ground engineering's growing alignment with natural systems. In a world where the built environment increasingly disrupts the biological, chemical, and mechanical equilibrium of the ground beneath us, it is necessary to witness a shift in paradigm, one that reimagines our material choices, methods, and models. This shift is articulated clearly in the vision offered by the NiSE (Nature-inspired Solutions for Built Environment) working party and its framework (Cetin et al. 2024; Assadi-Langroudi et al. 2023; Assadi-Langroudi et al. 2022), and provides both a critique of traditional engineering practice and a roadmap for its reinvention.

The ground, as NiSE reminds us, is not merely a foundation to be stabilised and built upon. It is a living integrated system composed of fractal, adaptive, self-forming, and self-healing systems. Nature's strategies for resilience and renewal offer a vast lexicon of ideas for modern engineering. Whether through the calcite-precipitating activity of soil bacteria, the pozzolanic reactivity of wood ash, the fibrous integrity of recycled dog hair used as reinforcement, or the emerging understanding of rocking isolation and partially drained soil behaviour, the papers in this booklet reveal an inspiring breadth of nature-inspired thinking.

With the closing of NiSE3, it has become clear that the research around biomimetics fit broadly into four thematic categories:

(1) Materials—cementitious and polymeric phases;
(2) Physical Modelling;
(3) Numerical Modelling and Systems Thinking;
(4) Sustainability and Implementation Barriers.

Each of these themes contributes to the overarching goal of a more regenerative, responsive, and responsible ground engineering practice.

Over the course of the 3rd NiSE conference, some important reflections emerged. Scale matters, and the disparity between the challenges faced at the field scale and the solutions developed at laboratory scale remains an evident concern. While the development of alternative binders and cementing agents has attracted an energetic cohort of younger researchers, their translation to real-world settings raises open questions: How can these materials be reliably applied to base soils in situ? Can we expect the same performance in the field as under tightly controlled lab conditions? What are the wider ecological and environmental risks, both immediate and long-term, posed by such additives? The durability and biodegradability of polymerisation products, in particular, remains to be thoroughly investigated.

The concept of soil health featured heavily in discussion, yet one is left wondering what defines soil health? What measures it? How do we balance biological function with mechanical performance in our engineering interventions?

Moreover, when it comes to materials, questions around procurement, including supply security, cost, and stakeholder acceptance, are increasingly pertinent. Some alternative additives (e.g., shredded tyres) offer attractive technical benefits but may be met with resistance from communities or regulators concerned with health and environmental consequences. For nature-inspired engineering to thrive, ground engineers must collaborate closely with ecologists, human scientists, and supply chain experts, to ensure that materials are not only functional, but also socially and environmentally acceptable.

To help bridge the scale gap, the incorporation of advanced physical modelling, IoT-enabled monitoring, meso-scale experimental tools, and machine learning-driven decision systems are vital. These tools are crucial in translating the laboratory research into durable, scalable, and workable ground solutions.

The contributions in this collection do more than report findings. They reflect an emerging ethos and represent a community that sees the value of working with nature, not against it. The collection stands as a testament to the idea that innovation, when rooted in the intelligence of natural systems, can be not only resilient but also regenerative. As you read through the pages of this collection, you will be inspired to build in ways that honour the ground's innate wisdom and in ways that leave it better, not worse, for future generations.

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Chapter 1. Materials and Polymeric Phases

Bacillus subtilis Bacteria in Soil Applications

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INTRODUCTION

Stabilization is of vital importance in many civil engineering applications, especially when the area is known for its problematic soil types.

Bio-stabilization of soils aligns closely with the NiSE (Nature-inspired Solutions for the built Environment) framework. MICP leverages biological mechanisms found in nature — specifically the metabolic pathways of soil bacteria — to produce calcite that binds soil particles, offering a sustainable alternative to traditional stabilization methods that often rely on chemicals or mechanical alteration. This approach fits the NiSE vision of working with nature rather than against it, preserving the soil's natural structure and ecological functions (Assadi-Langroudi et al. 2023), provision of enhanced soil fertility and biological diversity, reflecting the goal of using biomimetic, resilient, and regenerative solutions for ground engineering challenges in a changing environment.

The use of bacteria in soil stabilization has been an area of interest given proved outstanding results without the use of chemicals that could have adverse consequences on the environment as is the case with chemical stabilization. Efforts have also been made in combining the bacteria with various waste materials that could serve the bacteria at the same time as diminishing and reusing the waste, thus decreasing the amount of waste and aiding with otherwise cumbersome processes of waste handling.

Bacillus subtilis bacteria are known for its ability to precipitate calcite through its metabolic pathways, in what is called Microbially-Induced Calcite Precipitation (MICP), the calcite in most cases acts a binder between soil particles, helping to stabilize the soil and enhance mechanical performance.

Bacillus subtilis does not harm the natural soil, it acts as a fertilizer and a plant-growth-promoting agent, as well as a biocontrol agent and reduces the need for chemical pesticides, however, the controlled use and further research on the long-term effect of its presence is needed before it can be widely used or overused in any shape or form.

MATERIALS AND METHODS

This paper presents a review of previous works on the use of *bacillus subtilis* bacteria in soil applications. *Bacillus subtilis* bacteria was considered as the most common bacteria type used in ground engineering sector. Emphasis was put into studies published in English from 2018 onwards.

RESULTS AND DISCUSSION

Samsang et al. (2018) investigated the use of *Bacillus subtilis* bacteria in what is now referred to as bio-stabilization, aiming to address the problem of low bearing capacity in soft soils. They tested soil samples with and without the MICP process and concluded that the bacterial activity significantly increased bearing capacity. This was attributed to calcite precipitation, which helped bind soil particles together, enhancing subgrade construction applications. Compared to chemical or even mechanical stabilization methods, this form of stabilization was also found to be more environmentally friendly. Soft soils were further studied by Rokhman et al. (2023), who examined their unconfined compressive strength and shear resistance after exposure to MICP. The calcite induced by *Bacillus subtilis* contributed to improved mechanical performance, confirming that bio-stabilization can be a viable alternative to traditional chemical treatments.

Widjajakusuma et al. (2019) explored bio-grouting techniques for tropical organic soils such as peat, which are generally unsuitable for construction due to their low bearing capacity, high compressibility, and poor stability. Their study also employed MICP using *Bacillus subtilis* bacteria. Compressive strength and stiffness tests were conducted following calcite precipitation, and the results showed significant improvements in both parameters. As conventional chemical stabilization poses environmental risks, bio-grouting emerges as a more sustainable approach. Sugata et al. (2020) investigated bio-stabilization in expansive soils, which are prone to volumetric changes with moisture fluctuations. They again used *Bacillus subtilis*, this time with an external calcium source to facilitate calcite formation. Eggshell powder, an abundant and sustainable material, was selected as the calcium source. Tests on unconfined compressive strength, swelling behavior, and microstructure analysis revealed that the combination of bacteria and eggshell powder enhanced soil strength, reduced swelling and settlement, and produced calcite that acted as a binder between soil particles, resulting in a more rigid and stable soil structure.

Scopes for reusing organic waste as a calcium source for MICP were studied in Golovkina et al. (2023). They used waste materials such as eggshells, seafood shells, and plant-based residues to aid *Bacillus subtilis* in stabilizing soils from regions with low natural stability and high settlement risks. Strength and durability tests showed increased compressive strength, reduced settlement, and confirmed the presence of calcite through microstructural analysis. For marine sandy clay soils — known for their weak structure and exposure to water — Harianto et al. (2013) examined the effectiveness of bio-grouting using *Bacillus subtilis*. Their tests on unconfined compressive strength, permeability, and microstructure showed improvements in all three: the soil's compressive strength increased, permeability decreased, and cement-like crystals were observed binding the particles together, indicating successful stabilization.

CONCLUSION

Bacillus subtilis bacteria has a great potential of inducing calcite precipitation through its metabolic pathways and enhancing the mechanical properties of compressive strength, shear resistance, and swelling behavior. It has happened to various types of soil. This method is considered environmentally friendly, when compared to other methods of stabilization. Especially, when it goes hand by hand with sustainable sources of calcium for the MICP, gathered from waste materials such as eggshell powder or organic waste. All in all MICP is an alternative that enhances soil stability and promotes sustainable construction practices.

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The Power of Non-Recycled Materials for Enhanced Performance in Roller- Compacted Concrete Pavement

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INTRODUCTION

Conventional groundwork methods often disrupt soil's biological functions and adaptive capacities, through overexploitation of natural resources – such as mining, or direct disturbance of the topsoil, leading to a long-term loss of resilience. The use of alternative upcycled materials such as crumb rubber and crushed asphalt can partially ease the pressure on natural systems and environmental degradation (). This study explores the innovative use of non-recycled waste materials to enhance the performance of Roller-Compacted Concrete (RCC) pavements. RCC is renowned for its durability, cost- effectiveness, and environmental advantages. These qualities make it a preferred choice in modern road construction (Hafez et al., 2023). By incorporating waste materials like crumb rubber, crushed asphalt, and crushed concrete as partial replacements for traditional aggregates, this research examines their impact on RCC's mechanical properties. The aim is to assess whether these non- recycled alternatives can elevate pavement quality standards. Key attributes of interest include deformability, energy absorption, and long-term durability.

MATERIALS AND METHODS

The study employed both fine and coarse aggregates, including crushed sand, crumb rubber, asphalt mixture, and crushed concrete. Crumb rubber (density: 1.06 g/cm³, particle size <5 mm) was sourced from a recycling facility in Joybar, Iran, and used to partially replace the fine aggregate at rates of 5%, 10%, and 15%. Coarse aggregate was replaced with crushed concrete and asphalt mixtures at 25%, 50%, and 75%, obtained from sources in Sari, Iran. All aggregates conformed to the standards set by the Portland Cement Association and were crushed to a maximum particle size of 12.5 mm. Type II Portland cement, procured from Neka City, Iran, was used in all mixes. The RCC control mixture incorporated natural aggregates with a water-to-cement ratio of 0.35. Experimental mixes were prepared by substituting coarse aggregates with crushed concrete and asphalt mixtures at varying proportions (25%, 50%, and 75%), and crumb rubber was introduced into the fine aggregate at levels of 5%, 10%, and 15%.

All RCC mixtures were prepared using a specialized concrete mixer. Molds were lubricated, filled, and compacted using a plastic hammer, followed by vibration to ensure uniform compaction. Specimens were covered for 24 hours and then cured in a water bath maintained at 25°C. Cylindrical specimens (15 cm in diameter and 30 cm in height) were tested for compressive strength in accordance with ASTM C39. A compression jack was used to apply the load, and compressive stress was calculated by dividing the applied load by the cross-sectional area (Mansor et al., 2020). The indirect tensile strength was evaluated using the same cylindrical specimens, following ACI 325.10 guidelines (ACI 325.10 R-10, 2010). Flexural strength was assessed according to ASTM C293 using prism specimens measuring 50 × 100 × 300 mm. Each specimen was center-loaded, and bending strength was calculated based on the applied load and the specimen's dimensions (Ashteyat et al., 2024).

Figure 1. Condition of specimen before (a) and after (b) indirect tensile testing

RESULTS AND DISCUSSION

This study evaluated RCC with crumb rubber replacing fine aggregate at 5%, 10%, and 15%. Crushed asphalt replaced coarse aggregate at 25%, 50%, and 75%. After 28 days, crushed asphalt effectively substituted fine aggregate. However, specimens with crushed asphalt and concrete had lower tensile strengths. Notably, a mix with 75% crushed concrete did not meet the 2 MPa requirement. Flexural strength tests showed that mixes with high levels of crushed asphalt and concrete were below permissible values. Crumb rubber RCC exhibited better bending strength and deformation before failure, despite lower maximum loads. Crushed concrete notably reduced tensile strength and overall performance.

CONCLUSIONS

RCC mixtures incorporating 5%, 10%, and 15% crumb rubber, along with 25% to 50% crushed asphalt and 25% crushed concrete, demonstrate potential for pavement applications. While crushed concrete consistently reduces both compressive and tensile strengths, crushed asphalt contributes to improved mechanical performance. The inclusion of crumb rubber (up to 15%) and crushed asphalt (up to 50%) enhances deformability and energy absorption, which are desirable traits for flexible pavement systems. However, crushed concrete continues to underperform across key strength parameters. Notably, the reduction in tensile strength is less pronounced in specimens containing crumb rubber. In contrast, mixtures with crushed asphalt and concrete exhibit more significant declines in tensile and flexural strength than in compressive strength, highlighting their differing effects on load resistance under various stress conditions.

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Transforming Waste into Strength: Wood Ash for Sustainable Cement Solutions

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INTRODUCTION

This study explores the use of wood ash, a waste by product, as a replacement of Portland cement in concrete. As sustainability becomes increasingly important in construction, there is growing interest in utilizing waste materials to reduce environmental impacts (Liu et al., 2020). Portland cement production is a major contributor to CO_2 emissions and energy consumption. Using readily available materials like wood ash can help reduce both transportation emissions and landfill waste (Wang & Haller, 2022).

In Cyprus, wood ash is abundant but often disposed in landfills, which creates environmental concerns (Ekinci et al., 2020). This study evaluates key properties of concrete such as slump, bulk density, compressive strength, flexural strength, and water permeability. The goal is to assess whether wood ash can be a sustainable alternative to cement.

MATERIALS AND METHODS

The materials used in this study include Portland Cement (PC), Wood Ash (WA), Wood Ash Micron (fine particles), and their mixtures with water in specific proportions. Ordinary Portland Cement (CEM I) with a strength class of 42.5 MPa was used, in compliance with the TS-EN 197-1 standard. The Blaine fineness was 305 kg/m², and the specific gravity was 3.15. Wood ash, containing 44% CaO, was sieved through a 300-µm mesh and used to replace 10% of the Portland cement. The concrete mixes incorporated varying proportions of wood ash (WA) and natural fibers. These mix proportions are presented in Table 1.

Table 1. Mix design

Mixes	WA (micron) [g]	Water [g]	Cement [g]	WA [g]
90%PC-10%WA	300	540	1080	120

A mix consisting of 90% Portland cement (PC) and 10% wood ash (WA) was prepared, using 1080 g of PC, 120 g of WA, and 540 g of water. The mixture was then poured into molds and allowed to harden. To evaluate the properties of the fresh cement, several tests were conducted. In the mini slump test, workability was assessed by pouring the cement paste into a cone in three stages, with each stage tamped 25 times before recording the slump. For the flow table test, the cement paste was placed in two stages, each tamped 25 times, and the table was raised and dropped 25 times to measure dispersion and flow characteristics. Fresh density was determined using a mold divided into three equal parts, with weights recorded before removing the samples from the molds after one day. Flexural strength was tested at 7, 14, and 28 days, while compressive strength was measured at 7, 14, 28, and 56 days until failure.

Figure 1. Placement of cement in the cone for mini slump testing

RESULTS AND DISCUSSION

Flexural strength after 7 and 14 days of water curing showed a decrease over time. In contrast, compressive strength significantly increased. Other mix designs exhibited strength reductions. The decline in flexural strength may be attributed to the hydration characteristics of wood ash, whereas the notable increase in compressive strength suggests that wood ash contributes to overall structural performance, likely due to increased microstructural density. These results highlight the potential of wood ash as a sustainable additive in concrete production. However, further research is necessary to optimize mix proportions and investigate additional materials that may enhance strength.

Wood ash is a naturally derived, minimally processed waste material. In this paper, wood ash initiates microstructural transformations that mature gradually, leading to enhanced mechanical strength over curing periods of 7, 14, 28, and 56 days. This time-dependent evolution mirrors natural systems, where strength, resilience, and structure emerge progressively through internal reorganization, much like bone mineralization over time.

The reduction in slump and increased fresh density, paired with improved compressive strength, suggest that the cementitious matrix adapts as wood ash hydrates and integrates into the mix. This aligns with the biomimetic principle of functional material evolution, a cornerstone of nature inspired design (Assadi-Langroudi et al. 2023). Rather than relying on abrupt chemical fixes or high-energy processing, the approach encourages a low-energy, internally driven consolidation for regenerative intelligent engineering.

CONCLUSIONS

The mini-slump values decreased with the addition of 10% wood ash; however, the mixes continued to perform well, likely due to their effective water absorption capacity. Similarly, results from the flow table test showed a reduction, yet the mixes maintained satisfactory performance. Notably, the incorporation of wood ash led to a slight increase in fresh density. Flexural strength in mixes containing 10% wood ash improved between 7 and 14 days of curing. Meanwhile, compressive strength exhibited consistent values at both intervals, with a gradual increase over time.

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Mechanical Properties of Waste Glass, Plastic and Fly ash in Sustainable concrete

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INTRODUCTION

Industrial growth produces non-biodegradable waste like plastic and glass, impacting the environment. Recycling these materials in concrete can address pollution, reduce landfill issues, and lessen resource strain. This study investigates the effects of fly ash, recycled glass, and plastic on concrete's strength, density, workability, and fire resistance to optimize sustainability.

MATERIALS AND METHODS

The experiment used Type 3 Portland cement and sustainable replacements like waste glass, fly ash, and recycled plastic particles. Five concrete designs tested these materials' effects. Mixes were cured for 7, 14, and 28 days, with workability, compressive strength, and tensile resistance tested using ASTM C143, C109/C109M-20, and C496 standards.

RESULTS

The experimental findings reveal that substituting traditional aggregates with recycled materials—specifically 10% fly ash, plastic, and glass sand—has a measurable impact on concrete properties. Workability was notably reduced, with fly ash decreasing slump by 45% and glass sand by 19%, as illustrated in Figure 1. Early-age compressive strength (at 7 and 14 days) declined across all modified mixtures; however, by day 28, the mix containing 10% fly ash demonstrated a 16% improvement in strength, while the combined use of fly ash and glass sand resulted in an 11% increase, as shown in Figure 2.

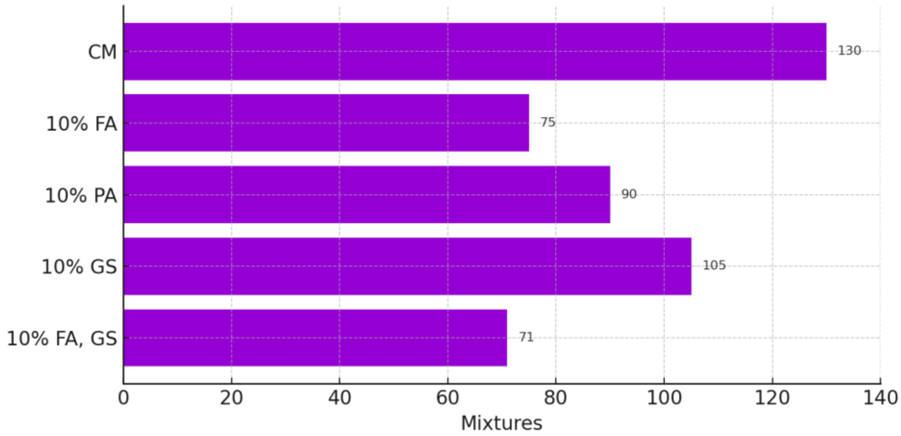

Figure 1. Slump Value

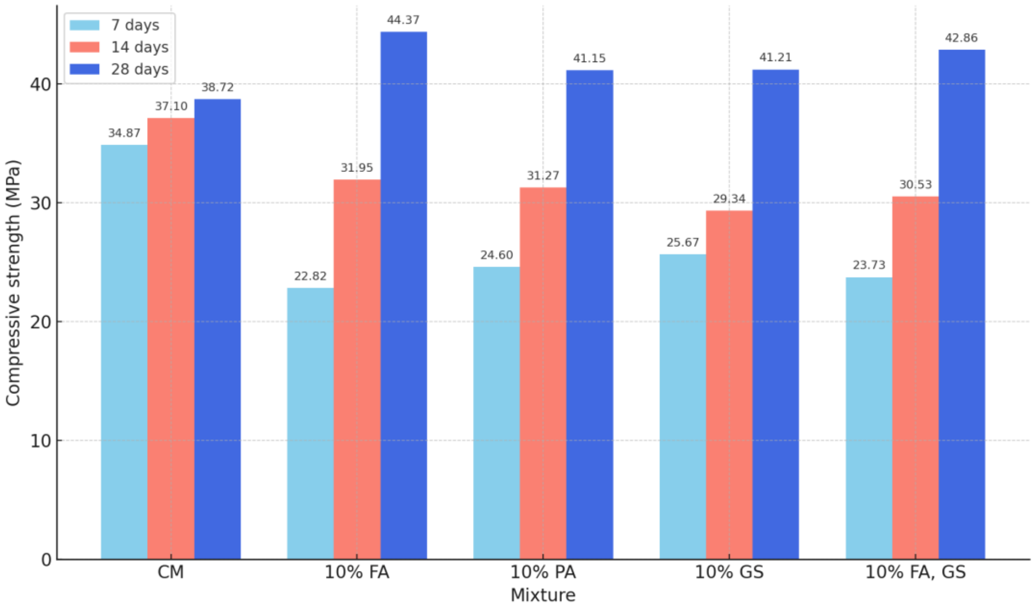

Figure 2. Results of Compressive Strength

Conversely, tensile strength was consistently reduced across all samples and curing periods, with glass sand causing the most significant loss (Figure 3). Dry density also declined due to the lower specific gravity of the added materials—fly ash resulted in an average 2.7% reduction and plastic up to 6%, with minor decreases observed for glass sand due to increased internal friction, as presented in Figure 4. Fire resistance testing revealed that plastic aggregates had the most severe negative effect, reducing compressive strength by 40%, while fly ash and glass sand both led to approximately 25% reductions. The analysis shows that adding glass sand, fly ash, and plastic aggregates to concrete reduces workability, compressive strength, and tensile strength. Fly ash (10%) decreased workability by 45%, while glass sand (10%) reduced it by 19%.

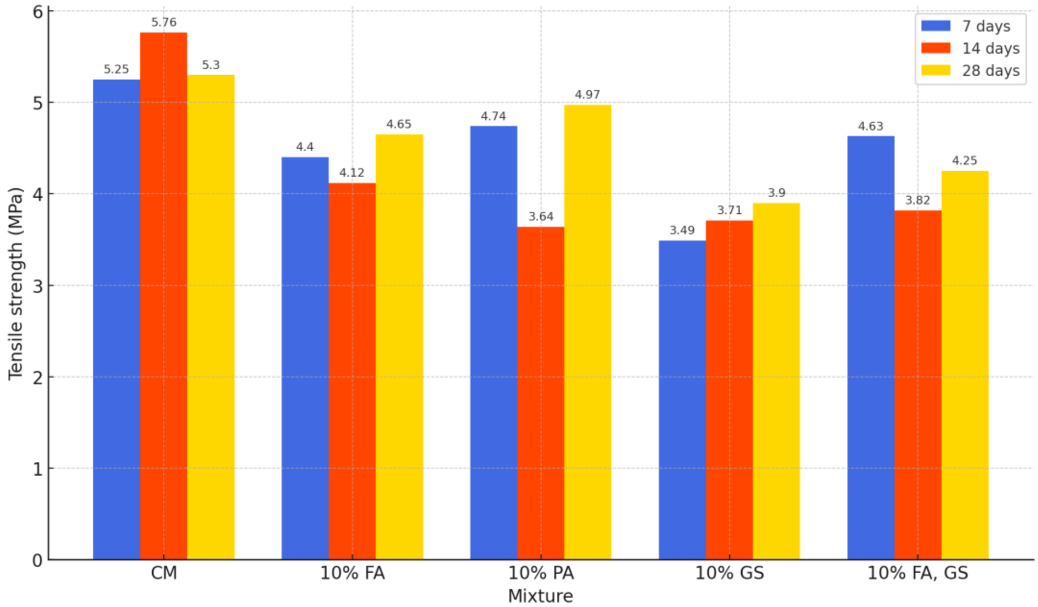

Figure 3. Results of Tensile Strength

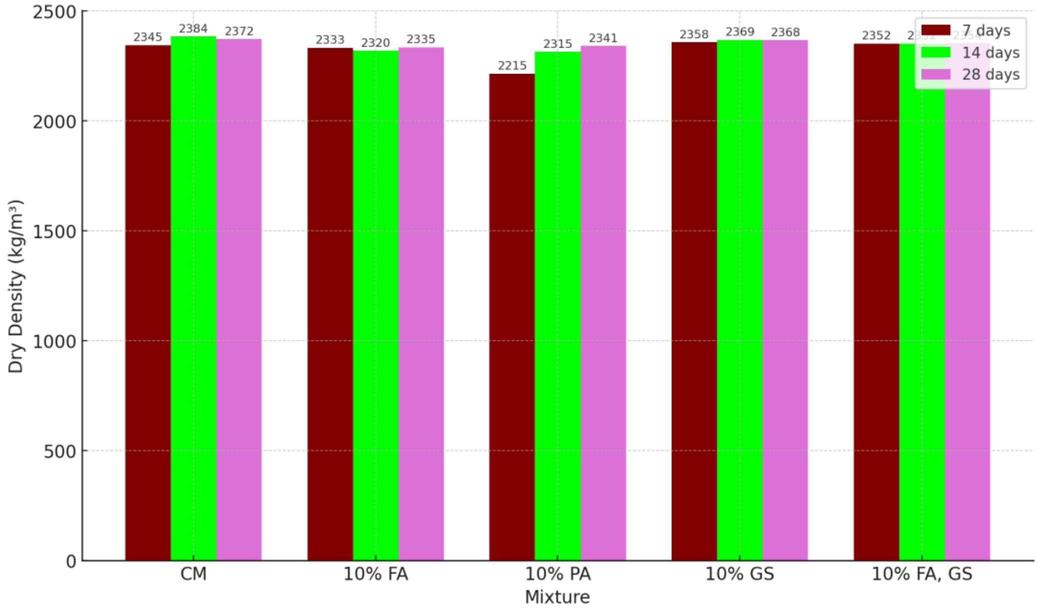

Figure 4. Dry Density

Findings indicate a performance-sustainability trade-off. The improvement in long-term compressive strength for fly ash and combined fly ash/glass mixes likely stems from pozzolanic activity and improved particle packing, whereas early-age weakness may relate to delayed hydration or insufficient early bonding. The consistent reduction in tensile strength underscores the challenges of interfacial bonding between recycled particles and the cement matrix. The density reductions suggest potential for lightweight applications but may limit structural use in high-load scenarios. The pronounced loss in fire resistance, especially with plastic aggregates, raises concerns for applications in fire-exposed structures. Thus, while promising from a sustainability perspective, these materials require tailored mix design or additional treatments to overcome their performance limitations. From the philosophical perspective, findings align closely with the tenets of nature-inspired design. As Assadi-Langroudi et al. 2023 put, the pursuit of sustainable, low-carbon construction materials is a key challenge. Findings in this paper demonstrate how industrial by-products—specifically glass, fly ash, and plastics—can be reused as concrete constituents to reduce environmental impact. The observed trade-offs between mechanical performance and sustainability reflect the broader issue raised regarding the transformation of natural and synthetic materials under emerging environmental stresses. In particular, the use of upcycled and waste-derived materials echoes the ideal emphasis on biogenic and upcycled innovations as viable alternatives to conventional materials in ground and structural applications.

CONCLUSION

The study shows that substituting traditional concrete components with glass sand, fly ash, or plastic aggregates affects workability, strength, and density. While pozzolanic reactions enhance long-term strength, initial workability and tensile strength can decrease, highlighting the need for balanced substitutions.

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Use of Glass Powder in Dog Hair Reinforced Cement Paste Production

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INTRODUCTION

A large amount of energy is used in the production of cement, and a significant quantity of CO_2 is released into the atmosphere, causing impactful changes to the environment. Ancient literature shows the use of cement throughout history; however, cement production has been one cause of the greenhouse effect, contributing to global warming. These issues have created an area of research for modern engineers, who are working to find possible eco-friendly substitutes for concrete (Zeybek et al., 2022). As sustainability becomes increasingly important in the global construction sector, the potential of recycling waste materials to produce eco-friendly construction materials is gaining attention. Mixed-color waste glass offers the desired chemical composition and reactivity for use as a supplementary cementitious material, which can enhance the chemical stability, moisture resistance, and durability of concrete (Federico & Chidiac, 2009). For fiber-reinforced materials, hair can be used due to its strong tensile properties (Manaf et al., 2017).

MATERIALS AND METHODS

This study employed Portland cement (CEM I) as the primary binder, with green soda-lime glass waste ground into powder (150 μm particle size) and used as a supplementary cementitious material. Dog hair, obtained as a waste product from a local pet shop, was sourced from a husky breed and used as a natural fibre additive. Glass powder was incorporated at three different replacement levels—5%, 10%, and 15%—by weight of cement. In parallel, mixes were prepared containing combinations of glass powder and dog hair at two volume fractions: 0.25% and 0.5%. These combinations resulted in ten different mixes, including control and modified specimens. The prepared samples were tested at 7, 14, and 28 days to evaluate various fresh and hardened properties. Workability was measured through the mini slump test in accordance with ASTM C143, and flow was evaluated using ASTM C230. Fresh density was determined using ASTM C138. For hardened properties, compressive strength was measured based on ASTM C109, and flexural strength using ASTM C490. Durability was assessed through porosity and seawater resistance tests according to ASTM C1585. In addition, a sustainability evaluation was conducted, considering both environmental impact in terms of carbon dioxide emissions and economic cost comparisons between the control and modified mixes.

RESULTS AND DISCUSSION

The workability of the samples modified with GP was observed to be higher, while the samples modified with DH exhibited lower workability. The fresh density of the GP-modified samples was approximately similar to that of the control (C) sample, with the DH-modified samples exhibiting higher fresh density values. The compressive and flexural strengths of the GP- and DH-modified samples were higher than those of the C sample. The increase in strength is due to the pozzolanic properties of the GP, which fills the voids in the cement paste, making it denser and further increasing the compressive strength. The incorporation of DH into the cement paste improves its durability, bonding strength, and resistance to cracking. The seawater resistance and porosity test results indicate that the porosity of the modified mixes reduced with age, confirming pozzolanic activity and the formation of hydration products. The sustainability assessment of the C and the modified mixes was carried out for both environmental and economic aspects. The environmental assessment indicated that the CO2 emissions for the modified samples were lower than those of the C sample, and the economic assessment showed lower or similar costs for the modified samples compared to the C sample.

MCDA mapping

Multi-Criteria Decision Analysis (MCDA) is used as a vehicle to measure the alignment of the technology studied here against tenets of nature-inspired design. The general approach outlined in the paper, which involves substituting traditional cement and reinforcement materials with powdered waste glass and natural dog hair fibres, reflects several key tenets of nature-inspired design as defined in the NiSE framework (Assadi-Langroudi et al. 2022). It demonstrates a deliberate shift toward using waste-derived and biogenic materials that mirror natural cycles of reuse and minimal environmental disruption. The use of fibrous organic waste imitates biological forms and bonding behaviours found in root-reinforced soils, while the incorporation of ground glass mimics mineral-based generative processes that enhance durability and long-term performance. These choices preserve pore structures, reduce carbon emissions, and promote compatibility with the surrounding environment. When evaluated against the NiSE rating framework's three axes—processes, forms, and functions—this study would likely score +2 on forms due to its mimicry of natural fibrous reinforcement, +1 on processes for its partial replacement of carbon-intensive cement, and +2 on functions for enhancing sustainability and resource circularity. Overall, the intervention appears beneficial, with an estimated composite rating of +5, placing it within the zone of good adaptability to NiSE objectives, although further work on biological integration and long-term self-healing would be required to reach higher scores.

CONCLUSION

This study demonstrates the potential of using GP and DH as eco-friendly additives in cement paste production. The modified mixes showed improved workability, fresh density, compressive strength, and flexural strength compared to the C mix. The pozzolanic properties of GP enhance strength by filling voids in the cement paste, while DH contributes to durability and resistance to cracking. The modified samples showed lower porosity over time and reduced CO2 emissions, indicating their sustainability benefits. The addion of GP and DH not only improves the mechanical properties of cement pastes but also objective with environmental goals in the construction industry.

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Soil Stabilization by Using Waste Glass with Consideration of Cement Addition and Geo-Polymerization

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INTRODUCTION

Soil stabilization is a key civil engineering technique aimed at improving soil's physical and mechanical properties to enhance load-bearing capacity, durability, and environmental resistance. The rising demand for construction and the need for sustainable practices have increased the urgency for innovative methods. Recent advancements show that materials such as glass powder and geopolymers are effective alternatives to traditional cement-based techniques. Recycling waste glass into powder addresses landfill issues while providing pozzolanic properties that strengthen soil. Geopolymers, derived from aluminosilicate materials, also offer a lower carbon footprint than conventional cement.

MATERIALS AND METHODS

Glass Powder in Soil Stabilization

Mechanical Properties Enhancement

The incorporation of glass powder markedly improves the unconfined compressive strength (UCS) of soils, achieving increases of up to 390% at optimal dosages. This enhancement results from the pozzolanic activity of glass powder, which reacts with calcium hydroxide to produce calcium silicate hydrate (C-S-H) gel, thereby enhancing particle bonding. Fine glass powder exhibits superior reactivity and strength gains at reduced dosages.

Reduction of Plasticity

Glass powder effectively reduces the plasticity index of clay soils, enhancing their stability and workability. Studies demonstrate that even a 5% addition can significantly lower plasticity, making soils less susceptible to deformation. The interaction between glass powder and clay minerals alters water absorption and improves soil structure, resulting in reduced shrink-swell potential.

Geopolymers in Soil Stabilization

Overview of Geopolymers

Geopolymers, formed through the reaction of aluminosilicates with alkaline solutions, present a sustainable alternative to cement. They demonstrate excellent mechanical properties and lower environmental impacts.

Environmental Sustainability

Geopolymers offer substantial reductions in CO_2 emissions compared to traditional cement, utilizing industrial by-products and requiring less energy for production. This approach fosters a circular economy by repurposing waste materials.

Optimal Mix Design

The effectiveness of geopolymer stabilization is influenced by the selection of alkaline activators and curing conditions. Optimal parameters are critical for maximizing strength and durability.

RESULTS AND DISCUSSION

Recent studies reveal that combining glass powder with geopolymers yields enhanced mechanical performance and environmental benefits. This synergistic approach can improve UCS by 35% while reducing carbon footprints significantly. The integration of these materials not only enhances the strength and durability of stabilized soils but also promotes waste recycling and sustainability in construction practices.

CONCLUSION

The incorporation of glass powder and geopolymers in soil stabilization represents a significant advancement in civil engineering, addressing both performance and sustainability goals. Optimal use of these materials can lead to substantial improvements in soil properties, reduced environmental impacts, and enhanced durability. This innovative approach contributes to more sustainable construction practices and the effective utilization of waste materials, paving the way for a greener future in civil engineering.

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Sustainability Assessment of Cementitious Materials Using Waste Glass Powder and Waste Brick Dust as Partial Cement Replacements

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INTRODUCTION

Crushed rocks (coarse aggregate), river sand (fine aggregate), cement, and natural materials make up the mix of concrete. To achieve high strength or performance, additional materials such as pumice powder, marble dust, brick dust, glass powder, cenosphere, silica fume, and superplasticizers are often included. These supplementary components help mitigate issues like alkali-silica reaction and sulfate attack. However, the use of concrete has significant environmental implications, particularly due to cement production, which accounts for approximately 8% of global CO_2 emissions. To improve sustainability, concrete as a building material must maintain quality and durability while also not compromise functions of the natural systems, and environmental spheres. Recent efforts have focused on reducing CO_2 emissions from cement production and incorporating pozzolanic by-products into cement mixes. This study explores the use of Portland limestone cement (CEM II-BL) along with waste glass powder (WGP) and brick dust (BD) as partial cement replacements. The experimental focus is on assessing mortar behavior using materials available in North Cyprus, following ASTM C270 and other related specifications. The mix includes WGP and BD as mineral admixtures and local superplasticizers.

MATERIALS AND METHODS

Six mortar mixtures were prepared, including a control mix and five mixes containing varying percentages of brick dust and glass powder (0%, 5%, 10%, 15%, and 20%). All mixes used a water-to-cementitious material ratio of 0.35 and included a superplasticizer. The replacement effects were evaluated through compressive strength, water absorption, dry density, fire resistance, flexural strength, and drying shrinkage tests. A water-to-binder ratio of 0.54 was applied. Testing adhered to ASTM C305-20 standards, and specific sample dimensions were used for each test: 50 × 50 × 50 mm cubes for compression, water absorption, dry density, and fire resistance; 40 × 40 × 160 mm prisms for flexural strength; and 25 × 25 × 285 mm prisms for drying shrinkage. Mortar blending followed ASTM C305-20 protocols using a mechanical mixer. The fine aggregates, cement, WGP, and BD were dry-mixed for two to three minutes. Moisture-containing mixtures were blended for 14–15 minutes in two stages. Two-thirds of the water and superplasticizer were added to the dry mix and blended for five minutes. The remaining water and superplasticizer were then incorporated and mixed again. During mixing, molds were oiled to prevent voids upon demolding. After flow testing, the fresh mortar was placed in molds: 50 mm cubes for compressive strength, fire resistance, and water absorption; 25 × 25 × 285 mm prisms for shrinkage; and 40 × 40 × 160 mm molds for flexural strength. Each sample was compacted 25 times per layer, and the surfaces were smoothed. After setting for 24 ± 0.5 hours at room temperature, specimens were demolded and transferred to a lime-saturated curing tank (3 g/L calcium hydroxide) at 25 °C until testing.

RESULTS AND DISCUSSION

The key findings of the work

1. The partaking of WGP in the mixture enhanced its flow to increase beyond the control mix as the level of glass powder increased, the improvement was caused concerning its hydration and surface area as glass as well is a material that is clean/ neat by nature. The optimum flow level was achieved when glass powder was 20%
2. The insertion of 20% WGP gave a 3% increase by comparison with to the control mix, the higher quantity of waste glass powder and curing days the more the strength. In the optimum use of brick dust at 15% BD and 5% WGP, the strength depreciates at 20% compared to other mixes.
3. The mix of 10 WGP and 10 BD showed the highest water absorption and material consisting of a higher amount of waste glass powder showed lower absorption, the water absorption of samples with brick dust increased this can be due to the dry nature of brick dust and high micro pores and unreacted particles during hydration. The high absorption of water for brick dust is accountable for its low flow.
4. The use of GP and BD as a partial cement replacement could lessen the environmental effects of cementitious materials, according to the ECO-efficiency and cost assessment. The findings of this study show that recycling glass and bricks into building materials is a feasible undertaking. However, due to the high EE AND EC of superplasticizer higher dosages are not recommended but can be further looked into.

SYMBIOSIS WITH THE NATURAL SYSTEMS

The use of waste glass powder and brick dust as partial replacements for cement, as presented in the mortar study, aligns closely with the core principles of the Nature-inspired Solutions for the Built Environment (NiSE) as an ideal design phylosophy. At its heart, NiSE advocates for engineered systems that emulate the self-sustaining, adaptable, and regenerative characteristics of natural systems, focusing on form, material, generative processes, and function (Assadi-Langroudi et al. 2022). The cementitious technology in this study leverages waste-derived materials with pozzolanic activity to reduce reliance on virgin cement, thereby reducing CO_2 emissions and promoting circularity—an ecological principle central to NiSE. The materials used—waste glass and brick dust—fit within NiSE's emphasis on generative processes and materials abstracted from nature or post-consumption cycles. The integration of such by-products promotes the long-term durability and mechanical integrity of the mortar while preserving its permeability and minimizing harmful environmental outputs such as dust and carbon emissions. Evaluated against the NiSE framework's traffic-light indicator system, this innovation would score positively across multiple domains: it preserves void structures, enhances durability, reduces environmental pollutants, and contributes to the rebalancing of natural and engineered systems. The technology receives a score of +2 for preserving voids and pore spaces, drainage, and water circulation, due to its improved flowability, and use of inert, recycled materials. It scores +1 for self-healing and intertwining forms, as the improved long-term durability and integration of secondary materials reflect adaptive traits found in natural systems. Carbon sequestration and preservation of life are neutral (0), as the technology does not actively engage with biogenic or bio-mediated processes. Air quality preservation also scores +1, given the reduction in cement content and its associated CO_2 and dust emissions. While superplasticizers present an ecological trade-off, the overall approach shows cautious yet meaningful alignment with NiSE's core tenets — especially its emphasis on circular use of materials, eco-efficiency, and system sustainability without disrupting the natural performance of the built environment.

CONCLUSION

In summary, considering the outcome and conclusion, the implementation of both brick dust and glass powder combined with Portland limestone cement in the accomplishment of mechanical and durable features of mortar has given great outcomes for different aspects. If the proper dosages and size of the particles are used. using waste glass and brick dust in building materials has a number of advantages, which comprise solving issues regarding the way resources from nature are presented, the environment's sustainability, cost-effectiveness, pollution in the air issues, and issues with managing waste without additionally adverse effects on the material's mechanical or durability performance.

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Utilization of recycled concrete aggregates' leachate water as supplementary activator in geopolymer soil stabilization

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INTRODUCTION

Recycling Construction and Demolished Wastes (CDW) has gained popularity in the construction industry over the last few decades. This is due to the physical and sustainable advantages it provides. The continues rely of the industry on natural raw materials and the packed landfills with CDW are creating global environmental concerns (Yuan and Shen 2011; Wu et al. 2014)

Recycled Concrete Aggregates (RCAs) are one of the most used CDW materials in the construction industry. They consist of aggregates covered with adhered mortar paste from the crushed concrete (Verian et al. 2018). RCAs have been used in construction of pavements and have proved useful in increasing the strength of the soil and reducing the need for crushing new queries for extraction of virgin aggregates (Xu et al. 2022).

To overcome the environmental concerns related to commonly used chemical stabilizers such as cement and lime, more sustainable and ecofriendly alternatives have been developed, such as geopolymers, enzyme-induced carbonate precipitation (EICP), microbial-induced carbonate precipitation (MICP) or fibers (Assadi-Langroudi et al. 2022).

Geopolymerization is the process by which aluminosilicates in precursor are dissolved in an alkaline activator into aluminates and silicates species creating a saturated solution, the species are linked forming gels (monomers) which polycondense into a strong 3D network. The presence of aluminates creates a negative charge that requires a metallic cation to maintain the neutrality and integrity in the structures. The most common metals hydroxide activators used are Na, K and Ca (De Silva et al. 2007; Khale and Chaudhary 2007).

An RCA leachate water is concentrated with Ca(OH)2 that is either dissolved from the surface of adhered mortar or by formation of portlandite from unhydrated cement. This leads to a medium saturated with hydrogen ions raising the pH to levels above 10 (Sanger et al. 2020).

RCA leachate can create a nature inspired native approach to enhance the geopolymerization reaction by mixing it with NaOH as a supplementary activator. The aim of this study is to enhance the Unconfined Compressive Strength (UCS) of the stabilized soil by geopolymer binder using the leachate water from RCA to reduce the economic and environmental impact of sodium hydroxide.

MATERIALS AND METHODS

Concrete samples were obtained from the chamber of civil engineering in North Cyprus having a compressive strength of 60 MPa. The concrete was crushed manually using a hammer and sieved accordingly to obtain fine particles passing sieve No. 4 (4.75 mm). The RCAs were soaked in demineralized water at a liquid:solid ratio of 2:1 for 24 hours. The leachate was then filtered, and pH measured to be 11.664.

The soil used in this study and was collected from Yiğitler, North Cyprus. It was dried at 70 C for 3 days prior to crushing and sieving. The portion passing sieve No.8 (2.36 mm) was collected and Maximum Dry Density (MDD) was measured to be 1.18 g/cm3 at an Optimum Moisture Content (OMC) of 42%.

Table 1. Table of Mixes

Mix ID	Mix Name	Mixing liquid/Activator	Binder
CM	Control Mix	water	-
Mix 1	Leachate-NaOH Geopolymer	5M NaOH	CBW
Mix 2	NaOH Geopolymer	5M NaOH + RCA Leachate	CBW

In this study, a control mix of untreated soil compacted at OMC and two Geopolymer (GP) mixes were prepared. For the GP mixes, Clay Brick Wastes (CBW) was used as the binder, which was added at 15% to the soil by weight. For mix one, RCA leachate water was used in dissolving NaOH pellets, while for mix two normal demineralized water was used. The activators were added to the soil at OMC and mixed homogenously, then the samples were placed in an oven to cure at 60 degrees for 24 hours.

To ensure an even stress distribution along the samples area during testing, sandpaper was used to smoothen the surfaces of the samples. The rate of loading was applied at 1mm/min. In addition, parts of each sample were collected for moisture content calculation during testing day.

RESULTS AND DISCUSSION

Mix one yielded to a 10% increase in UCS compared to mix two. The control mix of untreated soil showed a UCS value of 114 kPa where both GP mixes showed an increase of at least 590% and more. The stress-strain graph obtained from the test is shown in Fig-1 below:

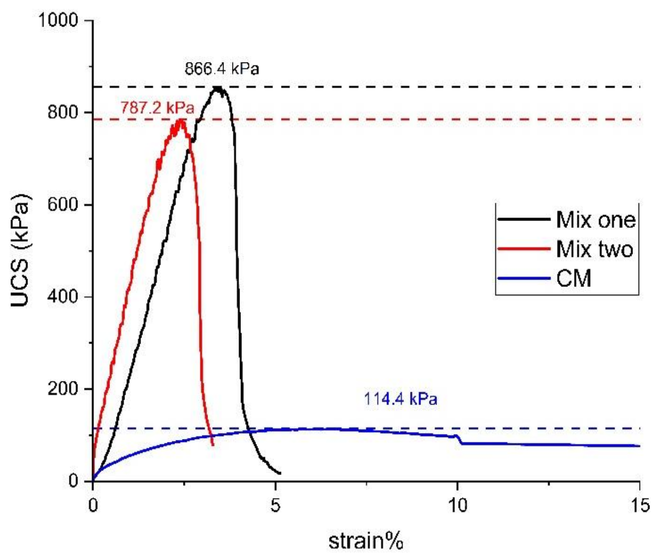

Fig- 1: UCS of mixes

In addition to the UCS increase, the leachate water sample showed a more ductile behavior despite the moisture content of both samples being the same during testing which was about 34%.

CONCLUSION

From the results shown it was proved that RCA leachate water has the potential to enhance the geopolymerization reaction by providing an ideal medium for higher dissolution of aluminates and silicates from binder. Moreover, more abundant Ca ions are present for formation of (C-A-S-H) gel.

However, the effects of different molarities of NaOH in the Leachate-NaOH activator and longer oven curing periods are yet to be studied. In addition, curing at room temperature requires longer periods for GP strength gain, and RCA leachate has the tendency to carbonate when exposed to carbon dioxide from atmosphere creating $CaCO_3$ which is denser and insoluble in water so precipitates in the medium dropping the pH.

Hence, more assessments are to be done to grasp an understanding of the effects of RCA leachate under different conditions. Moreover, microstructure analysis is needed to investigate the nature of the bonds formed in the matrix.

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Mechanical Characterization of Expansive Subgrade Soil Stabilized with Fly Ash

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INTRODUCTION

Soils are fundamental to civil engineering construction. A broad array of structures and infrastructure are built on, in, or with soil. Among the various types of soil encountered, expansive soils with large proportions of swelling clay minerals continue to pose engineering challenges. Typically found in the vadose zone, these soils undergo significant volume changes due to moisture fluctuations (Chompoorat et al., 2021; Alemshet et al., 2023) that may become more excessive should conditions allow preferential pathways for water influx (Assadi-Langroudi and Yasrobi 2013). Volumetric changes can lead to differential movement, heaving, and settlement, which in turn cause instability in civil engineering structures, particularly lightweight buildings, roadways, and slopes (Li et al., 2018). The high plasticity and sensitivity of expansive soils to moisture variations make them especially difficult to manage, posing long-term concerns for the durability and performance of structures built upon them (Mohamed et al., 2023).

To address these issues, stabilization techniques have received considerable interest. These generally are aimed at improving the performance of expansive soils under load-bearing conditions (Leelarungroj et al., 2018). Traditional stabilizing agents, such as lime, Portland cement, and various chemical additives, have long been employed to reduce shrink-swell behavior (Consoli et al., 2024). However, increasing environmental concerns and cost considerations have driven interest in sustainable alternatives (Dontriros et al., 2020). In this context, the use of industrial byproducts like fly ash and bottom ash as soil stabilizers has gained significant attention. These byproducts are typically sourced from coal combustion, offer alternative, more sustainable avenues for ground engineering by repurposing waste materials and reducing dependency on conventional stabilizers.

Various industrial wastes including brick dust, silica fume, bottom ash, and glass powder are there remains limited focus on the effects of Class F fly ash on the mechanical properties of expansive soils. The synergistic behavior of these byproducts when blended bring advantages such as improved soil stability, reduced sensitivity to moisture-induced volume changes, and greater cost-effectiveness, all while supporting environmentally responsible practices. This study aims to characterize the physio-mechanical response of expansive subgrade soils stabilized with Class F fly ash, evaluating physical and engineering properties in accordance with ASTM standards. By addressing existing research gaps, this work contributes new insights into the feasibility of using this industrial byproduct as a stabilizing agent.

MATERIALS AND METHODS

This study is designed to experimentally characterize the hydro-mechanical properties of expansive soil stabilized with fly ash and lime. The base material is an expansive soil, collected from Northern Cyprus. Class F fly ash is used for its pozzolanic properties as the stabilizer. Lime (calcium oxide) is used as a triggering agent to activate chemical bonding within the composite mix. The composite mixtures were prepared in accordance with ASTM standards, with optimal moisture content established via Proctor compaction tests. Table 1 highlight how the composite mix were coded while carrying out the experiment.

Table 1: Material Coding and Fly ash Mix Formulation

Mix Type	Mix Code	Fly Ash (%)	Lime (%)	Soil (%)
Control mix	C	0	0	100
	FA10	10	5	85
Fly ash mix	FA15	15	5	80
	FA20	20	5	75

Laboratory tests on the treated soil include physical properties tests, compaction test, and Unconfined Compressive strength test. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) analyses were further carried out to investigate microstructural and mineral composition changes, respectively. Specimen remolding and testing replicated field conditions.

RESULTS AND DISCUSSION

Emphasis was put on physio-mechanical analysis engineered clays. Particle size analysis, specific gravity, and Atterberg limits tests were executed to evaluate the plasticity and characteristics of soil particles. Table 2 summarizes the findings.

Table 2: Summary Result of Preliminary Physical Properties tests conducted

Silt (%)	43.0
Clay (%)	57.0
Specific Gravity	2.62
Liquid Limit (%)	70.0
Plastic Limit (%)	20.5
Plasticity Index (%)	49.0

Based on Table 1, the expansive soil sample consists of 57% clay and 43% silt. Combined with a specific gravity of 2.62, this indicates a clay-dominant soil with moderate particle density. The high liquid limit (70%) and plasticity index (48.97%) classify the soil as high-plasticity clay (CH), suggesting a strong tendency to swell and shrink in response to moisture changes. Such soils typically exhibit volume instability and compressibility, posing significant challenges for construction due to their sensitivity to moisture-induced expansion and contraction. The data suggests that stabilization techniques such as incorporating fly ash and bottom ash could reduce these expansive characteristics and improve the soil's performance for geotechnical applications.

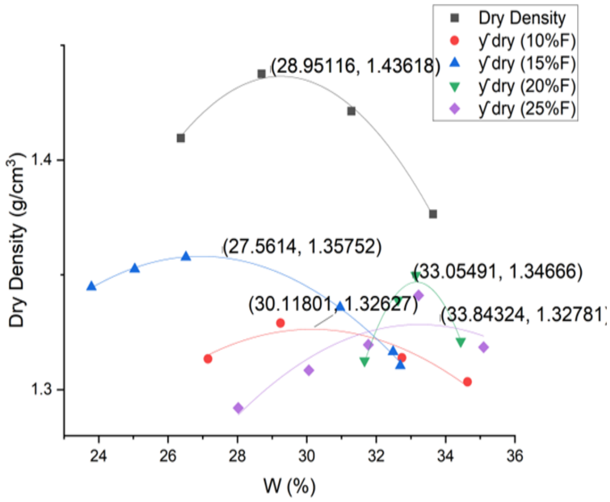

Figure 1: Compaction curves for a combined curve of fly ash with different mix formulations

Table 4: Summary of Mechanical Properties of base and treated soil

		Optimum moisture content (%)	Maximum dry density	Day-1	Day-7	Day-14	Day-28
				Stress at peak, q (kpa)			
Control mix	C	29.3%	1.44	125	138.5	120.5	119.0
10% Fly-ash	FA10	30.1%	1.33	188.4	780.0	1330.4	1,677.0
15% Fly ash	FA15	27.6%	1.36	373.4	974.0	1543.6	2,198.4
20% Fly ash	FA20	33.0%	1.35	340.4	1,068.0	1,520.0	1,863.8

The test results reveal that adding fly ash significantly improves the soil's compressive strength over time. The control mix, without fly ash, shows minimal strength change, while the mixes with fly ash (10%, 15%, and 20%) demonstrate progressive strength increases due to pozzolanic reactions. Among these, the **15% fly ash mix (FA15)** achieves the best balance between moisture content, density, and compressive strength, peaking at 2198.4 kPa by Day 28. This suggests that 15% fly ash is the optimal mix for effective soil stabilization, enhancing structural resilience while maintaining manageable moisture and density characteristics.

CONCLUSION

In conclusion, the expansive soil sample, characterized by high clay content (57%) and significant plasticity (PI of 48.97%), presents inherent challenges due to its susceptibility to moisture-induced swelling and shrinkage. Stabilization through fly ash shows considerable promise, with the addition of 15% fly ash emerging as the optimal formulation. This mix achieves a notable balance of increased compressive strength (up to 2198.4 kPa by Day 28) and manageable moisture and density properties, owing to pozzolanic reactions that improve the soil's structural resilience over time. These results indicate that a 15% fly ash mix is highly effective in mitigating expansive properties, enhancing the soil's suitability for geotechnical applications, and providing a sustainable solution for construction on expansive subgrade soils.

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Exploring the Use of Fly Ash as an Additive in Clay Amended Landfill Liner System: A Review

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INTRODUCTION

The vast majority of waste produced in most metropolitan areas ends up in landfills. Landfill leachate is defined as a liquid that leaked through waste and contained suspended debris and heavy minerals. In constructed landfills, compacted natural soils are frequently utilized as liner materials to reduce the environmental effects of landfills by stopping leachate and landfill gasses from migrating into the surrounding area and groundwater. This review highlights notable developments in the materials employed, noteworthy variations, and the evolution of liners since last year's begins with fly ash and how it is mixed with clay, which is the typical layer in landfills, as well as other readily available materials for liner applications. In this review paper, experts' extensive research on the suitability of several materials as landfill liners is concluded through experimentation to identify the right material.

MATERIALS AND METHODS

Laboratory tests such as chemical and mineralogical analysis was conducted on different proportions of different type of soil as local soil, Bentonite, fly ash, Silica fume etc. mixes to evaluate swell index, specific gravity, grain size analysis, Atterberg limits, standard compaction, unconfined compressive strength, and hydraulic conductivity tests were performed for liner materials. The curing period of different mixes is also considered.

RESULTS AND DISCUSSION

This study aimed to explore industrial waste such as fly ash; in combination with soil and other types of soils as composite mix and in turn, improving its engineering properties to the extent that it becomes efficiently suitable as landfill liner material. Fly ash helps in the enhancement of the geotechnical characteristics of the soil, which is a much-needed requirement in most civil engineering fields.

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Alkali-Activated Carbonate-Based Binders: Review

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INTRODUCTION

Alkali activated materials (AAMs) are a group of materials that promising to be an alternative to ordinary Portland cement (OPC) binder. It is known to be more environmentally-friendly construction materials. The significant carbon emission and high energy during production makes OPC less environmentally friendly. AAMs having much lower carbon footprint can offer similar mechanical strength to OPC. AAMs usually require silica alumina rich precursors having low or high calcium content to have strong and durable structure. However, materials having high amount of calcium are the new trend in the AAMs area. Researchers have shown the formation of calcium silicate hydrate (C-S-H) and sodium-calcium silicate hydrate (C-A-S-H), carbonaluminate, aluminum hydroxide (AH_3), and others during the alkali activation of carbonated base materials. These gels contribute significantly to the binder's structural stability (Ortega-Zavala et al., 2019, Liu et al., 2023c, Liu et al., 2023b).

One sustainable building practice to mitigate the environmental and waste management of industrial byproduct is maximizing their utilization. It is known that AAMs can utilize a vast majority of solid wastes. In recent years the use of calcium carbonate base materials has been the focus of the AAMs research, due to their worldwide availability (Liu et al., 2023c, Liu et al., 2024, Cousture et al., 2024, Cousture et al., 2021, Ibrahim et al., 2023, Hasnaoui et al., 2021, Komnitsas et al., 2021, Liu et al., 2023a, Wang et al., 2023, Ortega-Zavala et al., 2019). This review focused on the recent findings on alkali-activated carbonate binders. The chemical reactions, strength properties, and environmental benefits will be discussed.

ALKALI ACTIVATION MECHANISMS OF CALCAREOUS-BASED BINDERS

In Alkali activation of calcium-based materials using strong alkalis, such as sodium hydroxide (NaOH) or sodium aluminate ($NaAlO_2$), the dissolution of calcite ($CaCO_3$) and liberation of calcium ions (Ca^{2+}) is the primary objective of the reaction towards forming cementitious phases. Calcium silicate hydrate (C-S-H) and sodium-calcium carbonates, carbonaluminate, including pirssonite and gaylussite are some of the common phases that contribute to the binder's strength and durability (Liu et al., 2023c).

The reaction process and the phase formation are influenced by the type of the alkali activator. NaOH primarily simplifies calcite dissolution, but alone can lead to less durable phases like gaylussite. On the other hand, $NaAlO_2$ promotes stable calcium aluminate hydrates (CAH) and monocarboaluminate, enhancing early strength. Sodium silicate (Na_2SiO_3) supports additional C-S-H formation, contributing to a denser, stronger matrix (Liu et al., 2023b, Liu et al., 2024).

Primary hydration products, such as C-S-H and N-C-S-H, carbonaluminate are essential for mechanical strength (Liu et al., 2024, Ibrahim et al., 2023, Liu et al., 2023b), while phases like pirssonite and gaylussite vary based on curing conditions, impacting long-term stability (Cousture et al., 2024). It is stated by Ortega-Zavala et al. (2019) that the activator and curing condition are critical factors for optimizing the hydration product and durability of the calcium based AAMs (Ortega-Zavala et al., 2019).

ROLE OF ACTIVATORS IN REACTION MECHANISMS AND MICROSTRUCTURE

Activator concentration also impacts hydration products and strength. Higher NaOH concentrations speed up calcite dissolution but produce weaker phases like gaylussite (Hasnaoui et al., 2021). Moderate Na_2SiO_3 concentrations strike a balance by supporting C-S-H formation and minimizing unwanted phases (Liu et al., 2024). Optimal $NaAlO_2$ concentrations improve strength and durability, although too much can lead to delayed setting and higher porosity (Wang et al., 2023). Thus, balancing activator type and concentration is key for optimal strength, durability, and microstructure. Ther is still lack in fully understanding the relation of the activators and the reactive phases in the calcium carbonated materials.

INFLUENCE OF PRECURSOR MATERIALS (LIMESTONE, MARBLE, SEASHELL WASTE)

Limestone, marble, and seashell waste can be effective precursors in alkali-activated materials (AAMs) due to their calcium carbonate content and widely availability. Limestone, activated with sodium hydroxide (NaOH) or sodium aluminate ($NaAlO_2$), produces hydration products like calcium silicate hydrate (C-S-H) and monocarboaluminate, which enhance strength. In the available literature compressive strength of limestone based AAMs range between 3 to 34 MPa (Ortega-Zavala et al., 2019, Liu et al., 2024, Cousture et al., 2021). In the studies made by Komnitsas et al. (2021), Liu et al. (2023a), (Wang et al., 2023) marble waste was activated by sodium hydroxide and sodium silicates, the range of the compressive strength was around 3 to 11 MPa. The studies suggested the use of other precursors such as slag or metakaolin with marble waste to enhance the mechanical properties. Meanwhile seashell waste provides moderate strength up to 22 MPa at 28 days as it was only studied by Hasnaoui et al. (2021).

Overall, limestone and seashell offer moderate strength potential, while marble waste provide low strength suitable for lower-strength, non-structural applications.

CURING AND DRYING PARAMETERS

Curing temperature and drying time critically affect the hydration, microstructure, and mechanical properties of alkali-activated limestone binders. Higher temperatures (e.g., 45°C) accelerate reaction kinetics, forming stable phases like pirssonite, which enhances strength and reduces porosity (Cousture et al., 2024). Prolonged drying for 28 days at controlled temperature allows complete hydration, reducing shrinkage and increasing stability (Wang et al., 2023)

Studies show that while higher curing temperatures increases early strength, they can increase porosity if not balanced with enough drying time (Cousture et al., 2021), and durability challenges exist under freeze-thaw cycles where binders can crack and weaken due to expansive crystalline phases (Komnitsas et al., 2021). Extended curing at moderate temperatures minimizes microcracks, promoting better flexural strength and long-term durability (Liu et al., 2023a). Sodium aluminate activation and moderate curing reduce these effects by promoting stable microstructures (Liu et al., 2023c) Optimizing temperature and drying duration is essential for achieving both early and lasting mechanical performance.

CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Despite advancements in alkali-activated carbonate-based binders, gaps remain in long-term durability, scalability, and field applications. Current research is mostly lab-based, lacking data on performance under prolonged environmental stressors like freeze-thaw cycles and chemical exposure. Durability under real-world conditions remains unverified, as these materials show sensitivity to high temperatures and freeze-thaw effects.

Research into alternative activators (e.g., from industrial by-products) and hybrid systems could improve economic and environmental viability. Hybrid systems with materials like slag or fly ash could enhance durability and strength, broadening application possibilities. Future work should focus on long-term durability studies, scalable production methods, and alternative activators to position alkali-activated carbonate binders as sustainable, high-performance alternatives to Portland cement.

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A Comprehensive Review of Polymers Used in Soil Stabilization

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INTRODUCTION

This review paper provides a comprehensive overview of research on polymer applications for soil stabilization. It begins by examining the key characteristics that affect the performance of various polymer types—geopolymers, biopolymers, and synthetic organic polymers. Key factors include molecular weight, particle size, charge, conformation, solubility, viscosity, pH, and moisture behavior for organic polymers, as well as the types and ratios of precursors and activators for geopolymers. The review then summarizes the mechanisms behind soil stabilization for different polymer classes. Organic polymers interact with clay through electrostatic forces and entropy changes, with the impact varying based on whether the polymer is cationic, neutral, or anionic. Geopolymer stabilization involves forming a calcium and/or sodium aluminosilicate gel that binds soil particles into a denser, stronger matrix. The paper also explores how different polymers, and their ratios affect soil engineering properties such as strength, durability, and permeability.

Chemical stabilization modifies soil properties to improve its structural performance compared to untreated soil. Key factors for chemically stabilized soils include mechanical attributes such as compressive and shear strength, along with durability (Ingles and Metcalf, 1972). Traditionally, Portland cement and lime have been the predominant materials used due to their long-standing application and extensive research. However, the drive for better engineering performance, adaptation to varied soil conditions, cost efficiency, and environmental considerations have spurred the exploration of alternative soil stabilizers. This has led to growing interest in polymers for soil stabilization due to their potential to enhance soil properties and performance.

Polymers are large molecules made up of repeating units called monomers. When monomers are polymerized, the resulting polymer exhibits unique chemical and physical properties different from those of the original monomers. Both natural and synthetic polymers have been studied for soil stabilization (Davidovits 1991; Gu and Doner, 1992; Duxson et al. 2007; Song et al. 2019). Natural polymers, such as polysaccharides, and synthetic ones, such as polyacrylamides, have shown promise in agricultural applications (Rotimi Olafisoye et al. 2024) by improving soil aggregate stability, retaining soil water, providing nutrients, and mitigating erosion (Chang et al. 2015). Despite these advantages, the high cost of polymers has led to a preference for conventional stabilizers like Portland cement and lime. Nonetheless, polymers have been successfully used to improve slope stability, reduce wind erosion in arid regions, and control dust at construction sites (Fungaroli and Prager 1969; Duxson et al. 2007; Zhang et al. 2015; and Georgees et al. 2016a). Additionally, natural polymers are generally more environmentally friendly than cement and lime, producing lower greenhouse gas emissions, requiring less energy, and using fewer natural resources. Portland cement production is the second largest source of global greenhouse gas emissions from human activities, after fossil fuel combustion (Georgees et al. 2016b). In contrast, polymers typically involve lower energy use and generate fewer greenhouse gases. Some polymers are by-products of industrial processes, such as fly ash from coal power plants and pectin-based calcareous polysaccharides from the sugar refinery industry and can be utilized in soil stabilization (Assadi-Langroudi et al. 2019; Gumanta et al, 2023). Moreover, biopolymers like polysaccharides, abundant in nature and used in the food industry, and synthetic polymers like polyacrylamide, widely used in agriculture, are gaining attention for their environmental benefits and potential in soil stabilization (Iyengar et al. 2013).

This publication presents a review of the literature on polymers used in soil stabilization. It examines polymers specifically applied for this purpose, discussing their physicochemical properties and the mechanisms of their interactions with soil. The review also explores the engineering properties of polymer-stabilized soils as documented in existing research.

CURRENT STATE OF KNOWLEDGE

Enhancing durability and improving mechanical properties are the primary goals of soil stabilization. This section of the review outlines the key characteristics and testing methods used in the literature to evaluate the effectiveness of polymer stabilization. Extensive empirical research has explored how various polymers can enhance the strength of both coarse soils (such as sands) and fine soils (such as clays and sediments). Despite differences in the fundamental properties of the main organic polymers studied, most polymer-stabilized soils demonstrate immediate increases in strength. Research indicates that polymers can improve the strength of weak soils by anywhere from 16% (Song et al. 2019) to as much as 1000% (Chang et al. 2015; Zhang et al. 2016). Many studies have reported that using different polymers consistently boosts soil strength. The results of compression tests for soils treated with biopolymers and synthetic organic polymers are summarized in Table 1 and Table 2, respectively.

Table 1: A review of the soils treated using synthetic organic polymers in terms of compressive strength.

Polymer	Study	Concentration of Polymer	Soil type	Unconfined compressive strength
Acrylic	Fungaroli and Prager, 1969	2%	Silty clay	2.82-3.57 MPa (7days)
PAM	Georgees et al. 2016a-b	0.002%	GM	7.7 MPa
PVA	Mirzababaei et al. 2017	0.1, 0.3, 0.5, 1, 1.5%	CH	Dense: 710.1 kPa Loose: 116.8 kPa
Acrylate emulsion	Mirzababaei et al. 2017	0.25, 0.5, 1, 2%	GM-GC	2–3 MPa (7day); 2–3.8 MPa (28days)
Styrene-acrylic	Mirzababaei et al. 2017	0.5, 1, 1.5, 2, 3, 5%	SP	0.8–10.2 MPa (7days)
Acrylic polymer	Iyengar et al. 2013	2, 3, 4, 5%	CH	868.88–898.39 kPa (7days);
Acrylic copolymer, Stabilizer	Kolay and Dhakal, 2019	0.25, 0.375, 0.5% Polymer + 0.5, 0.75, 1% Stabilizer	CI (IS1498)	1.7–7.0 MPa (>7days)

PVAc	Kushwaha et al. 2019	1.5, 3.75, 5%	CH	900–1300 kPa
Urea	Zushwaha et al. 2019	3, 4, 5%	SP, ML, CH, MH-CH	0.05–1.7 MPa (7days); 0.3–3.4 MPa (28d)
Polyester	Moustafa et al. 1981	10, 20, 30%	SP	10–45 MPa (1-28days)

Table 2: A review of the soils treated using biopolymers in terms of compressive strength.

Biopolymer	Study	Concentration of Biopolymer	Soil type	Unconfined compressive strength
Glucan	Arasan et al. 2015	0.05, 2.46, 4.92 g/kg	Clay	1–4.4 MPa (28days)
Gellan gum	Chang et al. 2012	0.5,1,1.5,2,5%	SP	130.2–434.6 kPa (28days)
Xanthan gum	Chang et al. 2016	0.5,1,1.5,2,3%	CL	470.52–569.55 kPa (7days); 612.74–823.19 kPa (28days)
Chitosan	Arab et al. 2019	0.02, 0.04, 0.08, 0.16%	CL	1500–3000 kPa (7days)
Guar gum	Hataf et al. 2018	0.5, 1, 1.5, 2%	MH-CH	170–390 kPa (7days)
Lignin	Zhang et al. 2015	2, 5, 8, 12, 15%	ML	180–330 kPa (7days) 220–680 kPa (28days)

Soils stabilized with geopolymers have shown significant improvements in unconfined compressive strength. However, as shown in Table 3, the extent of these improvements varies widely depending on the geopolymer composition, dosage, and soil type. In addition to unconfined compressive strength tests, triaxial shear tests and conventional direct shear tests are frequently used to evaluate the effectiveness of polymer stabilization. Previous studies have consistently demonstrated that polymers enhance soil shear strength. For example, the addition of 1.2% and 2% lignosulfonate to silty sand and sandy silt, respectively, resulted in immediate increases in shear strength (Indraratna et al. 2013). To assess the durability of polymer stabilizers, tests such as abrasion, erosion, freeze-thaw, and dry-wet cycles are commonly conducted. Fungaroli and Prager (1969) found that soil-cement specimens modified with acrylic polymer exhibited greater resistance to freeze-thaw cycles compared to unmodified cement-treated soils, even after curing for seven to ninety-one days.

Table 3: A review of the soils treated using geopolymers in terms of compressive strength.

Precursor	Activator	Study	Concentration	Soil type	Unconfined compressive strength
FAF	Na_2SiO_3 + NaOH	Cristelo et al. 2011	20,30,40%	Sandy clay	11.4 MPa (28days)
MK	Na_2SiO_3 + NaOH	Zhang et al. 2013	3-15%	CL	1.5–3.5 MPa (7days); 1.3–3.8 MPa (28days)
MK	Na_2SiO_3 + NaOH	Zhang et al. 2015	8,13%	CL	2.5–4 MPa (28days)

FAC	Na_2SiO_3 + NaOH	Hataf et al. 2018	30%	Silty clay	5–7.5 MPa (7d Wet); 8.5–10.5 MPa (28d Wet)
PFA	NaOH, KOH	Sujatha and Saisree, 2019	15-30%	CH	400–700 kPa (7d); 800 kPa − 1200 kPa (28d)
FAF	Na_2SiO_3 + NaOH	Du et al. 2017	10,20%	Silty sand	2–6 MPa (28d)
GGBS	CCR + Na_2SiO_3	Zhang et al. 2016b	40%	CL	400–1200 kPa (7d); 600–1300 kPa (28d)

FAF: Class-F fly ash;
MK: Metakaolin;
PFA: Palm Fuel Ash;
GGBS: Ground granulated blast furnace slag;
CCR: Calcium carbide residue;
FAC: Class-C fly ash.

FUTURE DIRECTIONS

Polymers, encompassing geopolymers, biopolymers, and synthetic organic varieties, offer a compelling pathway toward sustainable ground improvement within the tenets of the Nature-inspired Solutions for Ground Engineering (NiSE) framework. These materials not only enhance mechanical properties such as compressive and shear strength, but also align with the NiSE principles of preserving voids, facilitating adaptability, and promoting self-forming and self-healing ground systems. For instance, biopolymers like xanthan gum and gellan gum mimic natural bonding agents such as plant mucilage and fungal hyphae, echoing the generative processes found in natural systems. Similarly, geopolymers derived from industrial by-products like fly ash and slag reduce reliance on high-emission binders such as Portland cement, thereby aligning with the NiSE emphasis on low-carbon, environmentally responsive materials. By enabling soils to retain porosity, accommodate precipitation, and evolve structurally through mechanisms like microbial calcite precipitation, polymers embody the biomimetic ideals of form, function, and self-regulation. These characteristics position polymers not just as chemical stabilisers, but as nature-symbiotic agents capable of transforming soil into a responsive and resilient geosystem that actively participates in its environmental context.

CONCLUSION

This research explores various types of polymers—geopolymers, biopolymers, and synthetic organic polymers—that are applied in geotechnical engineering for soil stabilization. The review examines the stabilization processes, the physicochemical properties of these polymers, and the resulting engineering characteristics of soils after treatment. A significant area of current research is the investigation of new polymers for soil stabilization. Many polymers have been studied, and their use in naturally occurring soils is gaining global popularity. Polymers and calcium-based binders offer an environmentally friendly alternative to traditional cement, making them increasingly relevant for soil stabilization applications.

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Sustainable Stabilization of Swelling Soils with Brick Dust, Glass Powder, and Silica Fume

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INTRODUCTION

This investigation delves into sustainable alternatives for the stabilization of clayey soils through the utilization of industrial by-products, specifically brick dust (BD), glass powder (GP), and silica fume (SF). Conventional stabilization techniques, including the use of cement and lime, have provoked environmental apprehensions due to their substantial carbon emissions (Behnood, 2018; Ezeokpube et al., 2022). This research examines the influence of these upcycled wastes and industrial by-products on the mechanical behaviors of clay soils, with a particular emphasis on strength, durability, and ecological implications.

Clay-rich soils pose significant obstacles in construction endeavors due to their inherent low strength and elevated compressibility (Ineza and Jie, 2022) and swell-shrink volumetric changes (Assadi-Langroudi and Yasrobi, 2009). Conventional stabilization methods, including the application of cement and lime, are extensively employed. However, these methods yield considerable adverse environmental consequences as a result of elevated carbon emissions (Behnood, 2018). Recent studies highlight the necessity for sustainable alternatives, potentially through the use of industrial by-products such as glass powder, and silica fume emerging as viable alternative stabilizers for soil (Khan et al., 2018). This study reports preliminary findings from application of these by-products on clay soils from North Cyprus, concentrating on their potential to enhance the engineering characteristics of the base clay soil at low environmental costs.

MATERIALS AND METHODS

The investigation utilized an experimental program of works to evaluate the effects of BD, GP, and SF on a base clay soil. Various ratios (5%, 10%, 15%, and 20%) of BD and GP, along with 10% SF, were incorporated into samples of a clay soil (Salimah et al., 2021; Balkıs and Ilman, 2024). A series of laboratory assessments, including compaction tests, Atterberg limits, unconfined compressive strength (UCS), and California Bearing Ratio (CBR), were conducted to analyze alterations in soil characteristics. The environmental ramifications were examined by evaluating the carbon footprint and the potential for waste reduction associated with these stabilizing agents (Gupta et al., 2020; Sapna, 2023).

RESULTS AND DISCUSSION

The preliminary findings show that the incorporation of BD, GP, and SF markedly improve the strength and durability of clayey soils. These are consistent with previous efforts, in particular those in Khan et al., 2018 and Balk and Bugse, 2024. The BD facilitates an enhancement in the unconfined compressive strength (UCS) by as much as 25%, GP contributes to about 18% improvement in the California Bearing Ratio (CBR), and SF effectively diminishes the plasticity index of the clay. The environmental impact assessment in Behnood (2018) substantiated that these stabilizers possess a reduced carbon footprint compared to conventional methods.

CONCLUSIONS

This investigation explores the potential of brick dust, glass powder, and silica fume as sustainable alternatives for the stabilization of clayey soils. The results reveal substantial enhancements in the geotechnical characteristics of the soil, alongside a diminution in environmental ramifications. Findings indicate that BD, GP, and SF markedly improve soil performance, thereby providing environmentally sustainable alternatives to traditional stabilization techniques.

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Enhancing Soil Properties Incorporating Silica Fume and Recycled Concrete Aggregates

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INTRODUCTION

Soil stabilization is one of the most common used techniques to enhance the weak soil properties which can be achieved either mechanically or chemically. In mechanical stabilization additives are incorporated to change the gradation of the soil mix hence densifying it, or by incorporating sharp edged inclusions to increase the particles interlocking. While in chemical stabilization, the soil properties are altered chemically creating cementitious gels strengthening it (Afrin, 2017). Cement and lime, also known as calcium-based stabilizers, have been one of the most used chemical additives in the geotechnical engineering world due to their proved effectiveness. However, their production comes with environmental concerns due to the mass carbon dioxide emissions (Behnood, 2018).

Recently, the usage of industrial by-products has gained popularity in this area due to cheaper prices and less environmental impacts. Silica fume is a by-product of silicon alloys production in electric arc furnaces. Silica fume consists mainly of amorphous silica making up to 85% of the fume content. Moreover, the particles are spherically shaped and are very fine in size ranging from 0.1 to 0.3 micron in diameter (Imbabi et al., 2012, Panesar and Zhang, 2020).

The usage of crushed aggregates for mechanically enhancing the soil strength has been used for decades especially in pavements applications. However, this process is energy consuming as it requires extraction of natural aggregates from quarries. Hence, recycling materials from construction demolished wastes is handy as it reduces the need for aggregates extraction, and it reduces the packed landfills with construction wastes. Recycled Concrete Aggregates (RCA) are aggregates crushed from concrete consisting of the parent aggregate covered with adhered mortar. Due to the crushing effect RCA have irregular shapes and sharp edges making them suitable for mechanical soil stabilization (Tavakol et al., 2019).

In addition, RCA have high pH levels due to abundant $Ca(OH)_2$ from the adhered mortar. This high pH can affect the soil chemically by leaching aluminates and silicates available in the clay content, this leads higher formation of cementitious gel.

An RCA leachate has the potential to be used as a leaching agent for aluminosilicates as it is very basic in nature having pH level of 10 and above (Sanger et al., 2020).

In this study, the effect of silica fume addition to provide extra silica content for gel formation is assessed. Moreover, RCA leachate is used to test the potential of triggering C-A-S-H gel. Hence enhancing the unconfined compressive strength of the soil (UCS).

MATERIALS AND METHODS

RCA were acquired by crushing four concrete classes divided based on their compressive strengths (30, 40, 50 and 60 MPa). The concrete samples were collected from the chamber of civil engineering in North Cyprus. A hammer was used to manually crush the samples and then the particles passing sieve No.4 were collected and used.

The soil in study was collected from Yiğitler village, North Cyprus and was dried at 60 degrees for 3 days prior to crushing. The soil was sieved under sieve No.8 (2.36 mm).

The fine aggregate used as a reference to the effect of RCA is acquired from Levent Mosaic Group LTD and is limestone based. The physical properties of the aggregates are shown in Table 1, as were found in previous study (Ojotisa and Ibrahim, 2023).

Table 2. Properties of aggregates

PROPERTY	NS	30 MPA RCA	40 MPA RCA	50 MPA RCA	60 MPA RCA
Water Absorption	1.5	8.5	9.79	12.15	12.06
Specific Gravity	2.65	2.13	2.30	2.37	2.47
pH (48hr)	8.32	10.59	10.66	10.56	10.45

This study contains two phases, where firstly the effect of silica fume at 3% of soil weight with 10% RCA acquired from different parent concrete strengths is compared to 10% Natural Sand in terms of Unconfined Compressive Strength (UCS).

Table 3. Phases one and two mixes

Mix No	MIX ID	SILICA FUME (%)	NS	RCA	RCA CLASS	MIXING WATER
1	CM	3%	10%	0	0	Tap water
2	$RA_{30}SF_3$	3%	0	10%	30 MPa	Tap water
3	$RA_{40}SF_3$	3%	0	10%	40 MPa	Tap water
4	$RA_{50}SF_3$	3%	0	10%	50 MPa	Tap water
5	$RA_{60}SF_3$	3%	0	10%	60 MPa	Tap water
6	CM-LW	3%	10%	0	30MPa	60 MPa RCA Leachate water
7	$RA_{XX}SF_3LW$	3%	0	10%	30 MPa	60 MPa RCA Leachate water

The mix yielding the highest 7-day UCS value will be utilized in the second phase to assess the possibility of incorporating RCA leachate water as mixing water providing calcium to trigger higher formation of C-S-H gel. In addition, RCA leachate has high pH which dissolves the aluminates available in the clay content of the soil, which is expected to lead to further formation of C-A-S-H gel.

Preliminary tests were done to find the OMC and MDD of each mix. According to that, three cylindrical sample of dimensions (38*76 mm) were prepared for each mix at 95% of MDD. The samples were wrapped in a cellophane wrap to avoid moisture loss and then cured in room temperature for 7 days.

At the day of testing the samples' surfaces were straightened using sandpaper to ensure proper stress distribution during the test. The rate of loading was kept constant at 1mm/min.

For the second phase leachate water prepared by soaking 60 MPa RCA at a solid:liquid ratio of 0.5 for 24 hours. The water was then filtered and used in preparing the soil mixture. The pH of the leachate water was measured to be 11.6.

RESULTS AND DISCUSSION

The dimensions and the mass of 3 samples from each mix were measured to calculate densities and moisture content at testing day. The average of 3 was taken and recorded in a table along with the max UCS. The results of phase one are shown in table 3 below.

Table 4. Average Strengths and densities of phase one

Mix No	MIX ID	Wet Density (g/cm^3)	UCS (KPA)	MC AT TESTING (%)	Dry Density (g/cm^3)	UCS / Dry density (kPa)
1	CM	1.914	242.173	14%	1.679	144.252
2	$RA_{30}SF_3$	1.866	290.890	15%	1.622	179.359
3	$RA_{40}SF_3$	1.966	162.585	18%	1.112	146.255
4	$RA_{50}SF_3$	1.965	261.333	17%	1.679	155.690
5	$RA_{60}SF_3$	1.893	199.697	15%	1.648	121.205

To eliminate the effect of density deviation on UCS, normalized stress was calculated by dividing average strength over the dry density of each mix. The results are showing that RCA from parent concrete of 30 MPa showed the highest strength gain over 7 days of curing. The reason for this could be that the lower the quality of RCA the easier the adhered mortar to break down during compaction. On the other hand, high water cement ratio in the parent concrete leads to higher void ratio in the RCA. Hence, more exposed surface area for portlandite to react and form C-S-H gel. Microstructure analysis including FT-IR is to be conducted to strengthen the findings.

Moreover, no clear trend is shown between the different qualities of RCA and 7 days strength. Testing at prolonged curing periods would give more time for the reactions to take place therefore increasing the strength.

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Chapter 2. Physical Modelling

An Experimental Study on Triaxial Compression Tests Considering Coupled Volumetric–Shear Strain Paths

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ABSTRACT Triaxial tests are conventionally conducted under either fully drained or fully undrained conditions. However, partially drained conditions—allowing simultaneous changes in both pore pressure and volumetric strain—can lead to more critical states. In certain events such as during or after earthquakes, the assumption of fully undrained paths may fail to accurately capture geotechnical phenomena. These scenarios may result in shear–volumetric coupled strain paths, an area that has garnered increasing research interest in recent years. Accordingly, this study highlights the importance of investigating such behavior. To emphasize the critical response of soil under different drainage paths, the implementation of triaxial tests and the corresponding results are presented. The findings indicate that assuming only the two limiting boundary conditions (drained and undrained) may significantly underestimate potential risks in soil behavior assessment. Furthermore, under partially drained conditions (e.g., ζ = -0.25), even dense sand specimens may approach the threshold of full liquefaction.

KEYWORDS: Granular materials; Partially drained; Stress path; Bilinear strain path; Traixial test

1. INTRODUCTION

The stress–strain behavior of soils plays a fundamental role in stability analysis and settlement prediction of geotechnical structures. This behavior is influenced by various factors such as stress history, loading paths, and strain patterns (Gananathan, 2002; Assadi-Langroudi and Jefferson 2013). During loading, the stress and strain response of a saturated soil element is affected by its physical properties and environmental conditions. Among these factors, drainage conditions are of particular importance, as variations in pore water pressure due to the presence or absence of drainage inevitably influence the strain pattern and stress path (Lashkari et al., 2021; Sivathayalan & Logeswaran, 2007; Zürn et al., 2024).

In conventional geotechnical engineering, it is typically assumed that soil behavior occurs under one of two extreme conditions: drained or undrained. However, this assumption is not valid in many field situations, as its realization depends on soil homogeneity and uniform pore pressure distribution within the soil element (Lashkari & Yaghtin, 2018; Sivathayalan & Logeswaran, 2007). Moreover, actual field conditions are significantly influenced by soil permeability, drainage boundaries, and loading rates (Chen et al., 2020; Sivathayalan & Logeswaran, 2007). During events such as earthquakes or traffic loading, the short duration of loading often leads to the assumption of undrained behavior (Sivathayalan & Logeswaran, 2008; Yamamoto et al., 2009). Nevertheless, due to their relatively high permeability, granular soils are prone to volumetric changes (Zhu et al., 2023). These changes result in the migration of pore water from high-pressure to low-pressure zones, leading to void redistribution and shear deformation (Adamidis & Madabhushi, 2018; Lashkari et al., 2021; Sivathayalan & Logeswaran, 2007)—a process that may continue even after the cessation of seismic loading. This condition, referred to as partial drainage, lies between the two extremes of fully drained and fully undrained behavior. Therefore, incorporating an appropriate level of drainage in design can enhance the safety and cost-effectiveness of geotechnical projects (Logeswaran, 2005).

In recent years, numerous studies have sought to simulate the effects of partial drainage under controlled laboratory conditions using triaxial testing (Logeswaran, 2005; Maleki Tabrizi et al., 2023; Sivathayalan & Logeswaran, 2007; Sivathayalan & Logeswaran, 2008; Umehara et al., 1985; Vaid & Eliadorani, 1998, 2000; Zürn et al., 2024). In this context, Sivathayalan and Logeswaran (2007) conducted triaxial compression tests on loose Fraser sand and identified five possible strain paths and their corresponding stress paths (see Figure 1):

- **Path 1** represents drained behavior, in which volume change is allowed under constant pore water pressure (Δu = 0).
- **Path 2** reflects undrained behavior, where drainage is prevented and deformation occurs at constant volume ($\Delta\epsilon_v = 0$).
- **Path 3** corresponds to partial drainage conditions, with the stress path located between Paths 1 and 2. This condition is often observed in granular soils subjected to rapid loading (Sivathayalan & Logeswaran, 2008).
- **Path 4**, known as expansive drainage, represents a situation in which the surrounding soil has higher pore pressure, leading to inward water flow and volumetric expansion. This condition can result in reduced shear strength and contractive behavior, potentially increasing susceptibility to flow liquefaction (Eliadorani, 2000; Lashkari & Yaghtin, 2018; Sivathayalan & Logeswaran, 2008; Yamamoto et al., 2009).
- **Path 5** exhibits excessive drainage, as the lower pore pressure at the boundary causes water to flow out of the soil element, resulting in a greater volumetric change than that observed under the drained condition (Path 1).

Nonetheless, Paths 3 through 5 can be categorized as subsets of partial drainage conditions, in which both pore pressure and volumetric strain vary simultaneously ($\Delta\epsilon_v \neq 0$ and $\Delta u \neq 0$) (Lashkari & Yaghtin, 2018; Vaid & Eliadorani, 1998).

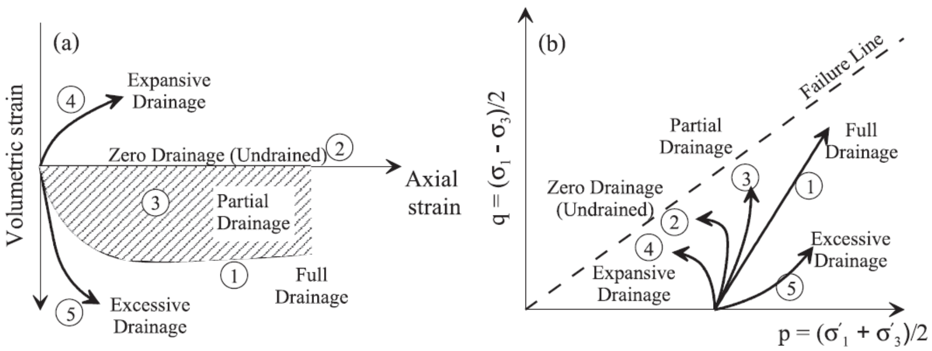


Figure 1. Schematic representation of triaxial strain and stress paths under different drainage conditions: a) Strain paths, b) Effective stress paths (Sivathayalan & Logeswaran, 2007; Sivathayalan & Logeswaran, 2008).

The present study is designed to investigate the effect of partial drainage on the monotonic behavior of Firoozkuh sand No. 161. To this end, a series of triaxial compression tests were conducted to simulate simultaneous changes in pore water pressure and sample volume by injecting or extracting water from a saturated soil specimen. To interpret the results, effective stress paths and volumetric strain variation under partial drainage conditions were compared with those under fully drained and undrained conditions. The findings demonstrate that partial drainage can have a significant impact on shear behavior and, consequently, on the stability of soil structures.

2. MATERIALS AND METHODS

2.1 DEFINITION OF THE PARTIALLY DRAINED PATH

In this study, to investigate soil behavior under triaxial shearing conditions, a bilinear strain path approach was adopted, following Lashkari and Yaghtin (2018). The volumetric strain during the test evolves at a constant rate from the beginning of shearing up to a predetermined axial strain level (e.g., 12.5% axial strain). Beyond this point, the volumetric strain remains constant until the end of the test, meaning that the volumetric strain rate becomes zero.

To quantify the rate of volumetric change, a parameter called zeta (ζ) is used. This parameter denotes the ratio of the rate of volumetric strain change ($d\varepsilon_v$) to the rate of axial strain change ($d\varepsilon_a$), where axial strain corresponds to deformation in the direction of deviatoric loading in a triaxial specimen (Jrad et al., 2012; Sivathayalan & Logeswaran, 2008; Vaid & Eliadorani, 2000):

$$\zeta = \frac{d\,\varepsilon_v}{d\,\varepsilon_a} \quad \text{(Equation 1)}.$$

In this study, the adopted volumetric strain path follows a bilinear loading history characteristic of partially drained tests, where the volumetric strain (ε_v) increases linearly with axial strain (ε_a) up to 12.5%, and then remains constant.

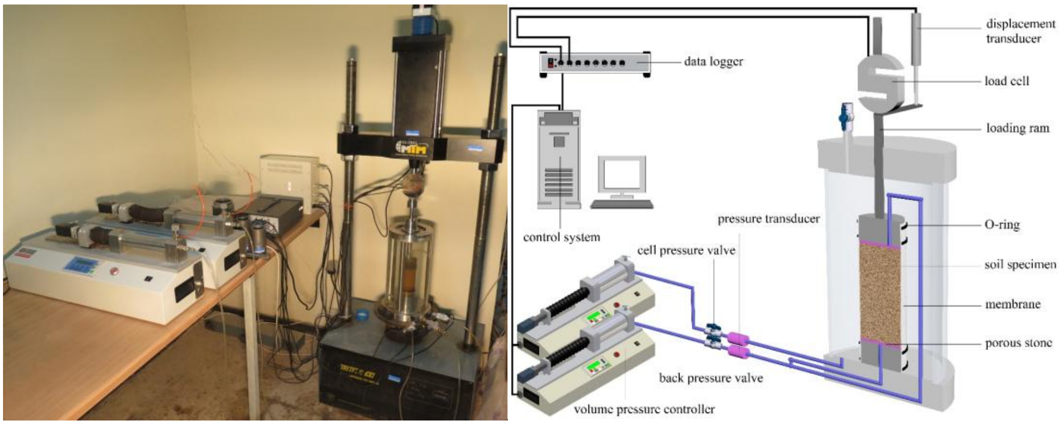
As is well known, during a triaxial compression test, the axial strain increases in the positive direction as the specimen shortens under applied load. In other words, a reduction in sample height corresponds to an increase in positive axial strain. Similarly, a reduction in the total volume of the specimen is also considered a positive volumetric strain. Therefore, if during a triaxial compression test (positive $d\varepsilon_a$) the volume of water within the specimen is reduced (e.g., by suction or drainage), the sample experiences a decrease in total volume, resulting in a positive $d\varepsilon_v$. Consequently, the ζ value in Equation 1 will be positive. In contrast, injecting water into the sample, which increases its volume, results in a negative $d\varepsilon_v$, and thus a negative ζ value. It should be noted that in a conventional undrained test, where no volume change is allowed, the ζ value is zero.

In the following sections, the experimental setup and materials used in this study are introduced. Subsequently, a step-by-step description of the partially drained triaxial testing procedure—from sample preparation to test completion—is provided, highlighting all critical considerations.

2.2 TESTING EQUIPMENT

In this study, a static electromechanical triaxial testing system was employed, compliant with ASTM standards D5311, D7181, and D3999-91. This system is capable of applying a static deviatoric load of up to 2 tons. It is equipped with an electromechanical volume-pressure control system (manufactured by WILLE, Germany) that can generate both cell pressure and back pressure up to 2000 kPa. Furthermore, the system is capable of injecting or withdrawing water with a high precision of 0.0001 mL/min.

Axial strain in the specimen is recorded using a Linear Variable Differential Transformer (LVDT) mounted along the axis of deviatoric loading. The overall setup of the apparatus is shown in Figure 2a, while a schematic representation of the triaxial system is presented in Figure 2b.



(a) (b)

Figure 2. The apparatus utilized for triaxial testing: a) overall setup, b) schematic representation of the device used.

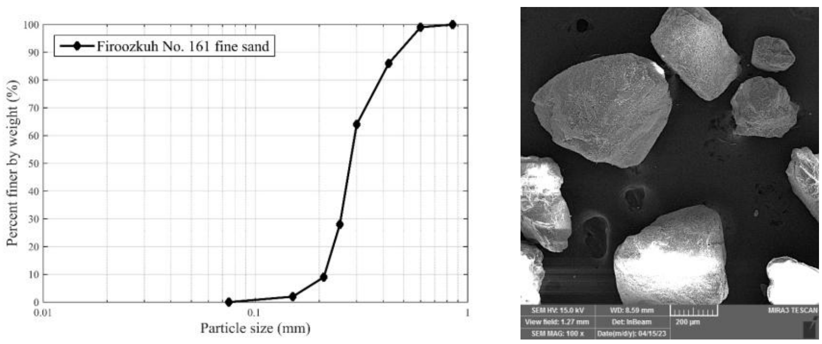
2.3 MATERIALS

The fine-grained sand used in this study is Firoozkuh Sand No. 161, a silica-based crushed sand. This soil consists of approximately 97% quartz by weight and has been extensively studied in recent years in various geotechnical research (Irani et al., 2024; Irani et al., 2021; Maleki Tabrizi et al., 2023; Tabrizi, 2022; Tohidvand et al., 2023).

The physical and mechanical properties of Firoozkuh Sand No. 161 are presented in Table 1. The grain size distribution curve for the sand is shown in the figure 3a, and Scanning Electron Microscope (SEM) images of the sand particles are also provided in the figure 3b.

Table 5. Physical properties of Firoozkuh No. 161 sand.

Specific Gravity, G_s	Median Diameter, D_{50} (mm)	Maximum Void Ratio, e_{max}	Minimum Void Ratio, e_{min}
2.65	0.27	0.94	0.54



(a) (b)

Figure 3. Sand sample No. 161 from Firoozkuh: a) distribution of particle sizes, b) SEM image showing particle shape.

2.4 SPECIMEN PREPARATION, SATURATION, AND CONSOLIDATION

Cylindrical specimens were prepared using a mold with a height of 100 mm and a diameter of 50 mm. The specimens were prepared by the dry pluviation method, resulting in an initial relative density of approximately 35%. To safely remove the mold without collapsing the sample, a suction pressure of approximately 20 kPa was applied to the bottom of the specimen.

Subsequently, CO_2 gas was introduced from the bottom and allowed to exit from the top of the specimen for a duration of 30 minutes. Following this, de-aired water, equivalent to three times the specimen volume, was flushed through the sample to enhance saturation. The B-value procedure was then carried out in 20 kPa increments until a saturation degree of over 95% was achieved. In all tests, the back pressure ranged between 280 and 320 kPa.

During the consolidation stage, the cell pressure was increased to the designated confining pressure. The specimen was allowed to consolidate until volumetric change measurements stabilized, indicating completion of consolidation.

2.5 TRIAXIAL TEST EXECUTION PROCEDURE

In this section, the procedure is described for conducting a triaxial test under a partially drained condition with a target ζ value of –0.25. Since the test follows a bilinear strain path, the volumetric strain rate must remain constant up to a predetermined axial strain. In this study, the total axial strain was set to 25%, while the volumetric strain control was applied up to 12.5% axial strain. This means that ζ was equal to –0.25 from 0% to 12.5% axial strain, and zero (undrained condition) from 12.5% to 25%.

The selected axial strain rate was 0.5 mm/min, corresponding to 0.5% strain per minute (based on an initial specimen height of 100 mm, with corrections made for any changes during consolidation). According to Equation (1), by substituting $d\varepsilon_a$ = 0.5%/min and ζ = –0.25, the corresponding volumetric strain rate $d\varepsilon_v$ is calculated to be –0.125% per minute.

Given the cylindrical geometry of the sample (50 mm diameter and 100 mm height), this corresponds to a volumetric change rate of approximately –0.2454 cm^3/min. Since the sign is negative, it indicates that water must be injected into the specimen during the shearing phase (adjustments may be needed to account for volume changes during consolidation).

To implement this in practice, upon completion of the consolidation stage, the drainage valve remains open, and the volume-pressure controller connected to the back-pressure line is switched to injection mode. As axial loading begins, water injection is carried out simultaneously, maintaining the desired volumetric strain rate until 12.5% axial strain is reached. At that point, the drainage valve is closed, and the test proceeds under undrained conditions, with the specimen volume remaining constant for the remainder of the test.

2.6 TESTING PROGRAM

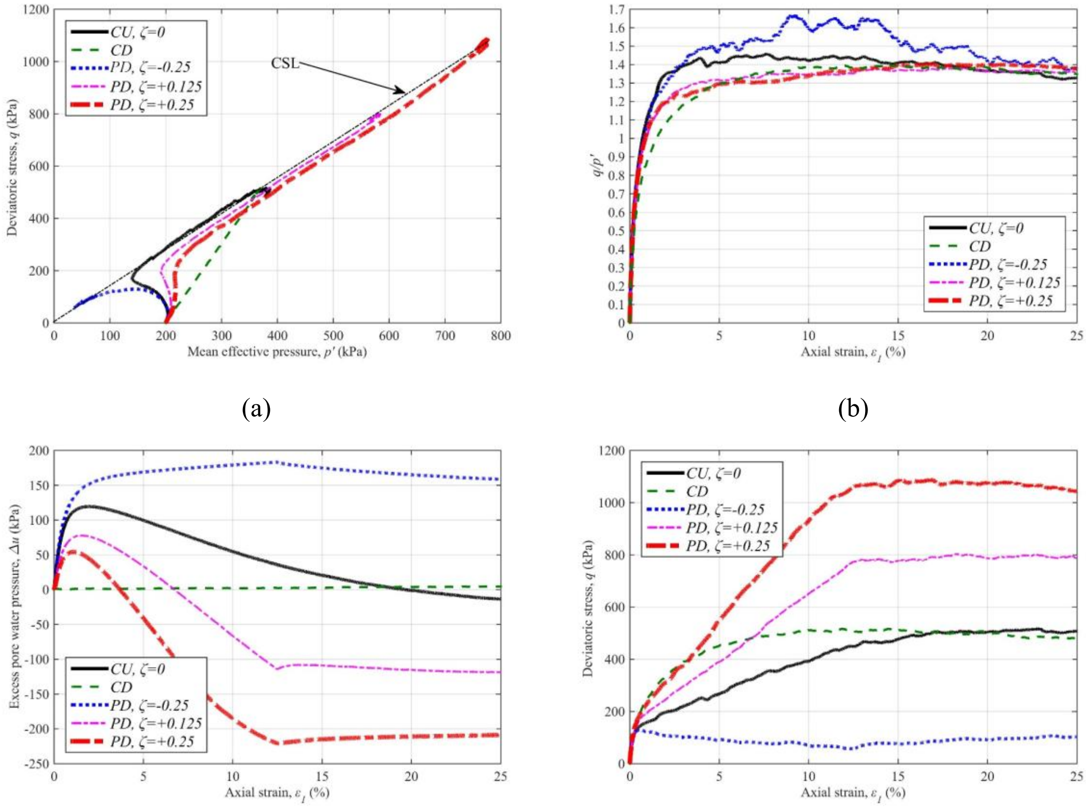
In this study, five triaxial tests were conducted on Firoozkuh Sand No. 161 under a constant confining pressure of 200 kPa to investigate its behavior under different drainage conditions. The details of the testing program, including the key parameters for each test, are summarized in Table 2.

Table 6. Programme of triaxial shear tests.

Consolidation Stress (kPa)	Initial Relative Density (%)	Initial Void Ratio	Type of the Test	$d\varepsilon_v/d\varepsilon_a$ (%)	Volume Change Rate (cm^3/min)
200	49.50	0.742	CU	0	0
200	45.25	0.759	CD	-	-
200	43.75	0.765	PD	−0.250	–0.2454
200	49.75	0.741	PD	+0.125	+0.1227
200	27.75	0.749	PD	+0.250	+0.2454

3. RESULTS

Figure 4a presents the effective stress paths for five triaxial tests conducted under a confining pressure of 200 kPa, plotted based on the Roscoe variables:
$p' = (\sigma_1' + 2\sigma_3') / 3$ (Equation 2),
$q = \sigma_1' - \sigma_3'$ (Equation 3).



(a) (b)

(c) (d)

Figure 4. The influence of drainage condition: a) effective stress path, b) variation of stress ratio, c) variation of excess pore water pressure, d) variation of deviatoric stress.

In the CU test, the specimen initially exhibits contractive behavior, followed by a phase transformation that leads to dilative behavior, eventually reaching the critical state. At this specific void ratio, the ultimate strength of the CU test approaches that of the CD test.

However, when water is injected into the specimen during shearing (ζ =–0.25), the soil shows a completely contractive response throughout the test. This behavior leads to a significant reduction in effective stress, eventually approaching liquefaction. Conversely, when water is sucked out of the specimen at a low rate (ζ = +0.125), the sand exhibits a more dilative response compared to the CU condition. Although it still begins with a slight reduction in effective principal stress (indicating contractive behavior), it transitions to dilative behavior and reaches the critical state at a higher strength level than in the CU test. Moreover, with an increasing rate of ζ to +0.25, the specimen shows a strongly dilative response from the beginning of shearing, achieving a higher resistance than CU without any initial drop in effective stress.

A noteworthy observation across all five tests is that, regardless of the drainage condition, all specimens ultimately converge to a unique critical state line (CSL), as shown in Figure 4a.

Figure 4b illustrates the stress ratio for different triaxial tests. As observed, all tests converge to a consistent value of stress ratio within the axial strain range of 20% to 25%. The critical stress ratio for Firoozkuh sand is approximately 1.33, which corresponds to a critical state friction angle of about 33°, calculated using:

$M = (6 \sin \Phi'_C) / (3 - \sin \Phi'_C) = 1.33$, $\Phi'_C \approx 33°$ (Equation 4).

Figure 4b demonstrates that the value of Φ'_C for this sand is independent of the drainage condition, confirming the inherent and intrinsic nature of the critical state line.

Figure 4c presents the results of pore water pressure evolution during the different triaxial tests. As shown, in the CU test, the excess pore water pressure nearly drops to zero by the end of the test, resulting in a final strength approximately equal to that of the CD test.

In the test with a partially drained path defined by $\zeta = -0.25$, continuous injection of water into the specimen leads to a significant buildup of pore water pressure, reaching approximately 185 kPa. Given the confining pressure of 200 kPa, this indicates that the specimen has approached the threshold of static liquefaction.

In contrast, for the test with $\zeta = +0.125$, an initial increase in pore pressure is observed, followed by a gradual reduction as the specimen undergoes phase transformation. The pore pressure eventually returns to zero at about 6.6% axial strain.

A similar trend is observed for the $\zeta = +0.25$ test, with the pore pressure reaching zero at a lower strain level, approximately 3.6%, indicating a stronger dilative response due to more aggressive suction.

It is worth noting that phase transformation occurred at different axial strains in the CU and partially drained tests with $\zeta = +0.125$ and $\zeta = +0.25$, specifically at approximately 2.0%, 1.5%, and 1.1%, respectively. This trend suggests that increasing the rate of water suction into the specimen leads to earlier phase transformation, occurring at lower axial strains.

Figure 4d illustrates the evolution of shear strength across the different test conditions. From this figure, it can be concluded that suction of water from the specimen, which reduces the void ratio, results in an increase in shear strength. Conversely, water injection, which leads to higher void ratios, is associated with a reduction in strength.

Finally, Figure 5 presents the volumetric strain paths for the five triaxial tests conducted. The three partially drained tests follow a bilinear strain path, enforced through the volume pressure control system. In these tests, the volumetric strain varies at a constant rate up to 12.5% axial strain, after which the drainage valve is closed, and no further volume change occurs. This approach enables the simultaneous evolution of pore pressure and volumetric deformation during shearing.

In contrast, during the CU test, there is no volume change throughout the entire test due to full undrained conditions. In the CD test, there are no excess pore water pressure changes, however, volume changes are freely allowed and recorded by the system. These comparisons highlight the unique capability of partially drained paths to simulate more realistic boundary conditions where both volume and pore pressure may evolve concurrently.

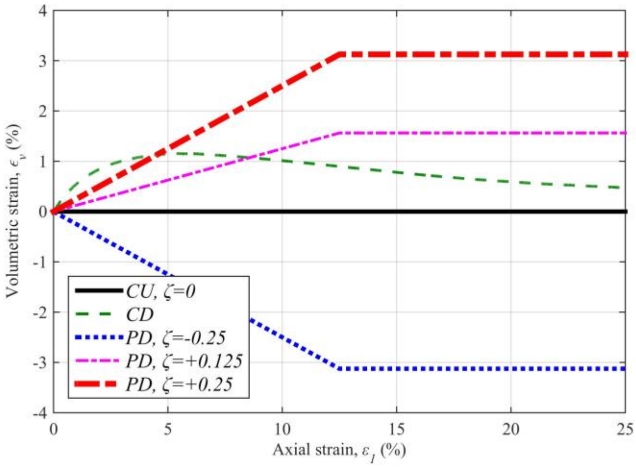


Figure5. Variation of volumetric strain under different drainage conditions.

4. CONCLUSION

In this study, the behavior of sand under different drainage paths was investigated by first describing the implementation of a bilinear strain path, followed by an evaluation of soil response under partially drained conditions. The results of the triaxial tests reveal new dimensions of sand behavior that have gained increasing attention in recent geotechnical research. The key findings are summarized as follows:

- As the ζ rate increases from negative to positive, the sand transitions from a loose to a dense behavior, accompanied by a significant increase in shear strength.
- An increase in ζ leads to earlier phase transformation (at lower axial strains) and reduced pore water pressure generation.
- Variations in the ζ rate have no influence on the critical state line (CSL) slope or the critical state friction angle (Φ'_C), confirming the intrinsic nature of Φ'_C.
- A decrease in ζ may lead to a fully contractive response, potentially resulting in static liquefaction.

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Numerical Modeling of Rocking Foundation on Granular Soft Soil

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ABSTRACT. The rocking foundation system is an innovative approach, enhancing seismic resilience in structures under severe dynamic condition. These foundations utilize controlled rotational responses and energy dissipation through temporary detachment from the soil, making the structure maintain its serviceability. The study covers factors influencing performance and presents a numerical study of a rocking bridge pier demonstrating energy dissipation and permanent deformations.

KEYWORDS: Rocking foundation . numerical model . FLAC . Soft soil . Rocking isolation . Bridge pier

1. INTRODUCTION

Modern geotechnical engineering has evolved beyond the conventional approach of simply increasing structural element dimensions or using higher strength materials to enhance seismic performance. This traditional methodology, while intuitively appealing, presents a fundamental contradiction: increasing structural rigidity also increases the proportion of lateral forces attracted to the structure during seismic events (Ardeshiri-Lajimi et al. 2015). As established in structural analysis theory, stiffer elements inherently attract greater forces from applied loads—an outcome counterproductive to seismic resilience objectives.

This recognition has led to the development of specialized foundation systems that exhibit distinctive behaviors despite their relatively compact dimensions. These foundation systems demonstrate controlled rotational responses under seismic loading, effectively increasing the damping characteristics of the structural system and dissipating earthquake energy. This innovative approach enables more optimized and economically efficient designs while maintaining or enhancing safety parameters.

The rocking behavior encompasses a series of alternating rotational movements of the foundation under dynamic loading conditions. This phenomenon may include temporary detachment between the foundation base and the supporting soil surface. Collectively, these movements constitute what is termed "rocking behavior" or "rocking motion" in the geotechnical literature.

A principal advantage of implementing rocking foundations is the strategic relocation of potential plastic hinge formation from structural elements to the soil beneath the foundation. This transfer mechanism effectively prevents damage to critical structural components during seismic events. However, depending on the strength parameters and mechanical properties of the structure.

The recognition and formal investigation of rocking behavior dates back to the early 1960s, with Housner's seminal work in 1963. Housner (1963) approached the problem by analyzing water storage tanks as simplified single-degree-of-freedom systems, investigating the influence of column slenderness ratios on the overturning potential of these structures during seismic events. In this study it is stated that tall, slender structures subjected to seismic loading demonstrate significantly greater stability than would be predicted under static gravitational loading conditions alone.

In recent years, significant progress has been made in the study of rocking foundations, with numerous investigations employing both physical and numerical modeling approaches. To evaluate the dynamic performance of rocking foundation systems, comparative and improving studies have been conducted on seismic isolation systems, such as comparing rocking isolation with rubber bearing and lead-rubber bearing systems (Chen & Li, 2020). The system employing rubber bearings was found to experience significant deformations and severe damage under dynamic loading.

Although lead-rubber bearings exhibited performance improvement, they still proved insufficient in achieving optimal seismic performance. In contrast, rocking foundation systems demonstrated superior behavior by effectively controlling plastic deformation and exhibiting merely elastic responses. The rocking isolated system achieved this by reducing seismic inertial forces on the superstructure and pier columns simultaneously.

This reduction in inertial forces is particularly critical for tall piers in bridge structures, where the considerable mass of the pier columns exacerbates the seismic inertial forces. Agalianos et al. (2017) further advanced the understanding of this phenomenon by numerically investigating the rocking behavior of bridge components, analyzing the rocking of footing and pier column independently.

Laboratory investigations have provided additional insights into rocking behavior by examining the influence of footing size with slow-cyclic tests (Drosos et al., 2012). These tests, conducted on varying sizes of footings beneath a same superstructure, revealed a direct relationship between the foundation's moment capacity, M_c, and the structure's seismic factor of safety, FS_E. Additionally, the embedment depth of footings has been shown to significantly affect dynamic behavior (Hakhamaneshi & Kutter, 2016). Embedded footings tend to exhibit uplift-dominant behavior, resulting in greater residual rotation compared to shallow footings. This is attributed to soil particles falling into the cyclically opening and closing gap between the footing and the soil surface during seismic loading.

The geometric configuration of the footing is another critical factor influencing rocking foundation performance. Hakhamaneshi and Kutter also investigated the effect of footing shape and concluded that wider rectangular footings experience less settlement compared to narrower ones. For H-shaped footings, they observed that increasing the missing area ratio led to greater settlement, increased uplift, higher damping, and a reduced recentering ratio, R_{RC} (Irani et al., 2021., Esmatkhah Irani et al., 2023; Irani et al., 2024; Maleki Tabrizi et al., 2023).

An innovative study explored the rocking behavior of foundations on dense soils through large-scale laboratory testing by Antonellis et al. (2015), considering variations in moisture content and groundwater table levels. The results revealed that soils with lower moisture content caused increased soil falling in the footing-soil gap, thereby exacerbating the structure's residual rotation. Furthermore, this study investigated the impact of seismic wave direction relative to the structure's orientation. It was found that seismic waves aligned with the direction of the structure induced maximum rotation, whereas increasing the angle between the isolated footing and the wave direction reduced the induced rotation (Tabrizi, 2022; Tohidvand et al., 2023).

A common approach to addressing the mitigation of seismic-induced deformation in structural systems founded on rocking foundations is improving the engineering properties of the supporting soil to enhance the post-earthquake performance of these systems. Among the various soil improvement techniques, densification through compaction has been investigated as a method to modify the soil's response under dynamic loading.

Anastasopoulos et al. (2012) and (Tsatsis & Anastasopoulos, 2015) employed physical model testing, specifically shaking table experiments, using structures with varying mass founded on shallow foundations resting on improved sand. The research examined the influence of both the intensity of soil compaction and the depth of the compacted soil layer on the dynamic behavior. It has been reported that increasing the vertical factor of safety, FS_v, of the footing by soil densification tends to shift the rocking response toward an uplift-dominated mechanism. This transition results in the footing experiencing cyclic uplift and localized contact at its edges.

Beyond the soil densification approaches, the implementation of structural elements such as piles has been used in recent research on rocking foundations. Allmond and Kutter (2014) conducted centrifuge testing to evaluate the performance differences between piles with moment-transferring (attached) connections to footings versus those with non-moment-transferring (unattached) connections. Their findings demonstrated the superior performance of unattached connections, which facilitate controlled rocking behavior while preventing undesirable uplift. Their research further established that enhancing pile bearing capacity increases the recentering ratio while simultaneously reducing the system's energy dissipation capacity.

Additional centrifuge investigations have new design recommendations suggesting the optimal implementation of short piles, with improvement depths limited to L/2 (where L represents the foundation length) (Ko et al., 2018). This recommendation originates from observations that significant soil plastic deformation beneath rocking isolated foundations is predominantly confined to this depth range. These studies also caution against the use of fixed connections between rocking foundations and piles, as such connections have been observed to exacerbate post-seismic residual deformations.

Alternative soil improvement studies include the implementation of stone columns, which have demonstrated effectiveness in mitigating liquefaction potential (Liu & Hutchinson, 2018). Another approach involves the installation of stiff diaphragm walls under the footing, which efficiently confine plastic strain propagation around the isolated footing edges (Sadjadi et al., 2021). This confinement technique offers dual benefits: reduction in structural deformations while preserving the essential energy dissipation of the system.

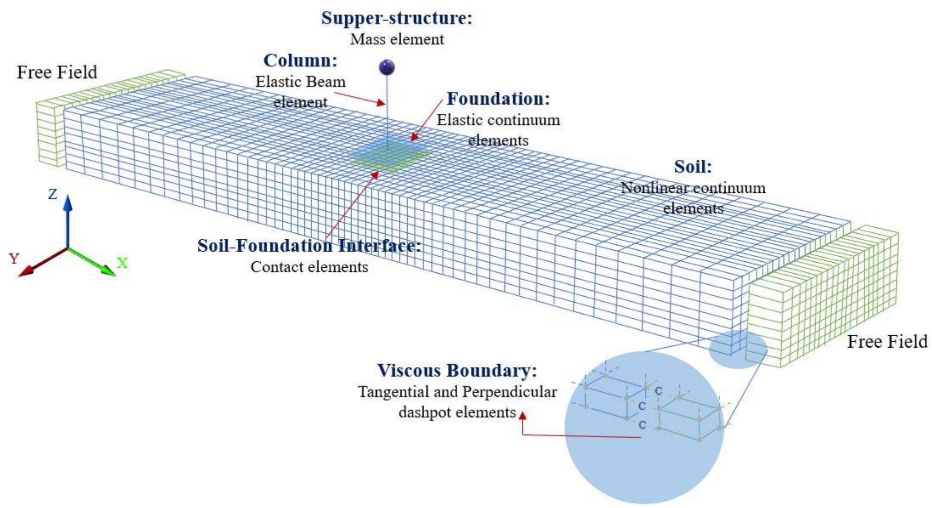

Figure 6. 3D model of rocking footing

2. ROCKING SYSTEM 2D MODELING

The present study employs two-dimensional numerical modeling to investigate the dynamic response of a rocking bridge pier. The model comprises a loose granular soil medium with dimensions of 15 m in length and 9 m in height, supporting a bridge pier with a 3 m long footing. The pier structure extends 9 m above the foundation level. The soil behavior is characterized using the Mohr-Coulomb constitutive model, while the structure is modeled as elastic, justified by its substantially higher stiffness relative to the surrounding soil medium. Figure 7 illustrates the model geometry, vertical stress contour, and applied boundary conditions.

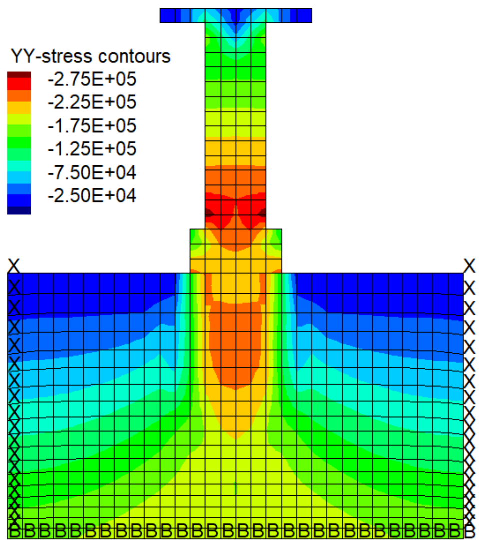

Figure 7 The 2D rocking bridge pier model

A specialized interface is defined between the footing and soil surface to accurately represent the load transfer mechanisms and capture the rocking isolation interaction. This interface implements a non-linear interaction through a series of zero-length non-linear springs with high normal stiffness and an interface friction coefficient of μ=0.7. Critically, this interface is designed to preclude tensile force transmission, reflecting the actual behavior observed in physical systems (Liu & Hutchinson, 2018; Tsatsis & Anastasopoulos, 2015).

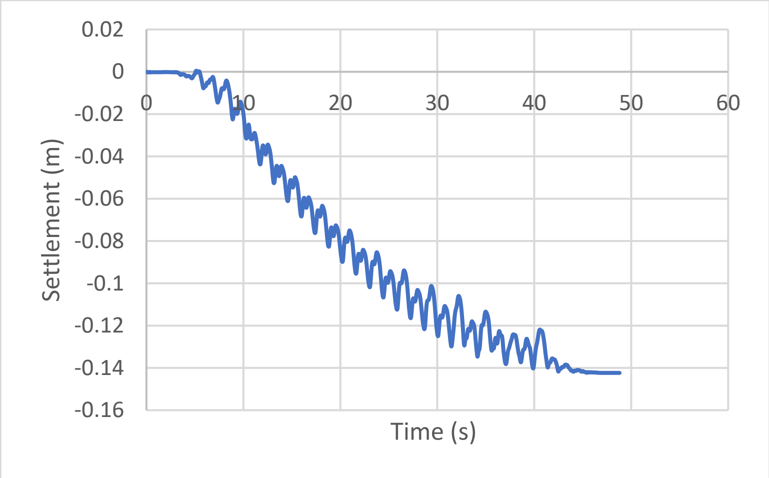

Figure 8 Time-settlement graph

The seismic excitation is modeled as a sinusoidal wave with a peak ground acceleration (PGA) of 0.2g. Given that the dynamic model represents an in-situ condition with extended boundaries the seismic excitation is applied exclusively to the lower boundary of the model, distinguishing this approach from dynamic modeling of soil contained within a rigid box.

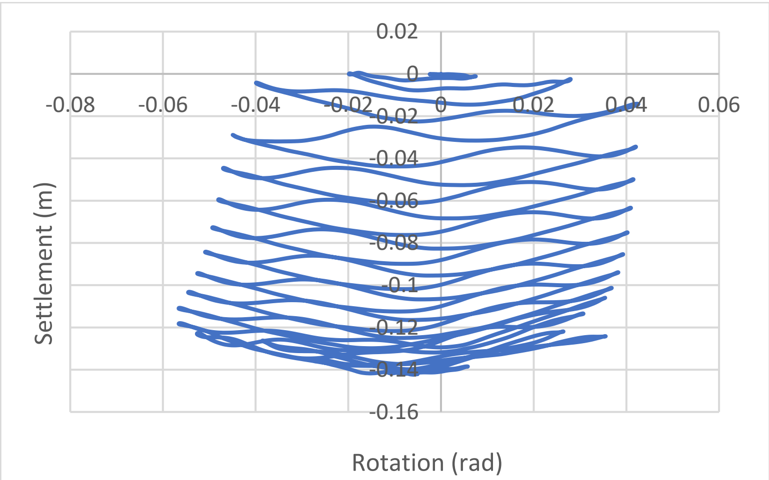

Figure 9 Rotation-Settlement graph

The dynamic analysis provided time-history data for settlement, rotation, and acceleration parameters, Figure 8-Figure 10. Post-seismic residual settlement reached 14.23 cm, while rotational response during the rocking motion oscillated between extremes of +0.0566 and -0.0426 radians. Examination of the acceleration-rotation graph indicates that the structure did not mobilize its full moment capacity during the seismic event, attributable to the relatively modest intensity of the applied ground motion.

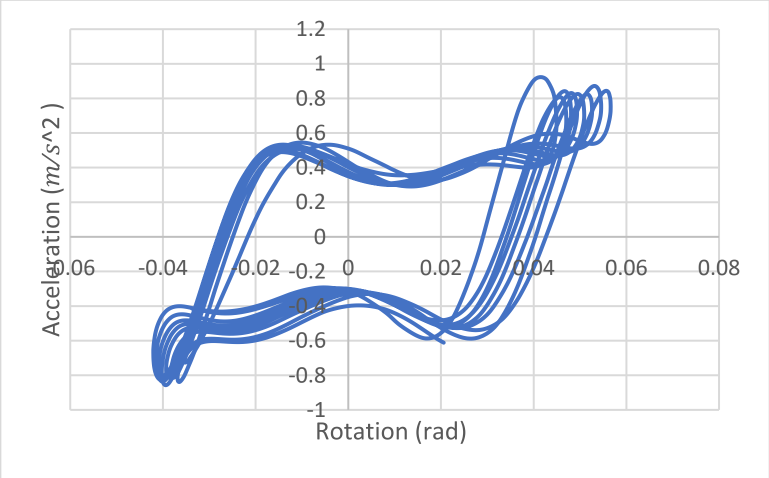

Figure 10 Rotation-acceleration graph

Detailed analysis of the expanded hysteretic behavior reveals substantial energy dissipation capacity, primarily due to the loose granular nature of the supporting soil medium. This energy dissipation mechanism represents a fundamental advantage of rocking foundation systems, particularly when implemented in loose or soft soil conditions.

The observed behavior confirms the efficacy of rocking foundation as an isolation strategy while highlighting the importance of anticipating and accounting for permanent deformations in design considerations. These findings align with previous experimental studies while providing quantitative insights into the performance expectations for similar systems under comparable seismic demands.

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Biomimetics for Engineering of Sands

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INTRODUCTION

This study presents preliminary findings from direct shear tests conducted on mixtures of a loose bi-modal sand and biochips. It explores the avenues for designing future flood defences, riverbanks, and foundations on or with sands, in their naturally loose state. Traditional ground engineering methods typically involve soil densification and the removal of voids — spaces that otherwise serve as natural conduits for water and air. The field continues to rely heavily on the use of chemical additives which, although increasingly are labelled as 'green', fill the voids, and compromise the soil's ecological functions, thus falling short of truly sustainable practice. This study explores the potential of enhancing particle interlocking to form strong, open microstructures.

The application of biochips in geotechnical practice remains relatively novel. These chips, inspired by natural forms such as organisms' shells, are designed to enhance the mechanical behaviour of soils through their geometry and surface texture. By promoting inter-particle friction, biochips may contribute to shear strength and deformation resistance (Martinez et al., 2022; Assadi-Langroudi et al., 2022).

MATERIALS AND METHODS

A novel biochip is digitally designed and fabricated, principally from sodium alginate and glycerine. The conical shape and surface texture is inspired by the shell of the sandhopper. The shape and texture are hypothesised to maximise interaction with surrounding loose sand, facilitate the self-orientation of the biochips within the soil matrix and promote interlocking. The sand is blended with a finer grade of sand up to 40 wt.%. The biochip content is fixed at 2 wt.%. Mixtures are remoulded at a low water content of 7% and a high void ratio of 0.6 and subjected to a series of unsaturated direct shear tests. The void ratio of 0.6 indicates a relatively loose packing of particles, which can influence the mobilised shear strength. Sands with high void ratios typically exhibit reduced shear strength due to limited interlocking between particles. However, the inclusion of fines and biochips may mitigate this effect to some extent (Chien et al., 2002). Previous studies have demonstrated that the shear strength of sands increases with the addition of fines up to a critical threshold, beyond which the fines begin to behave as a separate phase, thereby reducing overall strength (Carraro et al., 2009). In this study, the 40 wt.% fine content is considerable and expected to affect both the strength and the suction of the soil mixture.

The direct shear test is likely the most suitable method for an initial understanding of the steady states and stress–strain behaviour of non- to low-plasticity soils, due to its simplicity, reliability, and direct control over key testing parameters. It allows for clear observation of shear strength development under controlled normal stress, making it ideal for characterising the frictional resistance and dilation or contraction tendencies of granular soils. For sands and silty sands, which often exhibit distinct phase transformation and steady state behaviours, the test provides valuable insight into the evolution of shear stress with displacement.

RESULTS AND DISCUSSION

Initial findings from the direct shear testing programme indicate that, as the fine content increases and exhibits an upward trend under all three confining pressures tested (50, 100, and 200 kPa). After around **20% fine content**, the rate of increase slows down considerably, especially under 200 kPa, where the curve flattens. Beyond **20–25%,** adding more fines results in **minimal further gain** in shear strength. A **threshold fine content of approximately 20%** is evident from the data. Up to this point, fines contribute positively to particle interlocking and density. Beyond this, the fines likely start behaving more as a **separate phase**, reducing intergranular friction and dilative behaviour. This increase in strength is more pronounced at higher confining pressures, suggesting that the material's behaviour is more sensitive to fines content under greater stress levels (see Figure 1a). The inclusion of 2% biochips demonstrates a similar behavioural pattern, but has minimal effect on strenth at peak strain (Figure 1b).

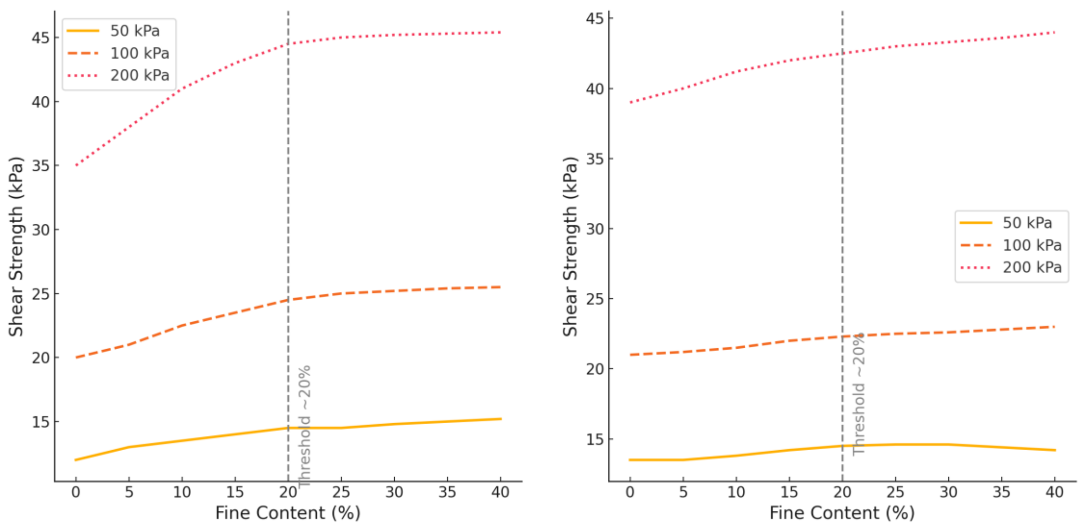

Figure 11 Shear Strength at peak strain in medium sand with increasing fine sand content (left) with no biochip; (right) with 2 wt.% biochip

The strength achieved in the Fig. 1b (with biochips) is slightly lower than in the Fig. 1a (without chips) across all confining pressures. In other words, the chips did **not significantly boost** peak shear strength. An initial hypothesis is that they may have introduced a **restructuring effect** that altered force chains or interrupted dense packing, especially at higher fine content.

Although the biochips did not contribute to shear strength to the extent initially anticipated, the samples containing biochips reached their peak shear stress at lower strain levels. The response is similar to that of a denser and more compact soil, although such densification was intentioanlly not imposed to samples. Denser sands typically mobilise their peak strength at smaller strains (Vangla and Latha, 2015). The early attainment of peak shear stress implies that the biochips may influence the soil structure by enhancing interparticle contacts, resulting in a potentially stiffer response — even if the overall increase in shear strength was less substantial than expected (see Figure 2).

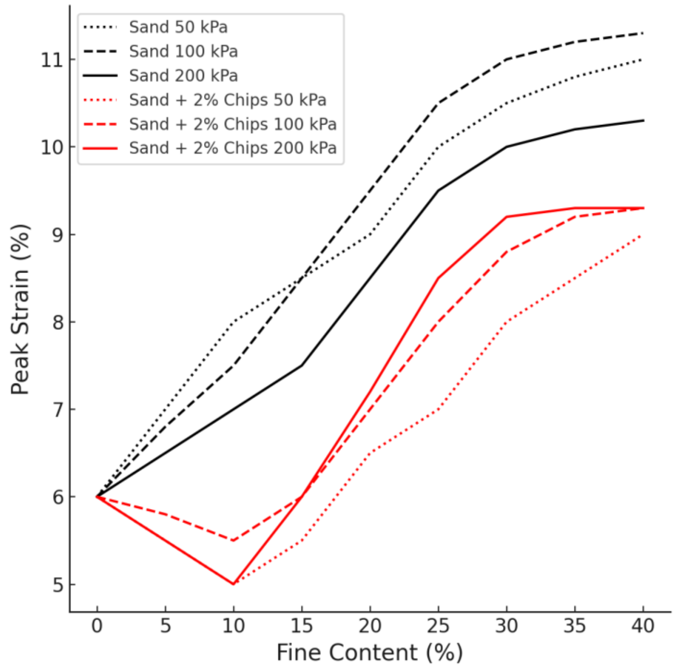

Figure 2 Peak stains for sand with the fine fraction and sand with the fine and biochips fraction

Figure 2 illustrates the variation in peak strain with increasing fine content for both untreated sand and sand mixed with 2% biochips under three confining pressures (50, 100, and 200 kPa). For plain sand, peak strain increases steadily with fine content, indicating that as more fines are introduced, the soil becomes more deformable before reaching its peak shear strength. This trend is particularly pronounced at higher confining pressures. In contrast, sand reinforced with biochips consistently exhibits lower peak strains across all confining pressures, suggesting earlier mobilisation of peak strength. This behaviour implies that the chips enhance interparticle contact, reduce macro-scale void volume, and generate a more interconnected soil structure that achieves strength more quickly. The difference is most notable at fine contents below approximately 20%, beyond which the influence of the chips begins to taper.

CONCLUSION

Biochips do not significantly raise ultimate shear strength. They however contribute to a stiffer response and faster strength mobilisation, making them particularly valuable in applications where early stiffness and rapid peak strength development are critical — such as in flood defence systems, slope stabilisation, or shallow foundation support under time-sensitive loading conditions.

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The Impact of the Degree of Consolidation upon Staged Loading on the Compressibility of Soft Clay

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INTRODUCTION

Urbanization and the subsequent construction of infrastructure, such as highways, railways, and ports, have significantly increased the demand for suitable ground. As a result, developers are now exploring regions with low bearing capacity, such as waterside areas along lakes, rivers, and marine shores. The soils prevalent in these areas, commonly referred to as soft soils, are characterized by low shear strength, high compressibility, and low hydraulic conductivity. To improve soft soils for land reclamation prior to construction, staged preloading is a widely used technique Le et al., (2012). Due to the extreme softness of these soils, pre-treatment is essential before implementing additional construction methods Garoushi and Uygar (2022). In theory, the time corresponding to the end of primary consolidation (EOP) is often used to estimate the onset of secondary compression. This research investigates the impact of accelerated and aged stress loading on both the virgin compression lines and rebound index of soft soils.

MATERIALS AND METHODS

Soil samples were collected from Tuzla and EMU campus located in Famagusta, North Cyprus. Two types of fine-grained soils were utilized in this classified as highly plastic clay (CH) and silt (MH). The study examines the behavior of virgin compression lines of soft clay under varying degrees of consolidation and their impact on the rebound curves, starting with standard oedometer tests to estimate times for 100%, 75%, and 50% consolidation. This was followed by modified oedometer tests (MOT), maintaining each load increment for three days to simulate prolonged loading, and long-term tests to observe creep effects and deformation behavior under extended consolidation period. Samples were prepared in their in-situ state, mixed with distilled water at their liquid limit. During testing, initial oedometer tests established consolidation times for each load increment, based on strain-log time curves. Subsequent tests involved applied load increments corresponding to specific consolidation levels, while long-term oedometer tests held each load for three days to observe compressibility.

RESULTS AND DISCUSSION

Figure 1(a, b) presents the virgin compression curves for both Tuzla and EMU soils. Both soils exhibit an increase in compression index with increase in the degree of consolidation. For a specimen preloaded to a 50% degree of consolidation, a nonlinear pattern is observed in the compression curves of both soil types, attributed to the presence of pore water pressure within the soil pores. An increase in the compression index of the virgin compression lines is noted when specimens are subjected to a higher degree of consolidation, with this effect being more pronounced in Tuzla clay than in EMU soil. Additionally, specimens demonstrate a higher rebound index as the degree of consolidation increases. The relationship between the compression index and rebound index is expressed as a linear function, as shown in Figure 1(c, d).

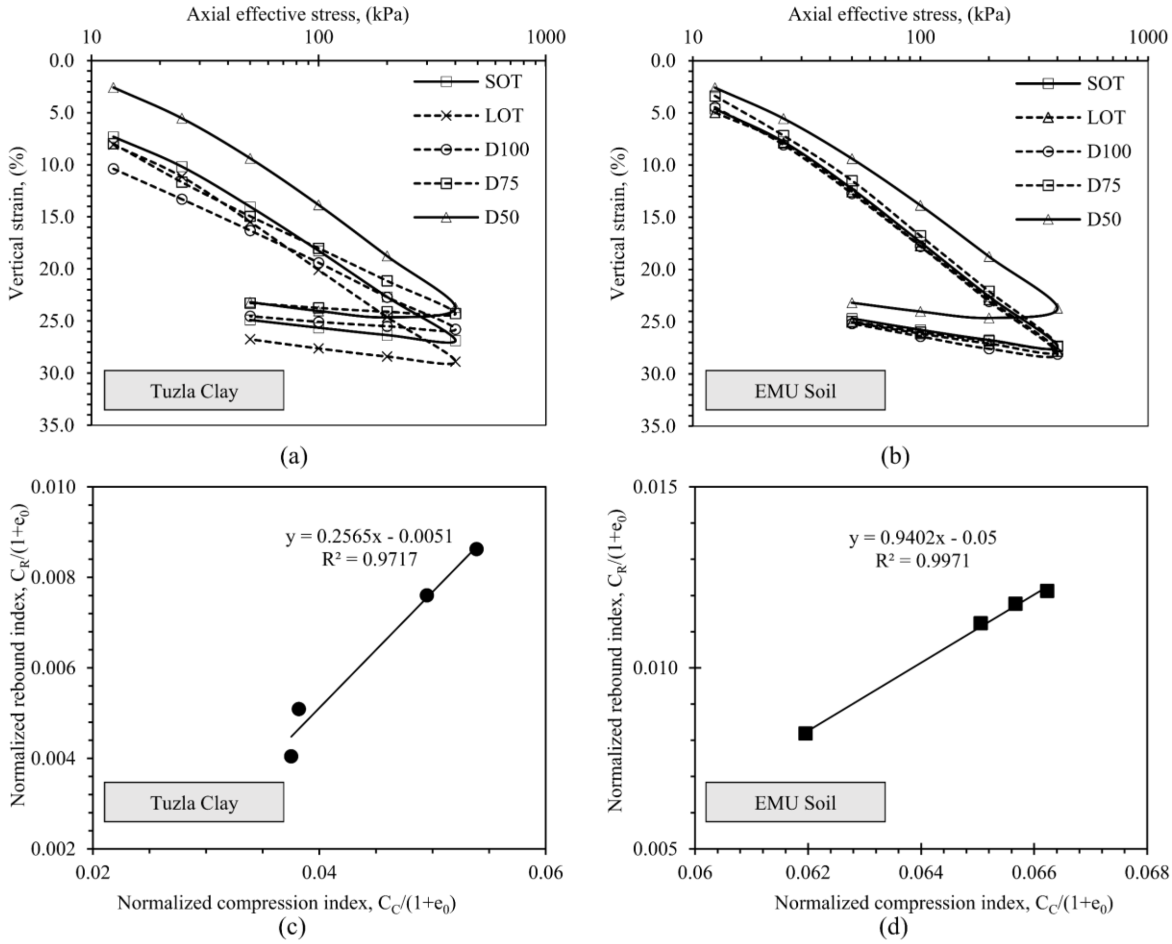

Figure 1. (a, b) stress strain curves for Tuzla Clay and EMU, (c,d) correlation between compression index and compression index for various degrees of consolidation.

CONCLUSION

This study examined the effects of degree of consolidation on the compression and rebound indexes of soft soils from Tuzla and EMU campus regions, focusing on how these factors impact soil behavior during consolidation. The findings indicate that both soil types exhibit an increase in compression index of the virgin lines with increase in the degree of consolidation, with the effect being more pronounced in Tuzla clay than in EMU soil.

Furthermore, the observed linear relationship between the compression and rebound indices highlights a predictable correlation, allowing for improved modeling of soil behavior under prolonged loading conditions. These results underscore the importance of considering aging effects in the preloading process, particularly in soft soil regions prone to significant deformation. The findings can inform the design and implementation of staged preloading techniques to enhance the stability and load-bearing capacity of soft soils.

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State-of-the-Art Review of Effectiveness of Compaction of Soil with Concentration on Effective Depth

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INTRODUCTION

Soil compaction is a crucial process in many civil engineering applications, especially in the geotechnical and infrastructural ones, where the improvement of load-bearing capacity and reduction of settlement is required. The proper assessment of variables such as effective depth in various compaction techniques ensure the durability of infrastructure and the overall stability in the long term. Recent studies have focused on the mechanical methods of compaction such as rapid impact compaction (RIC), rolling dynamic compaction (RDC), and intelligent compaction (IC), as well as the effect of different soil properties and the effect of pore water dynamics on the compaction effectiveness. Thus, the main aim of this research is to shed some light on the effective zone of influence across different compaction techniques on various types of soil and the factors affecting the overall efficiency of compaction, aiming to optimize this process through analytical analysis and empirical formulas employing both field measurements and laboratory testing.

METHODS

This paper presents an extensive and comprehensive review of previous works on the effective depth of compaction in soil for ground improvement for various compaction techniques on a verity of soil types. Thus a comprehensive search across Google Scholar, Scopus and Web of Science was conducted. Only studies published in English from 2018 till 2024 were included.

STATE OF KNOWLEDGE

Cheng et al. (2021) attempted to estimate the effective zone of influence of RIC by developing an analytical model based on wave propagation theory, the model accounted for the dissipation of energy through soil layers, and compaction was estimated through values of depth and lateral extent. The model was validated through numerical simulations. Under varying soil conditions accounting for different parameters, especially, impact energy and soil elasticity. Scott et al. (2021) examined the depth of influence in both cohesive and granular soils thus expanded on RDC's influence. They performed full-scale field trials to have the extent of compaction measured at various depths, later correlated dynamic roller parameters with compaction results. As for Li et al. (2022), who attempted to evaluate the effective depth of RDC employing a three-side compactor on granular soils. They developed numerical simulation for physical models and field tests. Using load-penetration curves, the compaction depth was evaluated showcasing that the design of the compactor does in fact significantly influence the depth of effective soil improvement. Fathi et al. (2021) investigated the depth of influence of intelligent compaction rollers, combining laboratory testing and field measurements. The study employed geotechnical sensors embedded in the soil to measure the compaction force transmitted by the rollers. Data from laboratory tests, such as Proctor tests and California Bearing Ratio (CBR), were used to model compaction behavior, while field trials provided real-time measurements of compaction depth. As can be seen from Figure 1, the responses from the numerical model were close to the measurements obtained from the field for those sample test sites.

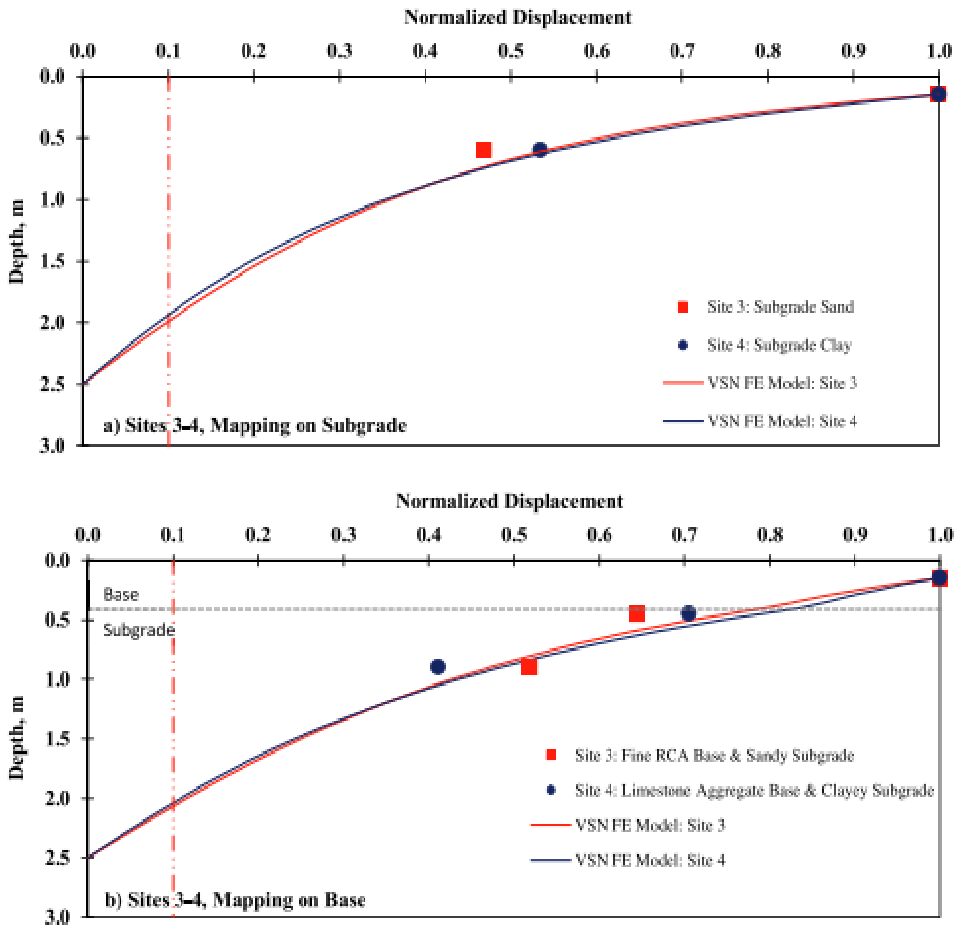

Figure 1. Comparison of normalized displacement obtained from FE model and field measurements during mapping (Fatih et al., 2021)

Faloye et al. (2021) focused on how the history of compaction applied and the effective stress as well as the pore water dynamics influences the soil during compaction. Laboratory testing was conducted to simulate varying soils with different initial compaction levels and moisture contents. They concluded that those two variables have a significant effect on the subsequent compaction efforts and the soils response to them. Assessment of soil degradation due to compaction is an important issue that was highlighted in a study by Håkansson and Voorhees (2020) they used different methods to measure soil strength, bulk density, and porosity. Examination of what change occurs with increasing compaction, especiallyin agricultural settings, and discussed methods to assess soil degradation that can be attributed to excessive compaction.

CONCLUSION

This review emphasizes the advances in identifying the effective depth of compaction that can be rigorously quantified for different methods including RIC, RDC and intelligent compaction. However, the efficiency of these methods is different depending on soil type, energy input and moisture conditions. Mechnical methods such as RIC and RDC provide and effective ground improvement especially in granular soil conditions, which can be especially useful in field project swhere logistics does not allow for on-going field testing because of the evolving site structure. This is unlike the compaction of unsaturated soils owing to pore water dynamics that Faloye et al. (2021). In agricultural soils, the problem is that excessive compaction alters soil properties and may lead to long-term soil degradation which may require regular assessments as proposed by Håkansson and Voorhees (2020). Future research should focus on optimizing mechanical compaction in hopes of enhancing soil stabilization techniques while ensuring sustainable soil management practices.

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Characterization Of Compressibility and Suction-Driven Permeability In Unsaturated Clay

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INTRODUCTION

In conventional geotechnical engineering practices, soil is often assumed to be either in dry or fully saturated state. However, soil naturally exists in a three-phase unsaturated state, with characteristics that make the conventional design approaches conservative. Unsaturated soil behaviour is characterized by Soil Water Characteristics Curve (SWCC). It illustrates the relationship between gravimetric and volumetric water content and suction, with mechanisms like capillary and osmotic action influencing water distribution across saturation levels (Bilsel and Uygar, 2000). Consolidation in saturated soils is governed by dissipation of the excess pore-water. For unsaturated soils, SWCC is required to capture the complex compressibility behaviour. Of earliest models are that developed by Fredlund and Hasan (1965) which characterizes one-dimensional compressibility using coefficients for net normal stress and matric suction. More recently, Alibrahim and Uygar (2023) proposed a new model for SWCC. This study aims to evaluate the compressibility characteristics of unsaturated clays, accounting for these intrinsic relationships and mechanisms.

MATERIALS AND METHODS

An experimental program was undertaken on alluvial clay from Famagusta Bay. The clay is rich in smectite and classified as highly plastic clay (CH) as per ASTM. To investigate the one-dimensional compression in unsaturated clay, specimens were prepared with varying initial water contents and void ratios using static compaction. Fully saturated specimens were tested in a conventional oedometer through incremental increase in normal stress up to 1800 kPa. Unsaturated compression tests were carried out in uniaxial test setup. Specimens were compressed at a constant strain rate of 0.07% of specimen height to avoid build-up of excess pore water pressure, reaching a maximum applied stress of 2000 kPa corresponding to the maximum load capacity of the testing equipment. The SWCC was evaluated according to ASTM D5298 standard.

RESULTS AND DISCUSSION

The one-dimensional consolidation on saturated specimens revealed a uniform final void ratio across samples and this consistent behaviour indicates that the applied stress level of 1800 kPa were not high enough to compress the soft alluvial clay to their ultimate void ratios. Specimens with lower initial void ratio required higher surcharge to maintain the initial void ratio during saturation (Figure 1-a). Matric suction was obtained using the contact filter-paper technique following McQueen and Miller (1968) where the circular Whatman No. 42 filter papers were sandwiched between trimmed clay discs. After reaching the moisture equilibrium, the gravimetric water content was determined and converted to matric suction using the ASTM D-5298 calibration curve and the resulting data were fitted to van Genuchten's (1980) model for simplicity. Results indicated similar SWCC across specimens with difference in saturated volumetric water content proportional to void ratio (Figure 1-b). Using the coefficients for matric suction, the unsaturated coefficient of permeability (k_u) was evaluated having higher permeabilities. For unsaturated compressibility, water seepage under applied stress is too complex to be measured, therefore, Equation 1 was developed to predict the seepage based on final water content and saturated permeability. The compressibility tests indicated a linear relationship between applied stress and void ratio, therefore final void ratios (e_f) can be estimated using Equation 2.

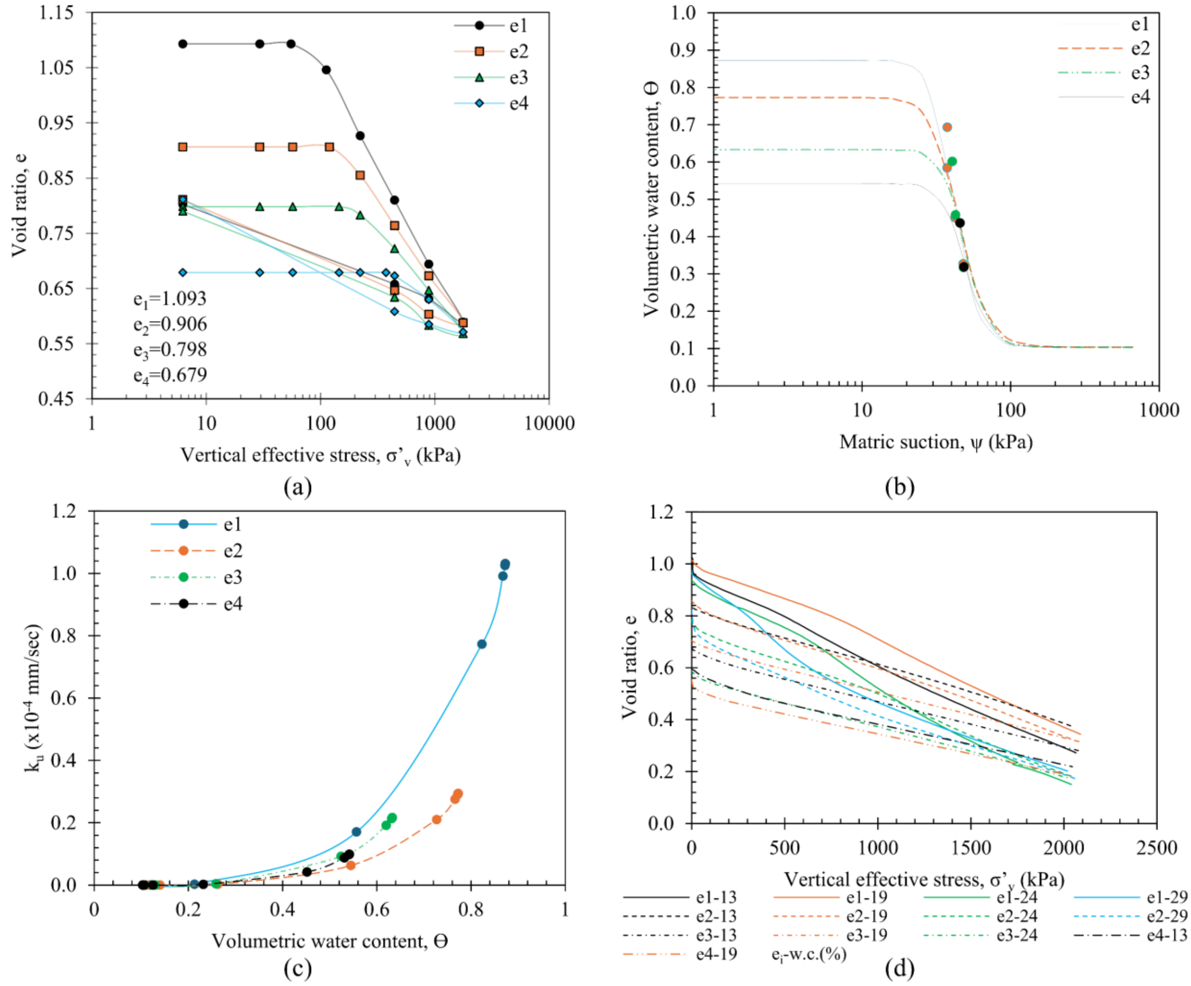

Figure 1. (a) Saturated specimens' compression curve, (b) SWCC of unsaturated specimens at e_o, (c) unsaturated hydraulic conductivity, and (d) compressibility of unsaturated specimens at different water contents (w.c.).

$$\Delta V_{wt} = \xi \sum_{t=0}^{t} k_s\,(e) A\, t \qquad [1]$$

$$\xi = \frac{w_{cf}}{\sum_{t=0}^{t=T} k_s\,(e)\, At} \qquad [1\text{-a}]$$

$$e_f = m_c\sigma + e_0 \qquad [2]$$

where, A is the cross-sectional area of the specimen, w_{cf} is the final gravimetric water content, t is the elapsed time, e_o is the initial void ratio, m_c is the slope of the compressibility curve and k_s is the saturated hydraulic conductivity.

CONCLUSION

Following are the key aspects of this study: Soil water characteristic curve showed similar behaviour for all the tested specimens at higher suction range. Matric suction results for high void ratio, k_u is higher. An equation for predicting water seepage based on final water content is proposed with saturated permeability as key factor. A linear compressibility trend for unsaturated specimen was observed, allowing final void ratio prediction.

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Chapter 3. Numerical Models and Systems Thinking

Qualitative System Dynamics Modeling of Soil Degradation with Emphasis on Climate Change

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INTRODUCTION

Damage to soil's physical, physicochemical, or biological characteristics due to natural or human processes is called soil degradation. One of the effective factors in soil degradation is soil erosion (Steiner and Williams, 1996). Soil erosion refers to surface soil's separation, movement, and deposition due to wind or water. Although the causes of soil erosion are natural, humans can exacerbate it, for example, agricultural activities such as plowing, planting, and harvesting crops on slopes, etc., all of which cause soil loss (Dragović and Vulević, 2020.). A tree can hold up to 500 liters of water during rain, and shrubby vegetation leads to more water infiltration into the soil. When vegetation and trees are lost, soil masses begin to move over the wet clays and slide downslope, and the soil is lost. On the other hand, soils with poor vegetation cover lose their root biomass (Tetteh, 2015). Therefore, their reserves of valuable minerals, organic materials, and biological energy sources are running out. Such soils are structurally unhealthy and can easily erode. Therefore, in this research, soil degradation has been modeled by emphasizing the climate change that aggravates each of the above-mentioned items, using qualitative system dynamics modeling.

At its core, biomimetics and nature-inspired methods advocate for a systemic, dynamic understanding of ground as a living, evolving medium rather than a static mechanical support (Assadi-Langroudi et al. 2022). Similarly, system dynamics modeling captures the complexity and interdependence of variables affecting soil health, including human-induced pressures and climatic changes. Emphasis on preserving soil's natural functions, such as self-healing, adaptability, and porous structure, aligns with the mission here, to model and eventually reverse degradation through interventions like vegetation recovery and erosion control. The feedback loops and long-term consequences reflect the paradigm of adaptive, circular, and resilient ground systems, where interventions are informed by natural processes and feedback mechanisms, rather than one-off engineered solutions.

METHODS

Correlation of changes of two variables or similar changes of two variables over time should not be confused with causal relationship between two variables. Correlation between two variables can be caused by common causal roots between those two variables. In the case of correlation, the simultaneous change of two variables cannot be a reason based on the cause-and-effect relationship between the two variables presented, and only the simultaneity and correlation of the change of the two variables is declared. In system dynamics, inputs, which are the main element in a closed system, include a chain of cause-and-effect relationships. Accordingly, the systems thinking is based on the principle of causality. At the macro level, the cause of a system's behavior is its structure. In other words, the structure of systems causes their behavior to appear. The structure of any system consists of components that interact with each other. In this interaction, the change in one component is the cause of change in other component or components, and the change in other component or components will be the origin and cause of change in subsequent components (Sterman, 1994). Therefore, in this research, qualitative system dynamics method was used to model soil degradation.

RESULTS AND DISCUSSION

As seen in Figure 1, things like overgrazing, deforestation, farming, overexploitation and industrialization are among the most important causes of soil degradation.

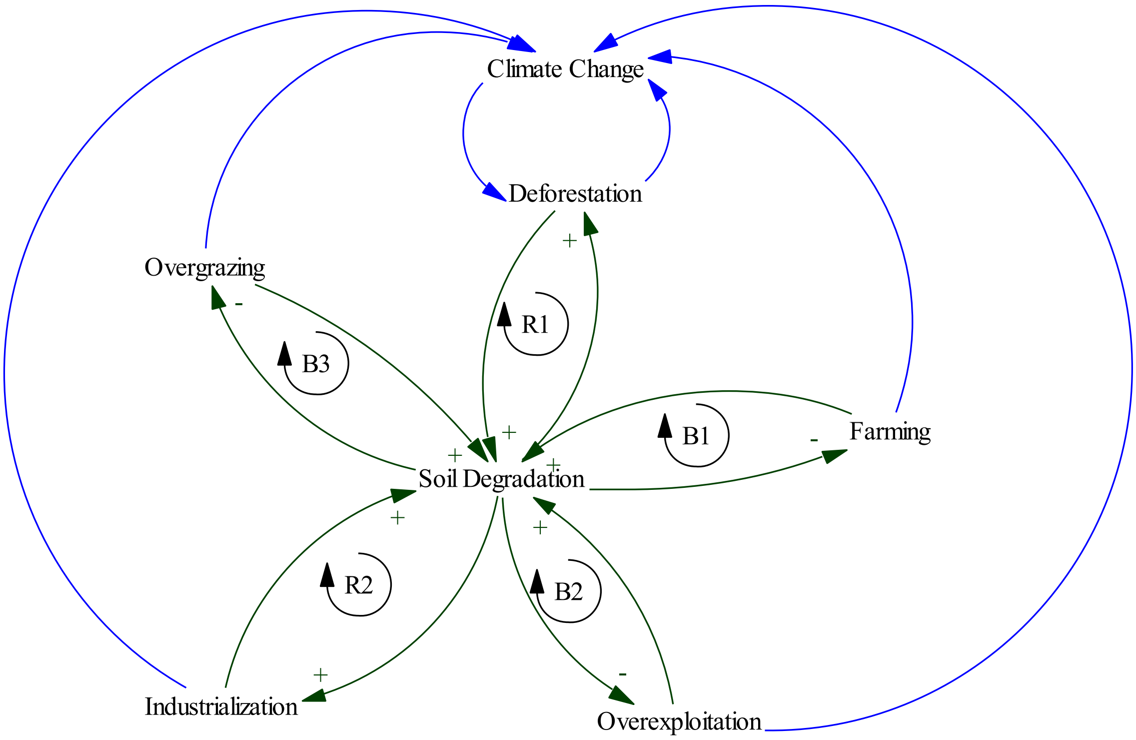

Figure 1. Causal loop diagram of soil degradation with emphasis on climate change

CONCLUSION

In this research, qualitative system dynamics method was used to model soil degradation. Considering the factors of soil degradation, which are all related to the increase in population, increase in the level of human well-being, and consequently climate changes, things like planting more vegetation, practicing better agricultural methods, and enforcing erosion control should be done to control soil degradation and soil protection and finally repairing it.

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Application of Artificial Intelligence in the Development of Sustainable Concrete Materials: A Review

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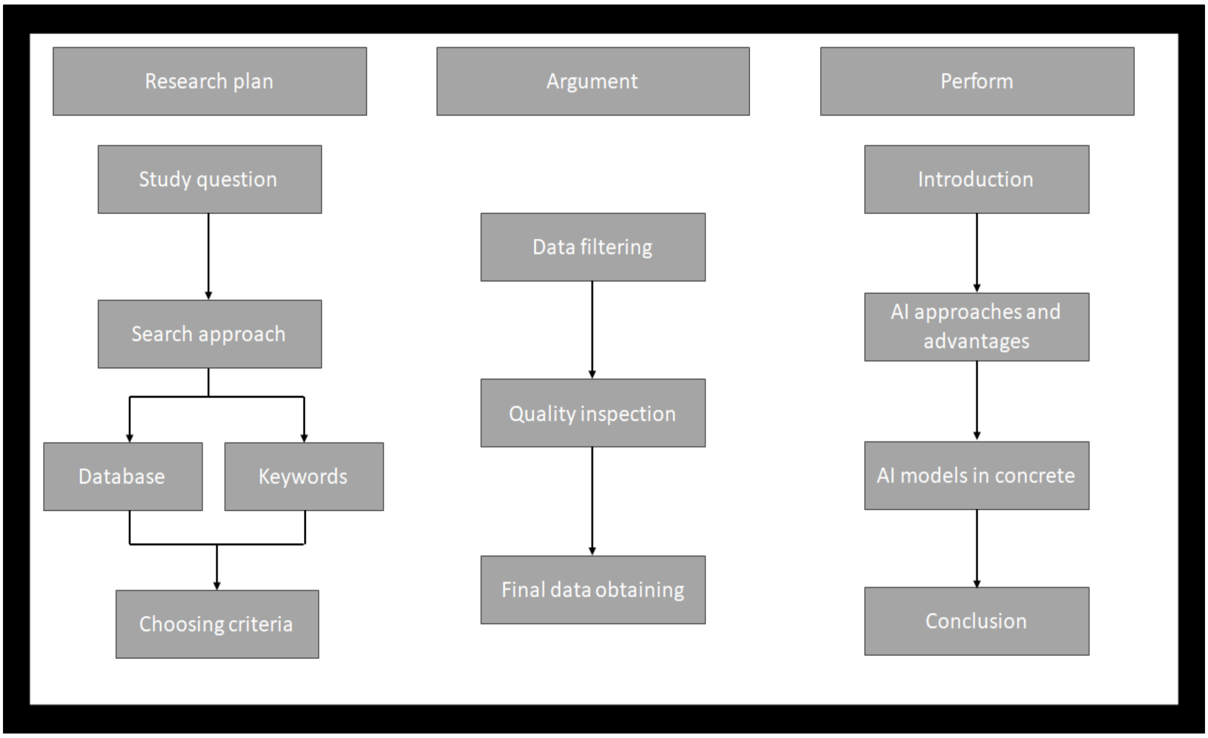
INTRODUCTION

Concrete is the second world's most frequently used material after water, which is produced from large amounts of ordinary Portland cement (OPC). The manufacture of OPC resulted in significant carbon dioxide (CO2) emissions [1, 2]. OPC manufacture reduces rare fossil fuel resources and consumes a lot of energy [3]. Burning fuels and losing natural resources will cause more environmental issues in the construction sector [4]. Therefore, supporting sustainable development in the building sector is crucial for reducing negative environmental impacts [5-7]. Artificial intelligence (AI)-based techniques are a suitable alternative for solving these issues since they provide a faster and more cost-efficient approach to assessing concrete than standard laboratory processes [8-10]. Machine learning (ML) is a subfield of AI that develops algorithms and models that can learn from information and make forecasts or judgments about it [11, 12]. It provides quick solutions for modeling complicated systems [13]. ML consists of three approaches, including supervised learning [14], unsupervised learning, and reinforcement learning [15]. Supervised learning is widely utilized in the area of concrete strength forecasting. Deep learning (DL) is a subtype of machine learning that concentrates on multiple-layer neural networks [16, 17]. DL strategies aim to automatically understand data elements and meanings, making them beneficial for complex tasks such as image identification, natural language processing, and concrete strength forecasting [18, 19].

MATERIALS AND METHODS

Increasing production of cement and concrete is leading to a detrimental influence on the environment. Make a construction cement-based material with sustainable aims makes this hypothesis to use AI approaches. This comprehensive review is focused on the AI approaches like ML and DL in the production of concrete and cementitious materials. Utilized algorithms such as artificial neural networks (ANN), decision trees (DT), support vector machines (SVM), etc. were assessed to aim to predict and optimize different properties of concrete materials. The study's data was obtained from various reliable databases like ScienceDirect, Scopus, Google Scholar, and ResearchGate in the last 15 recent years. The keywords of the study included "AI," "ML," "DL," "Sustainability," "Concrete," and "Cement." Data was collected using criteria that were appropriate for the scope and aims of the current study. Furthermore, quality inspections and filterings were done on the collected published papers to exclude any unnecessary or fraudulent data and ensure the validity of the data included in this research.



RESULTS AND DISCUSSION

ML is useful in terms of material characterizations, mix design development, fresh properties, hardening and hardened properties, durability, and crack detections [20]. Performance indicators are determined to assess each model's efficiency. This information, also referred to as model metrics, indicates the model's accuracy in different situations involving the test dataset. These parameters, including coefficient of determination (R^2), mean square error (MSE), root mean square error (RMSE), mean absolute error (MAE), and mean absolute percentage error (MAPE), etc., are commonly utilized. AI different models like ANN, SVM, DT, ANFIS, etc. illustrated in Table 1 to evaluate the mechanical properties of various concretes. The data utilized to construct these models is classified as distinct sources. Some are gathered in the lab, while others are obtained from the literature.

Table 1. Application of AI to forecast mechanical characteristics

Concrete type	Property	ML model	Data base	Assesement index	Reference
Self-compacting concrete	Compressive strength (CS)	ANN with several optimizers	301	R^2, RMSE and MAE,WMAPE, PI,VAF	[16]
High performance concrete	CS	ANN, ANFIS	2817	R^2, RMSE, MAE, SI	[12]
Normal concrete	CS	ANN, DT, SVM and ,Linear Regression (LR)	522	R2	[14]
Geopolymer concrete	CS	BPNN, SVM	110	RMSE, R^2, MAE,MSE	[13]
Recycled aggregate concrete	CS	ANN, CNN, SVM	74	R, RE	[15]
Ultra high performance concrete	CS	XGB	309	R^2, RMSE, MAPE, MSE	[17]
Foamed concrete	CS	ELM, LSSVR, M5-Tree	91	R, RMSE, MAE, Relative RMSE, Relative MAE	[18]
Steel fiber reinforced concrete	Tensile strength (TS)	SVM	980	R, R^2, MAPE, MAE, RMSE	[10]
Lightweight concrete	CS	BPNN	90	R^2, RMSE, MSE, akaika information criteria (AIC)	[19]

CONCLUSION

AI models showed great accuracy in predicting the mechanical characteristics of various concrete mixes. The precision of ML forecasting approaches is strongly dependent on the performance of learning algorithms and the accuracy of training datasets. ANNs are a popular and effective method for predicting mechanical features in all concrete categories, in spite of their large training data needs. Hybrid ANN and SVM models have the most accuracy and quality to forecast concrete strength. However, they raise estimation time; using these kinds of models in large databases with sufficient choosing features gives the most accurate outcomes.

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Assessment of Tree Trunk Patches as Protective Measures Against Debris Flow Hazards

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INTRODUCTION

Debris flows are a type of mass wasting event that happen when a mixture of water, soil and rock rapidly moves down a slope (Lei et al., 2018). These flows can cause significant damage to structures located in their path, including rigid walls. In recent decades, many research studies have been done to understand, assess and eventually reduce structural exposure and vulnerability (Cui et al. 2015; Yang et al. 2021; Yan et al. 2023; and Ahmadian and Türker, 2024). Recently, interest has been increasing in the study of tree trunks or vegetation in debris flow disasters to dissipate debris flow energy on their paths. The presence of the tree trunks increases the debris flow resistance, supports the deposition of debris, and most importantly, reduces the maximum impact forces on structures (Fidej et al., 2015).

In the present work, an analytical investigation and a numerical evaluation are conducted to determine the maximum impact pressure of debris flow over a rigid vertical wall, right after passing through different configurations of patches of tree trunks.

MATERIALS AND METHODS

To assess the peak impact pressure caused by debris flow against a rigid wall, the density of tree trunks (λ) increased within a predefined area in both linear and rectilinear configurations as shown in Figure 1.

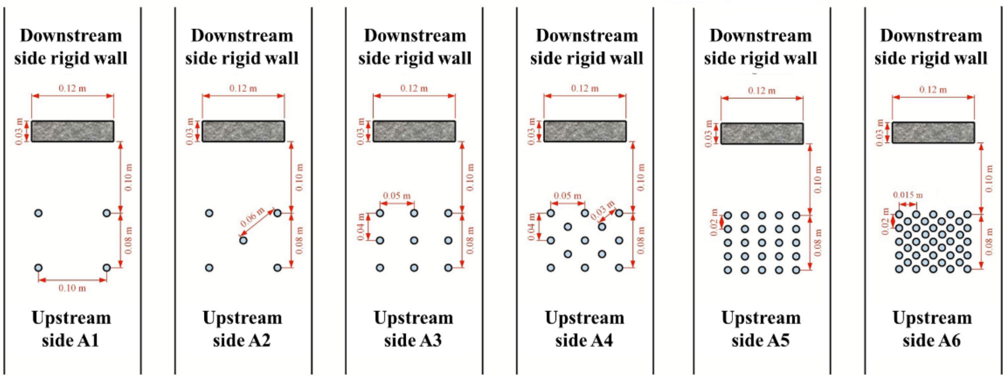

Figure 12: The top view of the six different linear and rectilinear patches of tree trunk arrangements for models (A1, A2, A3, A4, A5 and A6)

The cylinder with a 1 cm diameter and 14 cm height is placed on the flume. The cylindrical diameter and height are sourced from Cost (1979). Tree trunk density can be obtained as the ratio of the projected rigid tree trunks plan area to the total volume. The solid volume fraction is the ratio of the areal coverage of the tree trunk elements to the portion of measuring area covered by tree trunk elements previously defined by Türker et al., (2006). All values are presented in Table 1.

Table 7: Properties of tree trunk patch configurations, densities and the solid volume fraction.

Model						
`	*Tree trunk arrangement*	Horizontal distance on measuring plane ΔX (cm)	Vertical distance on measuring plane ΔZ (cm)	Tree trunk distance s_i (cm)	Solid volume fraction (ψ) %	Tree trunks density λ (m^{-1})
A1	Linear	10	8	10	1	1.3
A2	Rectilinear	10	8	6	1.96	2.8
A3	Linear	10	8	5	3.9	4
A4	Rectilinear	10	8	3	7.8	11.1
A5	Linear	10	8	2.5	15.7	16
A6	Rectilinear	10	8	1.5	31.4	44.4

To measure the debris flow impact pressure, 18 measurement points were selected over the wall. Measurements were performed at different vertical heights: 1.5 cm, 4.5 cm, 7.5 cm, 10.5 cm, 13.5 cm, and 16.5 cm from the bottom of the rigid wall.

RESULTS AND DISCUSSION

Figure 2 exhibits the front view impact pressure distribution along the rigid wall. It can be seen that the maximum impact pressure is concentrated in between 4.5 to 10.5 cm above the bottom of the rigid wall. As the tree trunk densities increased, independent of linear or rectilinear configurations of tree trunks, the effect of impact pressure decreased. When the maximum impact pressure at A1 are compared with the max impact pressures at A6, a reduction of 67.3%, 69.5% and, 70% in maximum pressures are observed at S4, S3, and S2, respectively. Another important observation is the increase in the depth of flow in parallel to the increase of solid volume fraction. Due to the velocity retarding effect (drag force effect) of the tree trunks, the velocity of debris flow experienced a reduction of 4.6 to 2.5 m/sec along the flow direction.

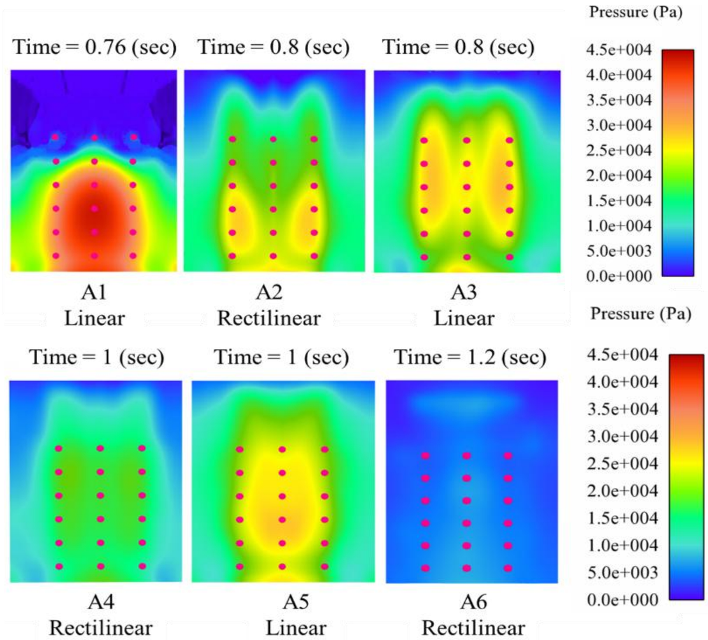

Figure 2: The pressure distributions in the 18 measurement points on the rigid wall with various tree trunks density (1.3, 2.84, 11.1, 16 and 44.4, m^{-1}) and solid volume fractions (0.98, 1.96, 3.9, 7.8, 15.7 and 31.4, %)

Based on the principles of continuity, a decrease in velocity increases the flow area, which in turn increases the depth of the debris flow. The depth ascended from 14 cm to 25 cm. In addition, the retarding effect of tree trunks on the occurrence time of peak impact pressures depicted 58% shift in the occurrence time of peak impact pressures.

CONCLUSION

In this study, the rectilinear configuration of tree trunks in a given spot area performed well in reducing the debris flow pressure over the wall than linear configurations. It can be seen that the peak impact pressure concentration was randomly distributed over the wall. The variation of impact pressure concentration is similar to the damaged regions of the wall. There is a relatively high impact pressure region over the wall from S1 to S4 in A1 (linear model). Increasing the tree trunk arrangements from A2 to A6 gradually reduces the effect of peak impact pressure and extends its effect to a larger area.

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Foundation Improvement by Using Micro-piles in Tuzla Region

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INTRODUCTION

Micropiles are one of the effective techniques used to increase the bearing capacity and reduce the settlement, particularly in strengthening existing foundations. In the current study;

Two borehole data in Tuzla region #10 and #34 (Lakayan, 2012) have been used, for the investigation settlement reduction of the foundation with the application of micropiles, for each soil profile region. Soil layers according to the boreholes data have been modelled and investigated by using Plaxis 3D software. Total 7 model were created for each borehole and settlement reduction of the building calculations were carried out in Plaxis 3D. The results indicate that ultimate reduction settlement of the foundation with micro-piles 300mm diameter with length of 9m at the borehole #10 region is 27.9% and at the borehole #34 region is 29.5%. Generally, as the length of micro-piles increase settlement decreased, and also as the diameter increased settlement also decreased.

METHOD

Two borehole data in Tuzla region #10 and #34 (Lakayan, 2012) have been used, for the investigation settlement reduction of the foundation with the application of micropiles, for each soil profile region. Table 1. shows the layer details of boreholes #10 and #34. The borehole locations in WGS84 (World Geodetic System dating from 1984 and last revised in 2004) coordinate system (BH-10 3891697.36(N)/ 581431.44(E) and for BH-34 3891355.36(N)/ 582699.44(E).)

Soil layers according to the boreholes data have been modelled and investigated by using Plaxis 3D software. For each region a typical 10m x 10m square mat foundation without micropiles, and with 9 micropile with 4m separation (Fig.1) were used in calculations. Micropiles two different diameters 200mm and 300mm, and with 3 different lengths of 3m, 6m and 9m were used. For each region a typical 10m x 10m square mat foundation thickness 0.6m and 4 columns 0.6mx0.6m section with 3.5m length supporting a rigid slab 0.30m thickness (Fig.2.), 40kPa surcharge is applied over the mat foundation and 20kPa surcharge over the slab.

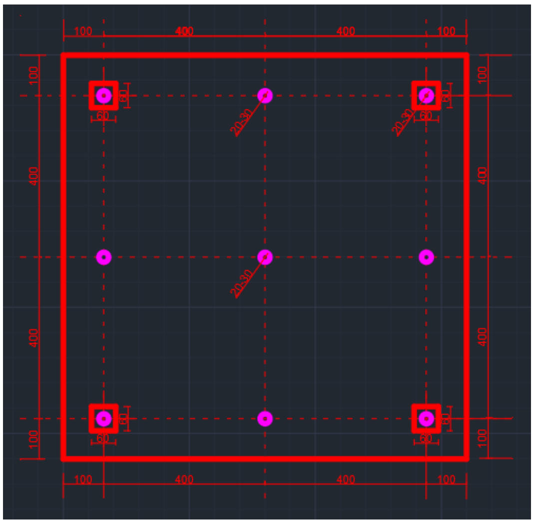

Fig.1. Micropile configuration.

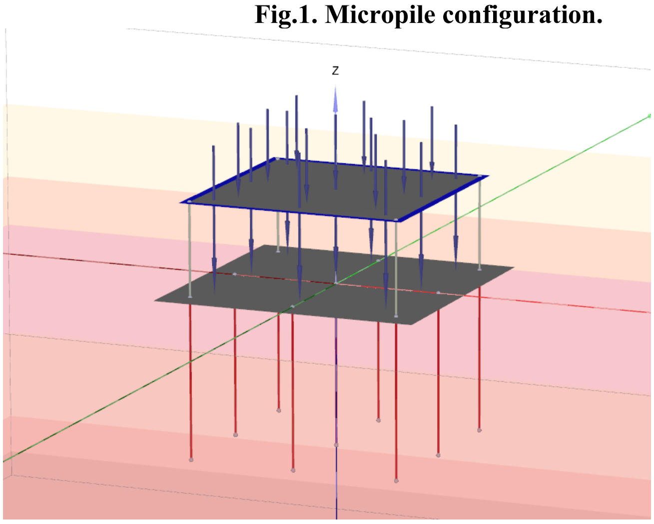

Fig. 2. Plaxis 3d building model

Depth1	Depth2	Soil type	Void Ratio	Dry Unit Weight	Saturated Unit Weight	Young's Modulus	Friction Angle	Undrained Shear Strength of Clay/Silt	Shear Wave Velocity	Shear Modulus	Dilatancy Angle	Poisson Ratio	Permeability
			e	γ_{dry}	γ_{Sat}	E_s (MPa)	φ (°)	S_u (kPa)	V_s (m/s)	G_{max} (kPa)	ψ (°)	ν	k (cm/s)
0	3	CH	0.93	14	18.9	17.3	---	41	194	47	0	0.31975	10^{-7}
3	5	SM	0.88	13.9	18.6	9.2	28.15	---	114.5	40.5	0	0.14725	10^{-3}
5	9.5	CL	1.04	13.3	18.4	9.2	---	14	114.5	48.5	0	0.29275	10^{-7}
9.5	13	CH	1.03	13.4	18.5	9.8	---	16	123	59	0	0.313	10^{-7}
13	14.5	SM	0.71	15.3	19.4	61	45	---	412	146	15	0.4	10^{-3}
14.5	15.5	LS	0.07	23.3	24	76.7	44.7	---	466	198	14.7	0.3955	0

Depth1	Depth2	Soil type	Void Ratio	Dry Unit Weight	Saturated Unit Weight	Young's Modulus	Friction Angle	Undrained Shear Strength of Clay/Silt	Shear Wave Velocity	Shear Modulus	Dilatancy Angle	Poisson Ratio	Permeability
			e	γ_{dry}	γ_{Sat}	E_s (MPa)	φ (°)	S_u (kPa)	V_s (m/s)	(G_{max}) kPa	ψ (°)	ν	k (cm/s)
0	0.5	OS											
0.5	6.5	SM	0.82	14.2	18.7	26.7	42.95	---	233.5	65.5	12.95	0.36925	10^{-3}
6.5	8.5	ML	0.79	14.8	19.2	9.8	---	16.00	123	140	0	0.25675	10^{-4}
8.5	13	SM	0.79	14.5	18.9	29.2	41.6	---	247	88	11.6	0.349	10^{-3}
13	15	LS	0.07	23.3	24	76.7	44.7	---	466	198	14.7	0.3955	0

Table. 1. The output of approximating Borehole #10 & #34 data by NovoSPT.

RESULTS AND CONCLUSION

Numerical analyze results indicate that ultimate reduction settlement of the foundation with micro-piles 300mm diameter with length of 9m at the borehole #10 region is 27.9% and at the borehole #34 region is 29.5%. Generally, as the length of micro-piles increase settlement decreased, and also as the diameter increased settlement also decreased. As the micro-piles rigidity increases the percentage of reduction in settlement increases.

Different micropile patterns can be worked, pile space and diameter ratio (S/D), pile length to diameter ratio (D/L) can be a different parameters, and their effect on bearing capacity and settlements of the foundation analysis will be interesting, also dynamic effect of the micropiles, their behavior during earthquake gain more important in earthquake zones which Tuzla is a critical region in this aspect.

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Nakamura Method Applications for Specific Sites in Cyprus

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INTRODUCTION

The Nakamura method (HVSR) has been developed as a single station method within the environmental vibration analysis to evaluate the frequency of resonance at a site. The H/V spectral ratio (HVSR) function was defined by Nakamura as the Quasi-Transfer Spectrum (QTS) (f), also known as the approximate soil transfer spectrum. In this method ambient vibrations in 3 directions (NS, EW, Z) are being recorded with a kind of seismometer. The ambient vibrations as we called microtremors have amplitude values vary between 0.1 and 1 micron. Microtremors with short periods have periods of 1s or less and are used to determine the amplification and period properties of shallow soil layers. Long-period Microtremors, on the other hand, provide information about the amplification and period characteristics of deep layers down to the engineering bedrock and whose vibrations are greater than 1 second. It refers to deeper soil layers like rigid rock formation and performed with natural forces such as wind and underground seismic activities. Therefore, Microtremor Nakamura Method applications carried out for obtaining Quasi Transfer Spectrums (QTS) in different specific sites of the island.

HVSR METHOD AND DATA COLLECTION

Nakamura Technique (HVSR method) is known as the method that gives the closest value to the amplification values that occur during an earthquake with the most accurate approach (Ansary & Rahman, 2013). Certain assumptions are made for the Nakamura (1989) method. These are generally: Microtremors are formed by the combination of different seismic waves; but especially by Rayleigh waves propagating in the surface alluvium layer located on the massive engineering bedrock. The noise effect of the Rayleigh wave (Erw) is in the vertical spectrum (Vs) at the surface of the layer, but is not included in the vertical component at the bottom of the layer (Vb) (Özyankı, 2015).

It is given by the H/V spectral ratio (HVSR);

$$\text{HVSR} = \sqrt{\frac{NS^2+EW^2}{Z^2}} \qquad [1]$$

In Eq. (1), H/V is the horizontal over vertical spectrum ratio, NS is the N-S component's amplitude spectrum, EW is the E-W Component's amplitude spectrum, and Z is the vertical component's amplitude spectrum.

In addition Teves-Costa approach can supply preliminary information about the thickness of the soil (Teves-Costa et al., 1996). For this consideration, the predominant soil period (T0) has been known as;

$$T_0 = \frac{4H}{V_S} \qquad [2]$$

In Eq. (2), H represents the soil layer thickness and Vs is known as shear wave velocity in this equation (Dindar et al., 2021). In the microtremor study, a 3-axis Raspberry 2513 recorder with N-S, E-W and Vertical axes was used. Microtremor study was conducted to find predominant soil period values with a minimum recording length of 30 minutes. Sampling interval was selected as 100 Hz, selected window number as minimum 10, window Length as average 80.92 s for data evaluation.

RESULTS AND DISCUSSION

As a result of microtremor studies, according to the observational Quasi Transfer Spectrum values, since the predominant soil period (T0) values are To>1 sec., the seismic impedance changes within the engineering bedrock affected the spectrum and created peak amplitude values surpassed 2 amplitude (H/V) values (Table 1). According to the Teves-Costa (1996) approach, it was determined that the soil thickness at the measurement stations were generally 30 m or thicker, according to the assumption of T0>1s.

Table 1. Nakamura method calculated parameters.

	H/V	T_0(S)	F_0(HZ)
M1	2,19	1,03	0,97
M2	3,87	1,75	0,57
M3	4,85	0,89	1,13
M4	4,25	1,45	0,69
M5	5,6	0,22	4,5

CONCLUSION

Peak amplitude and peak period changes evaluated from Quasi Transfer Spectrum (assumed soil transfer function) emphasize that there may be seismic impedance changes starting from the seismic bedrock boundary. In-situ measurements with microtremor method will be provide a better understanding to create a correct soil-structure relation before a massive earthquake shock.

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Chapter 4. Sustainability, Goals and Barriers

Optimizing Technology Integration in SME Construction Supply Chains: A Framework for Enhancing Procurement Processes

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INTRODUCTION

Materials procurement in the construction sector represents a complex and multifaceted challenge, particularly for small and medium-sized enterprises (SMEs). The intricate nature of materials purchasing processes can significantly impact project outcomes, and recent research, notably the study "Understanding the Complexity of Materials Procurement in Construction Projects to Build a Conceptual Framework Influencing Supply Chain Management of MSMEs" (Donyavi et al., 2023), has underscored the critical role that effective supply chain management plays in ensuring project success. Given that materials can constitute up to 70% of total project costs, any inefficiencies or delays in the procurement process can lead to substantial financial ramifications, hampering not only individual projects but also the long-term viability of SMEs within the construction industry (Saidi & Donyavi, 2022).

A pivotal finding from previous research highlights the stark contrast in operational capabilities between large construction firms and SMEs. Large firms typically leverage integrated information technologies that allow for streamlined procurement processes, encompassing everything from order placement to on-site delivery. In contrast, SMEs—which account for over 90% of construction enterprises globally (Ala-Risku & Karkkainen, 2006)—often operate with constrained resources and limited capacity to adopt similar technological frameworks. This gap in operational capability means that SMEs are frequently burdened by challenges such as delays in material delivery, miscommunication between suppliers and site managers, and overstocking, all of which stem from the absence of standardized procurement procedures (Bell & Stukhart, 1986; El-Haram & Horner, 2003).

To address these challenges, the initial study proposed a conceptual framework aimed at improving the procurement efficiency of SMEs. This framework delineates the procurement process into key stages: input, purchasing, tracking, data management, and feedback (Clough et al., 2000). By breaking down the procurement process into these essential components, the framework seeks to clarify the steps involved in ordering materials, tracking their movement, and utilizing feedback to optimize future orders. Despite the promise of this structured approach, the research identified a significant barrier: the limited adoption of technology among SMEs, which hampers their ability to achieve greater efficiency in materials management (Navon & Berkovich, 2006).

Addressing this technological gap is not only vital for improving operational performance but also essential for enhancing the overall competitiveness of SMEs in the construction sector. Building on the insights from the first study, this paper aims to advance and apply the conceptual framework developed previously by exploring how advanced technologies can be effectively integrated into each stage of the materials procurement process for SMEs. The integration of technologies such as Radio Frequency Identification (RFID) for real-time tracking, digital databases for improved data management, and mobile communication tools to facilitate coordination between suppliers and construction sites has the potential to revolutionize how SMEs manage their materials procurement (Hadikusumo et al., 2005). For instance, RFID technology can enable precise tracking of materials from the point of order to on-site delivery, significantly reducing the risk of delays and inaccuracies (Proverbs & Xiao, 2002).

Furthermore, this research will assess the practical application of these technologies within the context of SMEs, drawing on real-world case studies and on-site observations to evaluate the impact of technology-enhanced procurement processes (Saidi & Donyavi, 2022). By investigating how these technological solutions can be implemented effectively within the existing framework, the study aims to provide comprehensive insights into the potential benefits, including increased efficiency, reduced lead times, and lower costs associated with materials procurement. This research is also informed by broader studies of innovative strategies and approaches to enhancing operational efficiency in related fields, where the introduction of new methodologies and technologies has led to significant improvements in resource allocation and performance (Bevilacqua et al., 2017; Cantafio & Parisi, 2021; Parisi & Biancuzzo, 2021).

The specific objectives of this study are threefold:

1. Evaluate the Impact of Technology Integration: This objective focuses on investigating how technologies like RFID, digital databases, and mobile applications can enhance the accuracy and efficiency of each stage of the materials procurement process, from initial order placement to on-site delivery and usage. The analysis will explore how these technologies can improve real-time visibility into inventory levels and material movements, enabling SMEs to make informed decisions quickly.
2. Identify Practical Barriers to Adoption: Understanding the practical challenges that SMEs face in adopting these technologies is crucial. This study will delve into various barriers, including the costs associated with technology implementation, the need for training and skill development, and potential disruptions to established operational processes (Donyavi et al., 2023). By identifying these challenges, the research aims to provide actionable recommendations for overcoming them.
3. Demonstrate Efficiency Gains: This study will assess the potential improvements in time management, reduction in material wastage, and enhanced coordination between suppliers and project sites as a result of integrating technology into the procurement framework. By analyzing case studies that highlight successful technology integration, the research will showcase tangible benefits that SMEs can achieve, thereby encouraging broader adoption of these technologies within the construction sector (Christopher, 1992). Drawing parallels with other industries, where technology adoption has driven local economic growth and improved operational efficiency (Cantafio & Parisi, 2021; Parisi et al., 2020), this study aims to present a clear case for why SMEs in construction should embrace technology.

By addressing these objectives, this study seeks to provide a practical roadmap for SMEs to enhance their materials procurement processes through technology, ultimately contributing to greater productivity and competitiveness in the construction sector. The insights garnered from this research will not only help SMEs improve their operational efficiency but also position them better to compete in a rapidly evolving market that increasingly demands innovative approaches to procurement and supply chain management.

METHODS

Conceptual Frameworks in Construction Supply Chains

The management of materials procurement in the construction sector is a pivotal area of study, with direct implications for project outcomes, cost control, timelines, and overall productivity. Effective materials management ensures that materials are available when needed, minimizes waste, and aligns with project specifications. Various models and frameworks have emerged to streamline the construction supply chain, focusing on enhancing the coordination of materials flow, facilitating information exchange, and integrating procurement activities (Cox & Chicksand, 2005; Sweeney & McGowan, 2007). These frameworks aim to address the inherent complexities and inefficiencies present in traditional procurement practices.

One of the foundational concepts in construction supply chain management is supply chain integration, which emphasizes a seamless flow of materials and information between suppliers, contractors, and site managers. As highlighted by Lambert et al. (1998) and Christopher (1992), effective integration enhances alignment between supply and demand, significantly reducing delays and ensuring materials are available at the right time. This is particularly relevant for small and medium-sized enterprises (SMEs) in construction, which often struggle to achieve such integration due to limited resources and inadequate management systems (Croom, 2000). The challenges faced by SMEs necessitate tailored frameworks that consider their unique operational realities.

In previous research, a structured framework specifically designed to meet the needs of SMEs was introduced, breaking down the materials procurement process into five key stages: input, purchasing, tracking, data management, and feedback. This framework provides SMEs with a clear roadmap for managing materials effectively, reducing redundancies, and enhancing supplier coordination. Unlike traditional models that predominantly focus on larger enterprises, this approach emphasizes practical solutions for SMEs, acknowledging challenges such as the absence of dedicated procurement teams and the reliance on manual processes (Donyavi et al., 2024).

Technology in Construction Materials Management

The adoption of technology has emerged as a critical driver for enhancing materials management and procurement efficiency within the construction sector. Technologies such as Radio Frequency Identification (RFID), Global Positioning Systems (GPS), and digital data management systems have been extensively studied for their potential to improve tracking, inventory management, and information sharing among stakeholders (McKinney, 2010; Tsai et al., 2010).

1. **RFID Technology:** RFID technology allows for real-time tracking of materials, providing construction managers with the ability to monitor the flow of materials from suppliers to construction sites. Research conducted by Navon and Berkovich (2006) demonstrated that RFID systems can significantly reduce the time spent on manual tracking, enhance inventory accuracy, and minimize material loss or theft. However, the adoption of RFID remains limited among SMEs, primarily due to concerns regarding high upfront costs and implementation complexities.
2. **GPS and Geolocation Tools:** GPS technology further enhances logistics management by offering precise location data for material deliveries. Studies by Donyavi et al. (2011) have shown that GPS can assist SMEs in optimizing delivery routes and reducing transportation costs. Despite its advantages, many SMEs still rely on

traditional methods such as manual logs for tracking shipments, highlighting a gap in the effective integration of GPS systems.

3. **Digital Data Management Systems:** The implementation of digital databases and cloud-based solutions can greatly streamline procurement activities, providing centralized access to order records, delivery updates, and supplier information. Improved data management facilitates better communication between SMEs and suppliers, leading to more accurate material forecasts and reduced risks of over-ordering or under-supplying. Nevertheless, challenges such as data security concerns and the need for staff training hinder many SMEs from fully adopting these technological solutions (Mao et al., 2013).

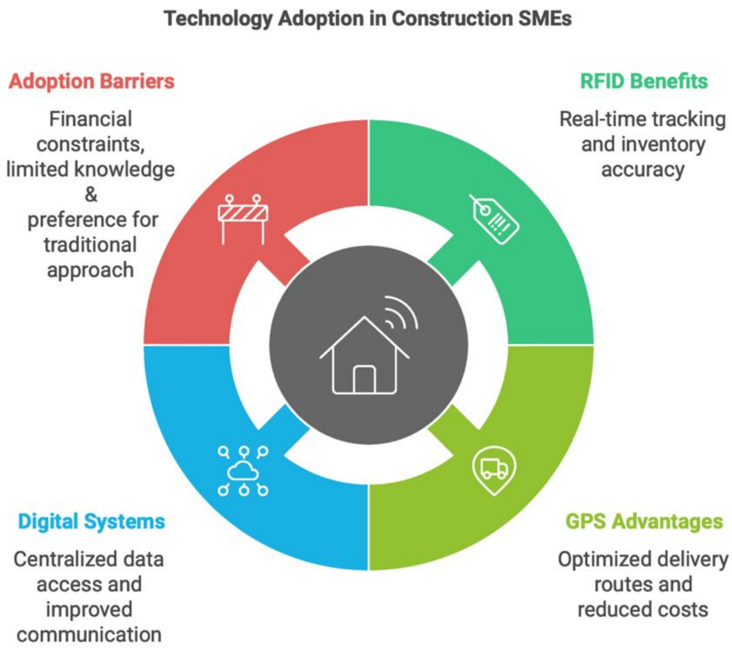

Figure 1: Technology in Construction

While the potential benefits of these technologies are substantial, their adoption among SMEs remains limited due to financial constraints, limited technological knowledge, and a preference for traditional, manual approaches to materials management. Addressing these barriers is essential for promoting technology adoption and improving procurement processes within the construction sector.

Importance of Structured Purchasing Processes

A structured purchasing process is crucial for SMEs as it streamlines operations, minimizes waste, and enhances overall project efficiency. Effective purchasing ensures that materials are ordered accurately, delivered timely, and used efficiently, thereby avoiding costly delays and budget overruns, which are prevalent in construction projects (Pérez-Foguet et al., 2008).

The previously proposed framework for structuring the purchasing process includes several key steps:

1. **Input Specification:** Clearly defining material requirements to ensure accuracy in orders.
2. **Purchasing Coordination:** Establishing effective communication channels with suppliers to confirm orders and manage delivery schedules.

3. **Tracking:** Utilizing basic tracking tools to monitor shipment statuses and ensure timely deliveries.
4. **Data Management:** Implementing simple digital tools to maintain records of purchases, deliveries, and material usage.
5. **Feedback Mechanisms:** Creating feedback loops to adjust future orders based on real-time data and insights from past projects.

This structured approach enables SMEs to overcome common challenges in materials procurement, including poor forecasting, supplier miscommunication, and inefficient material usage. Research conducted by Green et al. (2005) suggests that structured procurement processes lead to significant improvements in supply chain performance by minimizing errors and enhancing the visibility of material flows.

Figure 2: Structured Purchasing Processes

Adopting a systematic approach to materials management allows SMEs to gradually integrate technological solutions into their operations, facilitating a smoother transition from traditional methods to digital tools. The literature also indicates that structured processes can enhance the competitiveness of SMEs by improving their ability to meet project deadlines and maintain stronger relationships with suppliers (Thun & Hoenig, 2011).

Framework for Materials Purchasing Process

An Overview of the Framework

The framework for materials purchasing, developed in previous research, is designed to optimize the procurement processes for small and medium-sized enterprises (SMEs) in the construction sector. Recognizing the unique challenges faced by SMEs—including limited resources, lack of systematic approaches, and inefficiencies in supplier communication—this framework provides a structured pathway to enhance purchasing practices. By integrating technology, the framework aims to improve visibility, coordination, and decision-making throughout the materials procurement lifecycle. The key components of the framework are categorized into five stages: Input, Purchasing, Tracking, Data Management, and Feedback.

A. **Input: Identification of Materials and Initial Data Requirements**

The input stage serves as the foundation of the procurement process, where the types and quantities of materials required for a construction project are clearly specified. Accurate identification is crucial, as miscalculations can lead to material shortages or surpluses, ultimately inflating project costs (Ala-Risku & Karkkainen, 2006; Borcherding et al., 1980). SMEs often grapple with unpredictability in project conditions and fluctuating client demands, which complicates accurate forecasting. To mitigate these challenges, the framework encourages the adoption of user-friendly digital tools—such as spreadsheets or simple database systems—to systematically gather and update data regarding material requirements as project plans evolve. Clear communication between site managers and procurement teams is emphasized to ensure that input specifications reflect the real-time needs of the construction site (Agapiou et al., 1998).

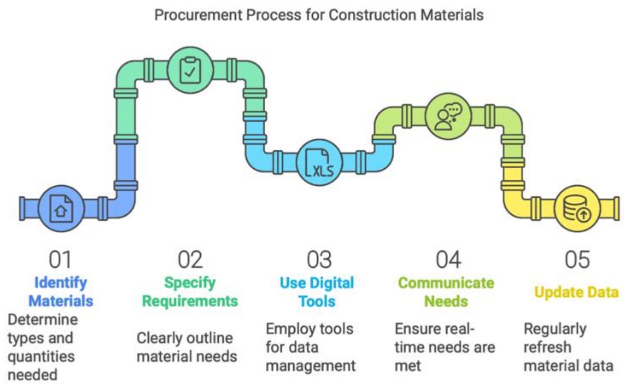

Figure 3: Input: Identification of Materials and Initial Data Requirements

B. Purchasing: Stages from Order Placement to Confirmation

In the purchasing phase, SMEs navigate the critical steps of selecting suppliers, negotiating terms, placing orders, and confirming delivery schedules. Establishing strong supplier relationships is essential for securing timely deliveries at competitive prices (Thomas & Napolitan, 1995).

The framework advocates for a structured order placement process, incorporating standardized procedures for requesting quotes, evaluating supplier capabilities, and finalizing contracts. This structured approach minimizes delays and ensures optimal value in material purchases. Additionally, utilizing digital communication tools, such as email templates for orders and digital tracking of purchase orders, streamlines this process, facilitating the management of multiple suppliers and ensuring timely order confirmations (Donyavi et al., 2024). The various challenges highlighted in Figure 1 illustrate the complexities involved in the ordering process, resulting in time, cost, and information losses that contribute to unproductive and inefficient materials management.

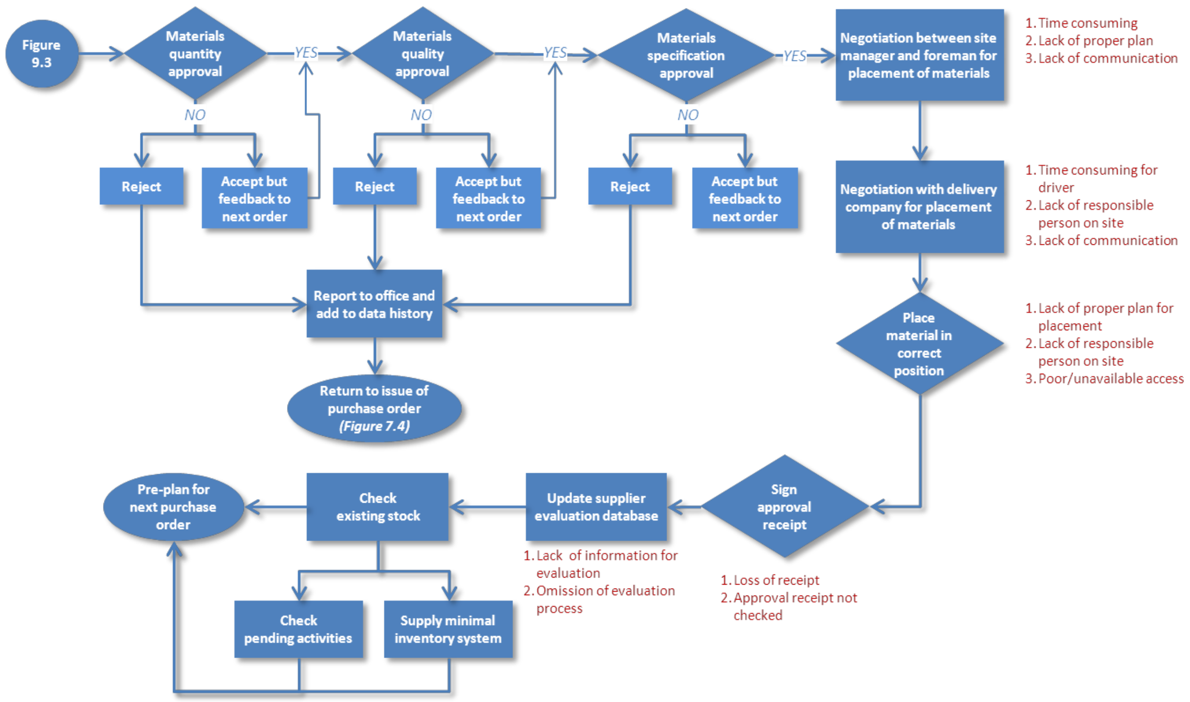

Figure 4: Ordering Process and Challenges Faced by SMEs After Delivery. Source: Authors' elaboration, 2024.

C. Tracking: Monitoring Material Movement from Suppliers to the Construction Site

The tracking phase is vital for ensuring that materials are delivered as scheduled and in the correct quantities. Delays or mis deliveries can substantially disrupt project timelines (Navon & Berkovich, 2006).

The framework highlights the potential of technologies like RFID and GPS for real-time tracking of shipments. While larger enterprises typically implement such technologies, many SMEs face barriers related to cost and training. The framework suggests that even basic tracking methods, such as GPS-enabled mobile apps, can significantly enhance visibility and control over material movement. To accommodate varying levels of technological comfort, this component of the framework is designed to be adaptable, enabling SMEs to scale their tracking capabilities incrementally as they gain familiarity with digital tools.

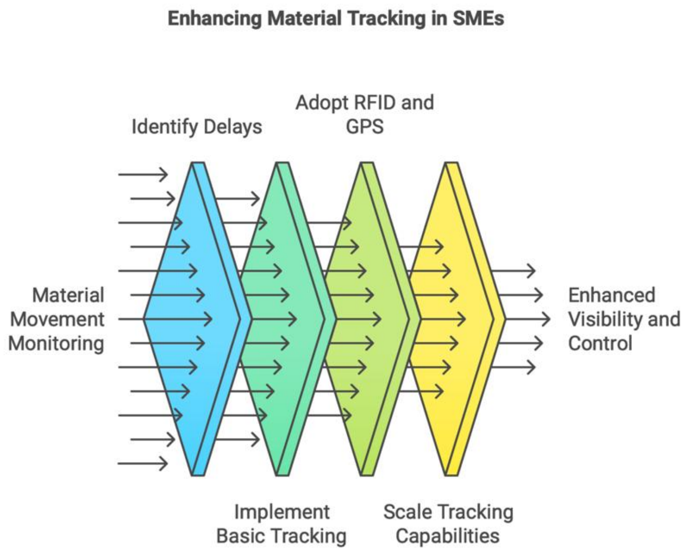

Figure 5**: Tracking Monitoring Material Movement from Suppliers to the Construction Site**

D. Data Management: Handling Procurement Data, Including Order Records and Delivery Updates

Effective data management is the backbone of the proposed framework, requiring meticulous maintenance of records concerning purchase orders, delivery schedules, and inventory levels. Ensuring that all stakeholders have access to current information about material statuses is paramount (Donyavi et al., 2022).

Research indicates that many SMEs struggle with data management due to their reliance on paper-based systems. To combat this issue, the framework promotes the transition to cloud-based databases, which offer accessible, real-time data updates, thereby enhancing coordination between office staff and site managers. Digital platforms not only reduce error risks but also enable better forecasting of material needs by analysing historical data trends, allowing SMEs to adjust purchasing strategies in line with project timelines and avoid last-minute orders that can derail workflows (Borcherding et al., 1980).

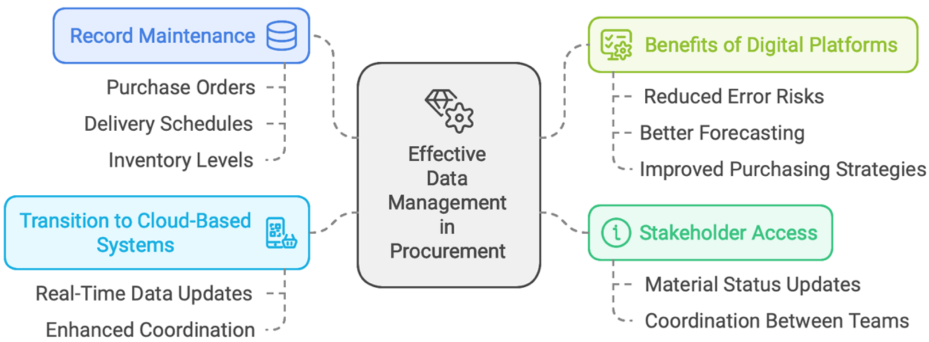

Figure 6: **Data Management**

E. Feedback: Mechanisms for Evaluating and Adjusting the Purchasing Process Based on Outcomes

The feedback component is integral for fostering continuous improvement in the materials purchasing process. SMEs are encouraged to review procurement strategies and outcomes after each project phase to identify areas for refinement (Bell & Stukhart, 1986).

Feedback mechanisms may include post-delivery evaluations with suppliers, assessments of material quality upon arrival, and internal debriefs to analyse whether purchased quantities aligned with actual usage. This iterative approach enables SMEs to pinpoint discrepancies and make necessary adjustments for future orders. The framework advocates utilizing digital survey tools or straightforward feedback forms to capture insights from site managers and suppliers, ultimately refining procurement processes and enhancing supplier relationships.

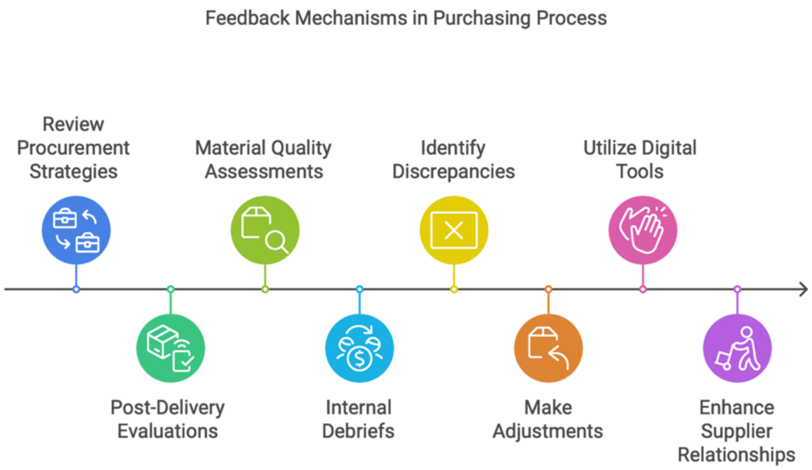

Figure7: **Feedback**

New Additions and Modification

In response to feedback from SMEs and the dynamic technological landscape, several refinements have been incorporated into the framework:

- **Enhanced Focus on Low-Cost Technology Solutions:** Recognizing the hesitance of many SMEs to adopt advanced technologies like RFID due to associated costs, the updated framework prioritizes affordable alternatives, such as mobile apps for tracking deliveries. This allows SMEs to initiate their technology integration with simpler solutions, providing a clear path for future upgrades as benefits become apparent.
- **Integration of Cloud-Based Platforms:** Addressing the difficulties SMEs face in maintaining up-to-date records with traditional paper systems, the framework now offers detailed guidance for transitioning to cloud-based databases. This shift centralizes procurement data, enhancing accessibility for all stakeholders and improving coordination between procurement teams and site managers (Ala-Risku & Karkkainen, 2006).

- **Streamlined Feedback Loops:** Highlighting the necessity for continuous learning, the refined framework emphasizes the creation of structured feedback loops. Digital survey tools are suggested to collect site managers' input after each delivery cycle, enabling SMEs to make informed adjustments to purchasing strategies and enhance supplier performance.
- **Simplified Implementation Guide:** Acknowledging that many SMEs may lack the resources for extensive training, the updated framework provides a step-by-step implementation guide. This practical guide offers tips for SMEs to gradually adopt the framework, beginning with basic digital tools and progressively integrating more advanced technologies, such as GPS-enabled tracking systems (Donyavi et al., 2024).

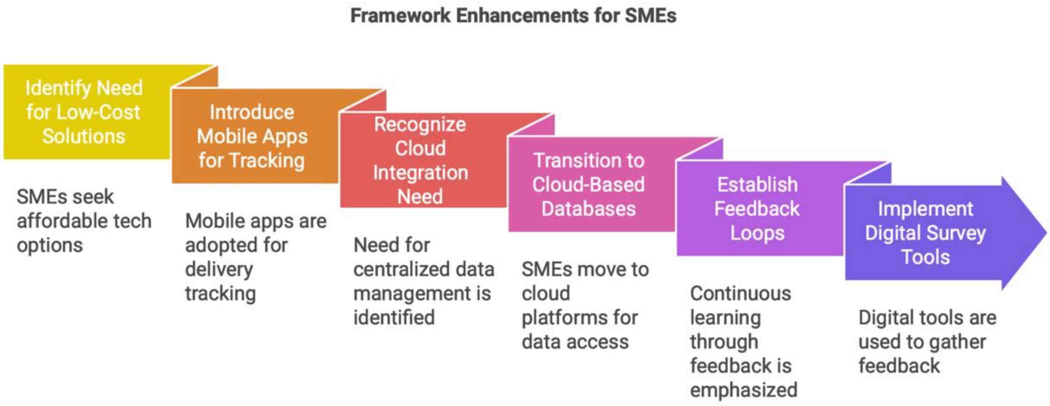

Figure 8: Enhancement for SMEs

These modifications ensure that the framework remains aligned with the needs of SMEs and the realities of the construction industry. By emphasizing gradual technology adoption and continuous improvement, the updated framework offers a sustainable pathway for SMEs to enhance their materials procurement processes and achieve greater operational efficiency.

Methodology

This study employed a qualitative research approach to evaluate the practical application of the materials purchasing framework developed for small and medium-sized enterprises (SMEs) in the construction sector. The emphasis on qualitative methods allowed for a rich, detailed understanding of the specific challenges and experiences of SMEs, which quantitative surveys might overlook. This approach facilitated an in-depth exploration of the interactions between SMEs and their materials procurement processes, particularly in relation to the integration of new technologies.

To gather comprehensive insights, semi-structured interviews were conducted with managers and procurement officers from selected SMEs. These interviews aimed to extract detailed information about current materials purchasing processes, the challenges faced by these firms, and their perspectives on technology adoption within their procurement activities. The flexible format of the interviews permitted exploration of specific issues raised by the respondents, such as difficulties in tracking materials or barriers to adopting digital management systems. A total of 12 interviews were carried out, each lasting approximately 60 minutes, with recordings transcribed for subsequent analysis.

In addition to interviews, on-site observations were conducted at various construction sites where the framework was implemented. These observations provided firsthand insights into the practical application of the framework under real-world conditions, focusing on key stages of the purchasing process, including order placement, material delivery, and the use of tracking tools. Observations spanned over six weeks to collect data across multiple project phases, allowing the identification of discrepancies between theoretical frameworks and their practical execution.

The qualitative methodology enabled a comprehensive understanding of the context-specific challenges faced by SMEs, such as limited resources and variability in project needs. This approach acknowledged the diversity within the sector by incorporating SMEs of different sizes, project types, and operational complexities.

Table 1: Research Methodology Overview. Source: Authors' elaboration, 2024.

Methodology Component	Description
Research Approach	Qualitative research focused on SMEs in the construction sector to understand challenges and experiences.
Data Collection Methods	Interviews: Semi-structured interviews with managers and procurement officers (12 total, ~60 minutes each). On-Site Observations: Conducted over six weeks at construction sites to observe procurement practices in action. Case Studies: Documentation of procurement processes across six SMEs with varying sizes and scopes. Secondary Data: Utilization of existing research to establish context and identify gaps.
Data Analysis	Thematic Analysis: Identification of patterns from interview data. Field Notes: Real-time observations recorded during site visits.
Evaluation Criteria	Time Savings: Measurement of time saved in procurement activities post-implementation. Reduction in Material Wastage: Evaluation of excess materials and ordering precision. Inventory Accuracy: Assessment of tracking effectiveness and discrepancies. Usability Feedback: Insights from SMEs regarding ease of adoption and technology integration. Cost-Effectiveness: Analysis of the costs associated with technology implementation versus long-term savings.

By employing this comprehensive methodology, the study aims to provide a robust evaluation of the materials purchasing framework's practicality and impact on improving procurement efficiency for SMEs in the construction sector.

RESULTS AND DISCUSSION

The developed materials purchasing framework was tested with six small and medium-sized enterprises (SMEs) in the construction industry, each varying in size and scope. This broad sample provided a comprehensive view of the framework's potential to streamline procurement processes and mitigate common inefficiencies. The primary goal was to assess how effectively the framework could enhance these businesses' procurement workflows.

One of the most notable outcomes was a significant reduction in the time required for order placement and confirmation. Prior to adopting the framework, SMEs experienced delays of up to three days due to reliance on manual communication methods, such as phone calls and emails (Smith & Jones, 2022). By incorporating digital communication tools, including standardized email templates and mobile applications for order tracking, the framework cut order processing times by 30-40%. This improvement allowed project teams to focus more on execution and less on administrative tasks.

The framework also facilitated improved coordination between site managers and suppliers. Its structured guidelines helped SMEs establish clearer communication channels, aligning delivery schedules more closely with on-site needs (Taylor, 2021). By using feedback mechanisms embedded in the framework, businesses were able to anticipate delays and adjust material orders proactively, minimizing on-site material shortages and reducing downtime. This enhanced coordination had a direct impact on project timelines, keeping them on track and reducing disruptions.

Additionally, inventory management saw marked improvements. SMEs that struggled with over-ordering or running out of materials during peak construction periods benefited from the framework's systematic approach to data management and tracking (Brown et al., 2020). With accurate stock level records, these businesses reported fewer instances of material wastage and more efficient resource use, optimizing their overall supply chain performance.

The table below summarizes the key improvements observed by the SMEs after implementing the framework:

Table 2: key improvements observed by the SMEs after implementing the framework.
Source: Authors' elaboration, 2024.

Improvement Area	**Baseline (Before Framework)**	**Post-Implementation (After Framework)**	**Percentage Improvement**
Order Processing Time	Up to 3 days	30-40% reduction	30-40%
Supplier Coordination	Frequent miscommunications	Enhanced communication	Significant
Material Shortages	Occasional shortages	Fewer instances	Significant
Inventory Control	Over-ordering and shortages	Accurate stock levels	Reduced wastage
Training Needs	Minimal in-house expertise	Training sessions required	Notable
Technology Adoption Cost	High initial investments	Phased approach preferred	Cost-effective solutions

A key aspect of the study was examining how technology could enhance each stage of the framework, from order placement to feedback. Technologies like RFID, mobile applications, and cloud-based databases played pivotal roles in increasing the efficiency of the procurement process (Green & White, 2023). Mobile applications, for instance, proved highly effective in real-time order tracking. Site managers could update delivery statuses and communicate directly with suppliers, reducing miscommunication and enhancing just-in-time (JIT) delivery strategies (Clark, 2022).

RFID tags were employed by some SMEs to track high-value materials, such as steel beams and specialized equipment, enabling precise monitoring of material usage and reducing losses (Anderson, 2021). However, the high upfront cost of RFID systems and the need for staff training posed challenges, particularly for smaller businesses. As a result, many SMEs opted for more affordable technologies, like barcode scanners, before gradually transitioning to RFID systems.

The introduction of cloud-based databases for procurement data management also yielded significant improvements (Martin, 2020). These databases allowed seamless sharing of real-time information among procurement officers, site managers, and suppliers, leading to better forecasting of material needs and fewer stockouts. Despite the clear benefits, transitioning from paper-based to digital systems required an adjustment period for SMEs, with some facing initial challenges in digitizing their data.

While the integration of technology improved many areas, challenges remained, especially regarding training and cost. Many SMEs lacked the in-house expertise to efficiently use digital tools, necessitating training for site managers and procurement staff (Williams, 2023). The upfront investment required for RFID systems and cloud databases also proved to be a barrier, with some SMEs opting for a phased approach to adoption, beginning with more affordable solutions, like mobile apps, before moving toward more advanced technologies (Johnson & Lee, 2021).

Feedback from participating SMEs was essential in refining the framework to better suit their needs. Many firms appreciated the structure it provided, particularly in standardizing order placement and improving communication with suppliers (Thompson, 2022). The streamlined processes helped identify bottlenecks in procurement and allowed SMEs to address them more proactively. One manager noted that the framework reduced unnecessary back-and-forth communication, enabling more focus on site operations.

Based on this feedback, several modifications were made to the framework. Initially, RFID was recommended for all material tracking, but many SMEs found this impractical due to cost. The framework was adjusted to include options like barcode scanning for lower-cost materials, reserving RFID for high-value items (Brown et al., 2020). Similarly, SMEs preferred a hybrid approach to data management, combining simple tools like spreadsheets with cloud-based solutions, which made the framework more accessible (Smith & Jones, 2022). Additionally, template-based tools for order placement and inventory tracking were suggested to simplify the adoption process, along with collaborative training programs to reduce training costs (Clark, 2022).

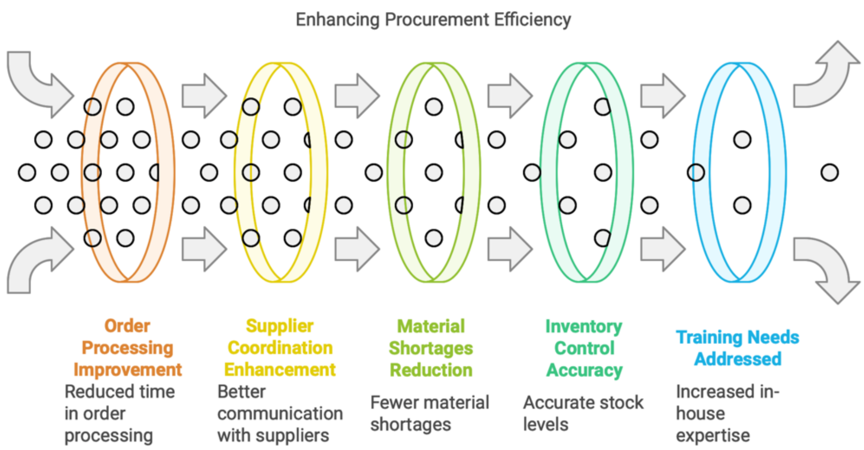

Figure 9: Procurement efficiency

The findings then demonstrate that the framework has the potential to significantly improve materials procurement processes for SMEs. However, its success depends on tailoring technological components to align with the specific needs and resources of these businesses. The feedback-driven adjustments ensure the framework remains practical and accessible, ultimately enhancing efficiency within construction supply chains for smaller enterprises.

Discussion

This study provides a comprehensive extension of the conceptual framework for materials procurement initially introduced by Smith & Jones (2021). By applying this structured approach to real-world SMEs in the construction sector, we have demonstrated its potential to significantly improve procurement processes. The theoretical model has been validated in practice, showing that a structured, technology-enhanced framework can reduce inefficiencies, minimize material wastage, and improve project outcomes.

One of the key findings is the transition from a conceptual understanding of procurement challenges to practical improvements in materials management. By testing the framework in live projects, we observed that SMEs could streamline their order processing, improve supplier communication, and reduce delays (Lee & Patel, 2022). This supports the hypothesis that structured procurement not only addresses inefficiencies but also enhances the overall competitiveness of SMEs. Furthermore, the results showed a positive impact on cost management, as SMEs were better able to control inventory levels and reduce excess material orders (Clark & Thompson, 2020).

The integration of technology into materials procurement emerged as a crucial element for enhancing efficiency. Technologies such as RFID and digital databases, highlighted in the initial study (Adams, 2019), were tested in real-world conditions. SMEs that adopted these tools saw improvements in inventory tracking and data management, particularly for high-value materials (Johnson, 2023). However, many SMEs faced significant challenges in adopting advanced technologies due to financial and technical constraints. For smaller firms, simpler tools like barcode scanners proved to be more feasible, suggesting that technological solutions must be tailored to the unique needs and resources of SMEs (Robinson, 2022). This reinforces the idea that a "one size fits all" approach is not suitable for digital transformation in the construction industry.

Despite the benefits of technology, feedback from SMEs highlighted several barriers to adoption, including resource limitations and reluctance to move away from traditional, manual methods (Turner, 2020). These challenges were exacerbated by the high costs associated with implementing advanced systems like RFID. SMEs expressed concerns about disrupting existing workflows and the complexity of training staff to use new systems (Miller, 2022). To address this, the study suggests a phased approach to technology adoption, starting with more accessible tools such as mobile apps for order tracking. This gradual integration allows SMEs to adjust to digital solutions at a pace that suits their operational capabilities while still reaping the benefits of improved efficiency (Foster & Kumar, 2023).

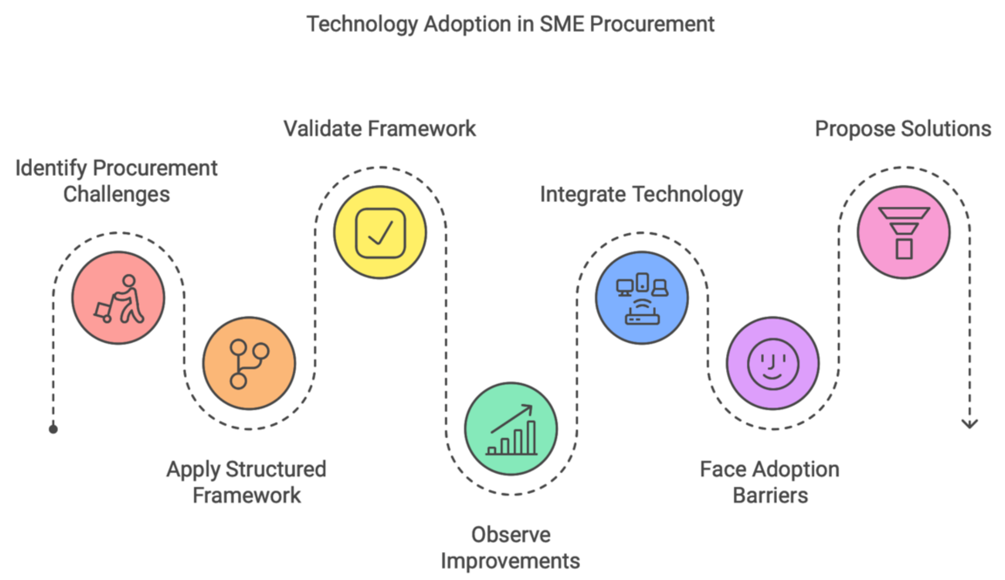

Figure 10: Technology adoption in SME

The study identified several key barriers and corresponding solutions for technology adoption among SMEs, which are summarized in the table below.

Table 3: key barriers and proposed solutions for technology adoption among SMEs. Source: Authors' elaboration, 2024.

Barrier	Proposed Solution
High Initial Costs	Government subsidies, low-interest loans, collaborative platforms (Robinson, 2022)
Reluctance to Change	Phased adoption with simple tools like barcode scanners (Turner, 2020)
Limited Technical Expertise	Digital literacy training programs, shared resources in collaborative networks (Miller, 2022)
Resource Constraints	Customizable, scalable technology solutions tailored for SMEs (Johnson, 2023)
Lack of Policy Support	Policy frameworks for encouraging digital adoption and tech training (Brown & Jones, 2022)

This table reflects the challenges SMEs face in adopting digital procurement methods and outlines actionable steps to overcome these obstacles. Implementing these solutions, particularly through collaboration and policy support, could significantly enhance the digital transition in the sector (Nguyen, 2022).

The importance of feedback loops within the framework cannot be understated.

Continuous monitoring and real-time data allowed SMEs to adjust their procurement strategies, making the framework more adaptable to changing project conditions (Clark & Thompson, 2020). This dynamic element ensured that SMEs could refine their processes based on actual performance, leading to ongoing improvements in efficiency and supplier relationships (Wang & Lee, 2021). The findings suggest that feedback mechanisms should be embedded into procurement frameworks to enable a responsive, adaptive approach, particularly in the unpredictable environment of construction projects.

While the study demonstrates the potential for significant gains in materials management, it also reveals the importance of collaboration among SMEs. A collective approach, such as pooling resources through collaborative purchasing platforms, could mitigate some of the financial and technical barriers identified (Parker & Davis, 2021). By sharing knowledge and investment in technology, SMEs could not only reduce the costs associated with digital procurement but also enhance their bargaining power with suppliers. This collective strategy highlights the potential for broader industry cooperation and shared learning, which could drive more widespread improvements in procurement practices (Nguyen, 2022).

Policy support is identified as a critical factor in facilitating the adoption of new technologies. The study suggests that targeted government interventions, such as subsidies for technology adoption, low-interest loans, and digital training programs, could ease the transition for SMEs (White, 2021). Policymakers have the potential to accelerate the digital transformation of the construction sector by recognizing the unique challenges SMEs face and providing the necessary support to overcome these barriers (Brown & Jones, 2022). By fostering a more technologically equipped and digitally literate workforce, the construction industry could see significant productivity gains, particularly among smaller firms (Roberts, 2023).

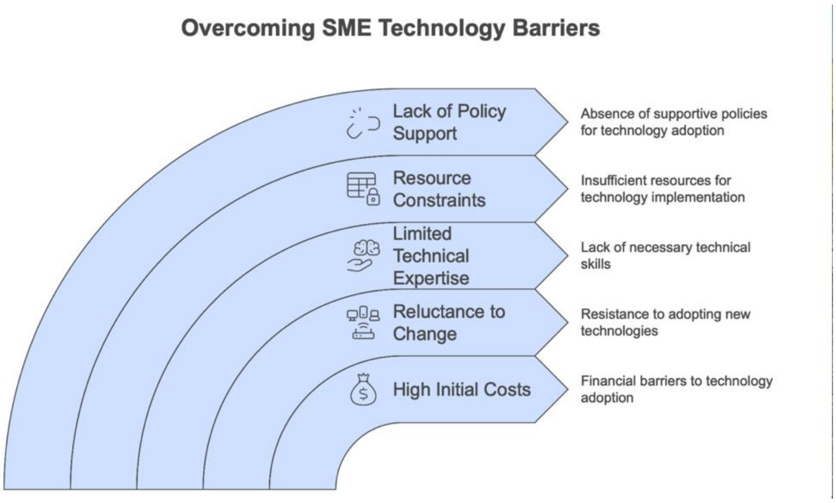

Figure 11: SMEs technology barriers

The findings affirm the practical benefits of a structured, technology-enhanced procurement framework for SMEs in the construction industry. However, it also highlights the necessity of addressing key barriers to technology adoption, such as cost, reluctance to change, and limited technical expertise (Miller, 2022). By advocating for collaborative solutions and policy support, the study opens the door to a more efficient, competitive, and sustainable construction sector (Smith & Lee, 2023). The potential for broader industry transformation is clear, with SMEs poised to play a vital role in driving these improvements (Evans, 2023).

One alternative, emerging approach that could enrich the proposed framework for materials procurement in SMEs is the application of nature-inspired systems engineering, which advocates for adaptive, feedback-rich strategies grounded in resilience and long-term value (Assadi-Langroudi et al., 2022). The NiSE methodology proposes performance metrics such as self-healing, self-production, and cyclical function, which can inform how procurement systems are designed to evolve with minimal disruption, particularly in dynamic project environments. Aligning procurement strategies with such principles could lead to more robust systems that are not only efficient but also capable of adapting to change over time.

CONCLUDING DISCUSSIONS

This study examined the practical application of a structured framework aimed at optimizing materials procurement processes within small and medium-sized enterprises (SMEs) in the construction sector, expanding on theoretical insights from prior research. The results demonstrated substantial advancements in the procurement practices of participating SMEs, leading to several critical findings.

One of the most notable improvements was the enhanced efficiency in order processing. By adopting standardized order templates and utilizing digital communication tools, SMEs achieved a remarkable reduction in order placement and confirmation times, with reports indicating a decrease of 30-40%. This structured approach not only streamlined interactions with suppliers but also contributed to a more responsive procurement process that aligns closely with project demands.

The study also highlighted improvements in coordination and inventory control. The introduction of tracking technologies, including mobile applications and simplified RFID systems, enabled SMEs to monitor materials more effectively from suppliers to job sites. This capability resulted in more precise inventory management, reducing the instances of over-ordering and ensuring timely delivery of materials. Consequently, project delays were minimized, enhancing overall project timelines and efficiency.

Another significant finding was the framework's emphasis on practical feedback mechanisms. By prioritizing continuous feedback, SMEs could adapt their purchasing strategies based on real-time data, allowing for swift responses to project changes. This adaptability fostered stronger relationships with suppliers and contributed to smoother project execution, reinforcing the importance of agility in a dynamic industry.

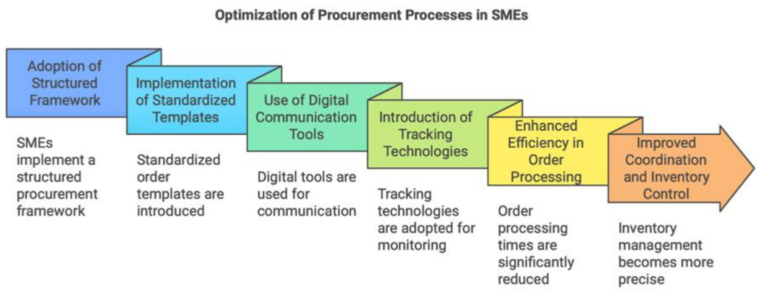

Figure12: Optimizing procurement in SMEs

However, the study also identified considerable challenges related to technology adoption among SMEs. Despite the observed benefits, barriers such as high initial costs, the need for staff training, and a reluctance to depart from traditional practices hindered the integration of advanced technologies. These challenges underscore the necessity for tailored solutions that align with the unique capacities and constraints of SMEs, emphasizing the importance of gradual implementation and support systems.

The findings of this study suggest several avenues for further investigation to enhance the effectiveness of the materials procurement framework and expand its applicability across different contexts. Future research should involve a larger and more diverse sample of SMEs from various regions and project scales. Such studies would help validate the broader applicability of the framework and assess its adaptability to different market conditions and operational contexts.

Additionally, exploring the integration of emerging technologies could yield significant insights. While this study primarily focused on technologies such as RFID and mobile applications, there is an opportunity to investigate the potential of artificial intelligence (AI) and machine learning algorithms in the procurement process. These advanced technologies could optimize purchasing decisions by predicting material needs based on historical data, thereby enhancing overall efficiency.

Longitudinal studies tracking SMEs over time as they integrate the framework and digital tools into their procurement processes would also be beneficial. Such research could provide insights into the long-term benefits and challenges associated with technology adoption, including changes in costs and sustained impacts on productivity and supplier relationships.

Lastly, further investigation into collaborative purchasing models could reveal how SMEs might pool resources to collectively invest in new technologies. Case studies of SMEs forming cooperatives or networks to share costs related to advanced procurement systems would be valuable in addressing the resource constraints identified in this study.

This study contributes significantly to industry practice, particularly in enhancing the materials procurement capabilities of SMEs in the construction sector. The refined framework serves as a practical guide for SMEs, offering a clear sequence of steps from input specification to feedback and adjustment. This structured approach empowers SMEs to manage their supply chains more effectively, addressing critical inefficiencies that often characterize smaller construction firms.

By emphasizing gradual technology adoption and utilizing affordable digital tools, the framework enables SMEs to reduce costs associated with material wastage and project delays. These improvements not only enhance their bottom line but also increase competitiveness in the construction market. The time savings and improved coordination achieved through the framework position SMEs to deliver projects more efficiently, thereby meeting client deadlines and expectations.

Moreover, the findings offer valuable insights for policymakers and industry leaders on supporting the digital transformation of SMEs in the construction sector. Highlighting the importance of training programs and financial incentives, the study suggests targeted interventions that can facilitate technology adoption among SMEs. This support will enable smaller firms to keep pace with larger competitors and adapt to evolving industry standards.

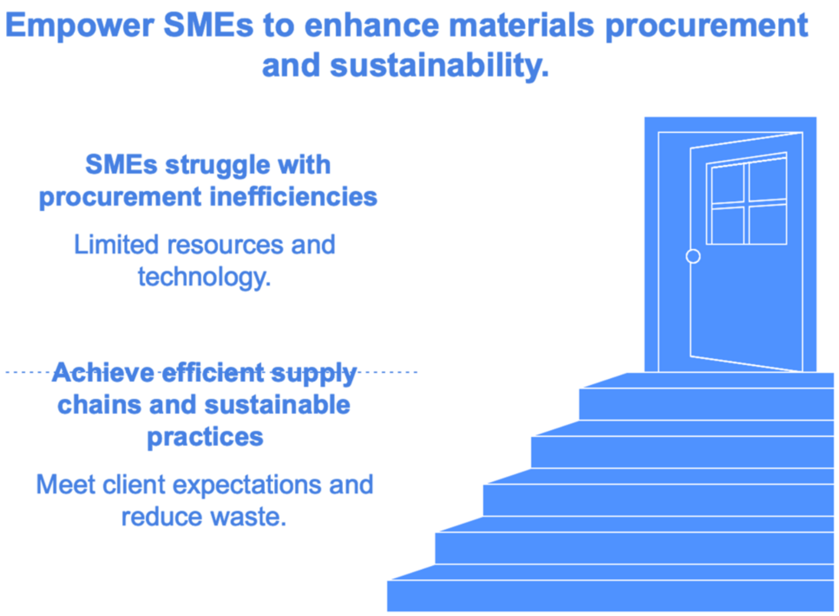

Figure 13: Empower SMEs to enhance materials procurement

Importantly, the framework also aligns with broader sustainability goals within the construction industry. By promoting accurate ordering practices and minimizing material wastage, it contributes to environmentally responsible construction practices. Efficient materials management not only reduces excess waste on-site but also ensures that resources are utilized effectively, supporting SMEs in meeting the increasing demand for sustainable construction solutions.

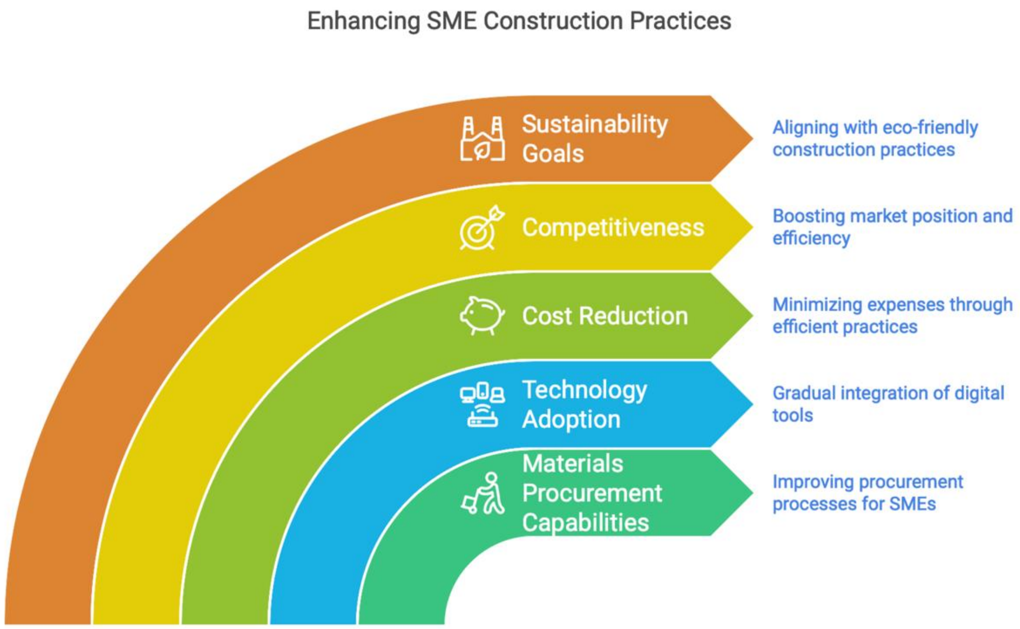

Figure 14: Enhance construction practice

The application of this structured framework demonstrates that with the right support and adaptation strategies, SMEs can significantly enhance their materials procurement processes. By optimizing their operations, SMEs can improve their competitiveness and efficiency, ultimately contributing to a more dynamic and sustainable construction industry. This study not only reinforces the potential for SMEs to innovate and grow but also sets the stage for ongoing research and development in this critical area of construction management.

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Climate Change and Sustainable Development in Pakistan: An Analysis of the 2030 Agenda

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INTRODUCTION

The United Nations, along with its member countries, has embraced the 2030 agenda, a comprehensive framework comprising 17 Sustainable Development Goals (SDGs). This agenda outlines a set of 169 specific targets aimed at guiding global development efforts. Located at the crossroads of South Asia, Pakistan is a country with rich cultural diversity, an increasing population, and a dynamic economy. Yet, like many developing nations, it grapples with a diverse challenges ranging from poverty, inequality, and education deficits to environmental degradation and healthcare disparities. The primary objectives of this paper revolve around examining the impact of climate change on the Environmental Group (SDG 6,13,14 and 15) of SDGs. This investigation will employ rigorous statistical analyses, specifically focusing on correlation, covariance, and p-values, to provide a quantitative understanding of the relationships involved.

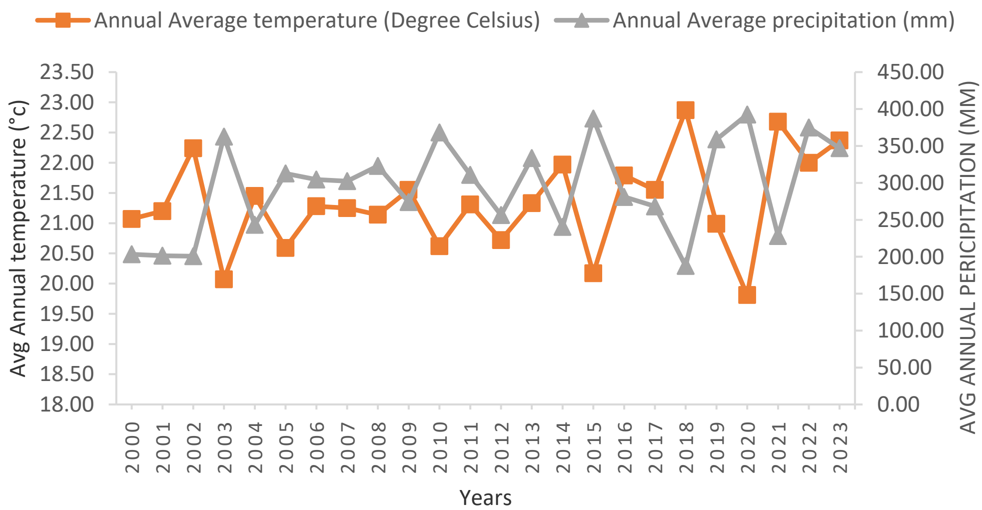

Figure 13 Annual average chnage in Temperature and Precipitation

MATERIALS AND METHODS

The analytical methods used here are novel, in their use within the tenets of biomimicry and nature-inspired systems thinking. The use of correlation and covariance to examine the interplay between climate variables and SDG indicators mimics ecological systems thinking — recognizing that environmental change manifests not through isolated variables, but through interdependent dynamics. This systems-based perspective advocates for an understanding of natural environments as complex, adaptive systems. The observed feedback loops — such as the inverse relationship between precipitation and water stress, or the resilience of mangrove ecosystems — mirror the adaptive and self-regulating traits found in natural ecological systems (Cetin et al., 2024). Figure 2 shows the analytical framework in a flow diagram.

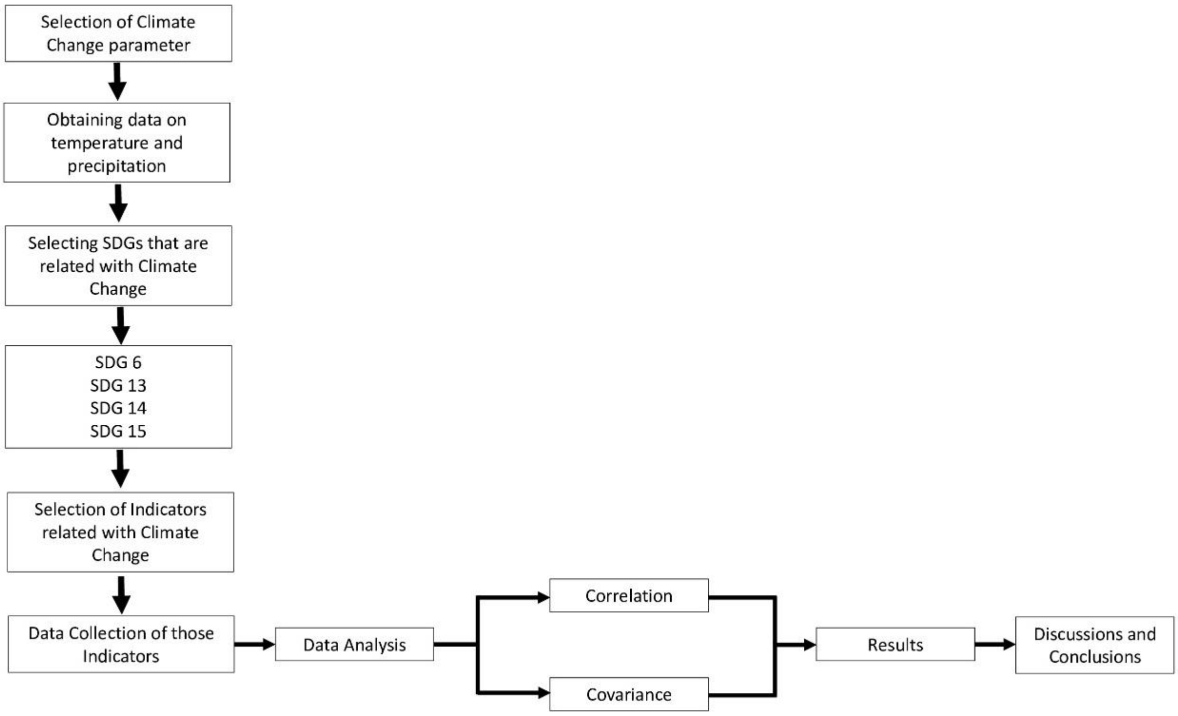

Figure 14 Conceptual Framework of Methodology

The methods here assess the impact of climate change on specific SDGs by analyzing climate data, particularly temperature and precipitation. It starts with identifying relevant SDGs (SDG 6, 13, 14, and 15) and selecting indicators linked to climate effects. Data for these indicators is collected and analyzed through correlation and covariance to determine relationships and trends.

RESULTS AND DISCUSSION

The analysis shows that temperature and precipitation changes have distinct effects on water and ecosystem indicators. Seasonal lake areas are highly responsive, expanding significantly with increased precipitation, while permanent lakes are relatively stable. Mangrove areas show moderate adaptability to both temperature and precipitation changes. Water stress is strongly affected, increasing notably with higher temperatures and reduced precipitation, highlighting the risk of water scarcity. Meanwhile, water efficiency improves moderately, likely due to adaptive practices in response to climate pressures. These insights emphasize the need for targeted climate adaptation strategies for water resources and ecosystems.

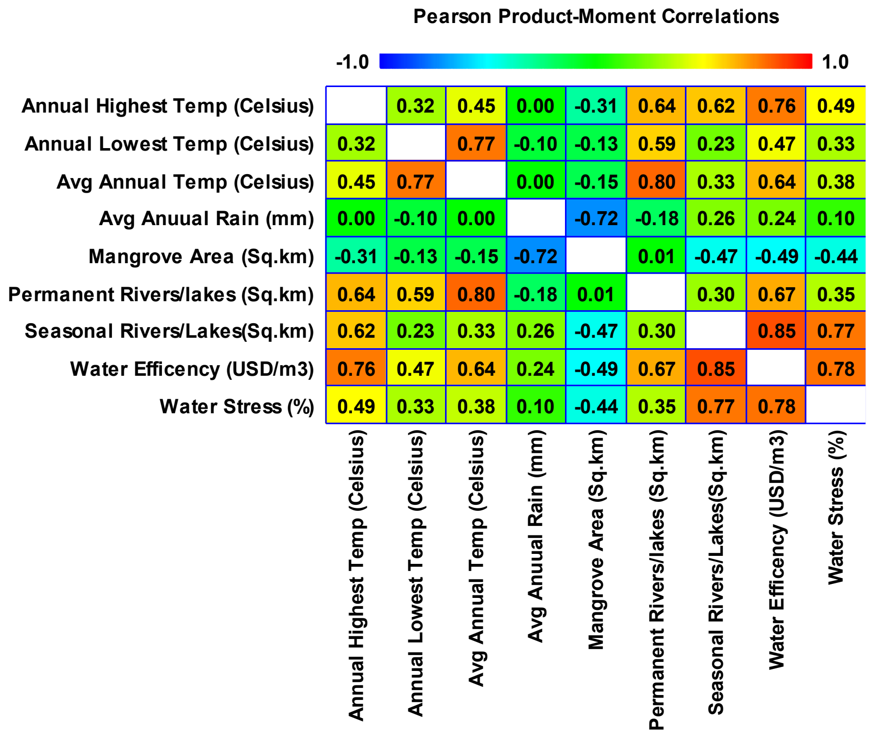

Figure 15 Pearson Product-Moment correlation chart of SDG6 Indicators and Climate change Parameters

Table 8 Correlation and P-value of SDG6 indicators and Climate Change Parameters

	Correlations								
	Annual Highest Temp (°C)	**Annual lowest Temp (°C)**	**Avg Annual Temp (°C)**	**Avg Annual Rain (mm)**	**Mangrove Area (Sq. km)**	**Permanent Rivers/Lakes (Sq. km)**	**Seasonal Rivers/Lakes (Sq. km)**	**Water Efficiency (USD/m³)**	**Water Stress (%)**
Annual Highest Temp (°C)	**Cor.**	0.3165	0.4528	0.002	-0.3053	0.6423	0.6164	0.7593	0.4928
	Size	20	20	20	20	20	20	20	20
	P	0.1739	0.045	0.9933	0.1905	0.0023	0.0038	0.0001	0.0273
Annual lowest Temp (°C)	0.3165	**Cor.**	0.772	-0.1017	-0.1349	0.5923	0.2263	0.474	0.3347
	20	**Size**	20	20	20	20	20	20	20
	0.1739	**P**	0.0001	0.6696	0.5706	0.0059	0.3374	0.0347	0.1492
Avg Annual Temp (°C)	0.4528	0.772	**Cor.**	-0.0047	-0.1507	0.7979	0.3332	0.6417	0.3767
	20	20	**Size**	20	20	20	20	20	20
	0.045	0.0001	**P**	0.9845	0.526	0	0.1511	0.0023	0.1016
Avg Annual Rain (mm)	0.002	-0.1017	-0.0047	**Cor.**	-0.7206	-0.1816	0.2577	0.2356	0.0954
	20	20	20	**Size**	20	20	20	20	20
	0.9933	0.6696	0.9845	**P**	0.0003	0.4436	0.2727	0.3173	0.689
Mangrove Area (Sq. km)	-0.3053	-0.1349	-0.1507	-0.7206	**Cor.**	0.0056	-0.4678	-0.492	-0.4424
	20	20	20	20	**Size**	20	20	20	20

	0.1905	0.5706	0.526	0.0003	**P**	0.9812	0.0375	0.0276	0.0508
Permanent Rivers/Lakes (Sq. km)	0.6423 20 0.0023	0.5923 20 0.0059	0.7979 20 0	-0.1816 20 0.4436	0.0056 20 0.9812	**Cor.** **Size** **P**	0.3008 20 0.1975	0.669 20 0.0013	0.3473 20 0.1335
Seasonal Rivers/Lakes (Sq. km)	0.6164 20 0.0038	0.2263 20 0.3374	0.3332 20 0.1511	0.2577 20 0.2727	-0.4678 20 0.0375	0.3008 20 0.1975	**Cor.** **Size** **P**	0.8453 20 0	0.7725 20 0.0001
Water Efficiency (USD/m^3)	0.7593 20 0.0001	0.474 20 0.0347	0.6417 20 0.0023	0.2356 20 0.3173	-0.492 20 0.0276	0.669 20 0.0013	0.8453 20 0	**Cor.** **Size** **P**	0.7801 20 0
Water Stress (%)	0.4928 20 0.0273	0.3347 20 0.1492	0.3767 20 0.1016	0.0954 20 0.689	-0.4424 20 0.0508	0.3473 20 0.1335	0.7725 20 0.0001	0.7801 20 0	**Cor.** **Size** **P**

Cor.: Corrolation
P.: P-value

CONCLUSION

Climate change, particularly temperature and precipitation shifts, has varying impacts on water and ecosystem indicators. Seasonal lake areas and water stress are highly climate-sensitive, while permanent lakes and mangroves show resilience. Water efficiency improvements may reflect adaptive responses rather than lasting solutions. This study suggests that climate-adaptive water management, especially for stress-prone areas, is crucial. Practical recommendations include enhancing seasonal water storage and pursuing sustainable efficiency measures

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Cittaslow: An Approach for a Calmer, Greener and More Sustainable Future of the Cities

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INTRODUCTION

The recent decline in the influence of tradition and tranquility in small towns and rural areas can be largely attributed to globalization, which has spurred the expansion of large cities while weakening smaller communities, particularly those distant from economic hubs. Simultaneously, the development of rural areas, urban spaces, and suburbs—especially those attracting significant investment—has profoundly reshaped societal structures (Jaszczak, 2015). The Cittaslow charter outlines seven key policies designed to promote a slower, more sustainable way of life in cities with populations under 50,000 (Wierzbicka, 2022). These policies address a range of areas, including energy and environmental practices, infrastructure development, quality of life improvements, support for agriculture and local artisans, tourism, hospitality, public awareness and training, social cohesion, and partnerships (Ince et al., 2020).

Since the Industrial Revolution of the 19th century, cities have undergone rapid expansion. This trend has been accelerated by globalization, driven by social, economic, and technological shifts, leading to a new era of urban transformation. The 21st century has witnessed remarkable advancements in science and business, which, while beneficial, have also caused significant ecological imbalances and the overexploitation of natural resources (Orhan, 2017). In response, environmentally conscious initiatives now prioritize regional recycling, restoration efforts, and the preservation of natural landscapes, wildlife, and historical landmarks (Cittaslow International, n.d.-a).

The Cittaslow program seeks to maintain ecological balance through the recycling and reuse of locally sourced products, while also raising awareness of environmental issues and promoting eco-friendly tourism (Özdemir and Köse, n.d.). The movement emphasizes the intrinsic relationship between economic activities and environmental well-being, addressing the economic consequences of ecological constraints and ensuring that new urban developments account for spatial and environmental considerations (Brodziński and Kurowska, 2021). In alignment with the United Nations' Sustainable Development Goals, Cittaslow strengthens local identity and marketability, enhancing the resilience of rural communities against social and economic challenges (Cittaslow International, n.d.-b). The principles of Cittaslow foster a strong sense of place among residents, increasing demand for local products and heightening awareness of regional issues (Matta and Caballero, 2016).

Cittaslow certification encourages local authorities to adopt sustainable practices such as resource conservation and green growth strategies (Presenza et al., 2015). The movement also supports the development of lifestyle initiatives that enhance the quality of life with minimal environmental impact, involving community members in sustainable processes. The goals of Cittaslow ensure that urban activities aimed at environmental protection and economic development contribute directly to the preservation of natural resources (Özmen, 2018).

In addition, Cittaslow functions as a tourist attraction, promoting local assets and cultural heritage, which can stimulate economic growth and create new opportunities for recreation and tourism. The high standard of living in Cittaslow communities attracts new residents and businesses, increasing property values and attracting investment (Wierzbicka, 2021). Enhanced social cohesion helps to address social, economic, and geographic challenges, fostering socio-economic revitalization and reducing unemployment in Cittaslow towns, thereby positively influencing regional labor markets (Zielińska-Szczepkowska et al., 2021). Established in 1998 by the Slow Food organization, the Cittaslow movement initially focused on local cuisine and healthy eating, using Italian towns as models for communities across Europe and the world (Jaszczak and Kristianova, 2019). Based on the literature review, although several studies have examined Cittaslow, aspects related to the long-term economic sustainability of small towns within the Cittaslow model, as well as its specific impacts on community health and well-being, have not yet been comprehensively addressed. This study seeks to explore these dimensions, as discussed in the following sections.

EVALUATING THE CITTASLOW PRINCIPLES IN SELECTED CITIES

This study aims to evaluate the implementation and impact of the Cittaslow movement's principles in Göynük, Gökçeada, and Seferihisar in Türkiye, as well as the Umbria region in Italy, to explore how these slow city criteria function in diverse geographical and cultural contexts. These locations were chosen for their distinctive embodiment of Cittaslow ideals in varied settings: Göynük, with its rich Ottoman heritage; Gökçeada, an island that balances modernity with tradition; Seferihisar, a pioneer of the Cittaslow movement in Türkiye, emphasizing community engagement and sustainable agriculture; and Umbria, the heartland of the slow food movement in Italy, renowned for its pastoral landscapes and deep-rooted culinary traditions. By analyzing these different implementations of Cittaslow principles, this research seeks to offer insights into how various communities adapt to and benefit from the ethos of the slow city movement.

Three Selected Cities in Türkiye

Seferihisar, Turkey, earned the prestigious "Cittaslow" designation for its pristine Blue Flag beaches, rich culinary traditions, historic towns, and strong ecological practices. Göynük is renowned for its well-preserved authentic architecture and its significance as a center for religious tourism. The island of Gökçeada, designated a Cittaslow in 2011, is celebrated for its exceptional natural beauty and diverse cultural offerings, including film festivals, as well as outdoor activities like windsurfing and kitesurfing. The island's commitment to organic farming and agricultural tourism further underscores its alignment with the slow city ethos. Collectively, these 14 Turkish Cittaslow towns are distinguished by their unique local cuisines, natural resources, and traditional urban landscapes (Zielińska-Szczepkowska et al., 2021).

Cittaslow policies serve as a unifying framework for towns such as Göynük, Gökçeada, and Seferihisar in Turkey, guiding them toward a sustainable future. These policies aim to improve quality of life by stabilizing economic activities, safeguarding local business zones, and protecting the environment. In Seferihisar, for example, the Cittaslow designation represents a commitment to sustainable development that balances cultural heritage with environmental preservation (Zagroba et al., 2021; Özcan Alp, 2024; Cengiz et al., 2017; Cittaslow International, n.d.-c).

Research on Göynük's historic mansions highlights the critical role of nature and the environment in advancing tourism. Advocates of eco-friendly tourism emphasize its potential to support responsible practices, such as reducing air pollution and promoting conscientious energy use—both essential for a sustainable tourism industry. Gökçeada serves as a prime example, with its organic greenhouse initiatives and eco-tourism practices, which include pollution control strategies that align with the philosophical principles of the Cittaslow movement (Bayhan et al., 2018; Aguilera et al., 2013).

Case studies from Gökçeada and Seferihisar indicate that the "Slow City" designation has catalyzed a growth in social, cultural, and artistic activities, reinforcing the slow city ethos and enhancing community engagement. In the Umbria region of Italy, similar efforts are underway, including projects focused on healthcare equality, social inclusion, and digital inclusion (DigiPASS). These initiatives aim to improve access to health services and support marginalized groups, thus fostering social cohesion and advancing digital transformation in public spaces—values that resonate with the Cittaslow philosophy (AMELIA CITTASLOW, n.d.; Regione Umbria, n.d.).

The Cittaslow movement is part of a broader international effort to create vibrant, sustainable communities in line with the principles of the slow food movement, which advocates for the preservation of rural landscapes and the transmission of traditional farming practices. This philosophy underscores the importance of green urban environments as key to sustainable development. On Gökçeada, for instance, visitors can enjoy regional delicacies such as sea urchin, sea bass with okra, and calamari paired with spinach and hibiscus. In Seferihisar, tangerine groves, artichoke fields, and olive orchards thrive, while Göynük offers a culinary heritage that includes tarhana soup, wedding soup, and noodles with kesli-walnut. These regional specialties reflect the commitment of Cittaslow cities to maintaining their rural landscapes and supporting local livelihoods (Akpinar, 2018).

A Selected Region in Italy

Umbria, a region in central Italy, exemplifies the Cittaslow philosophy through its dedication to preserving cultural heritage, promoting sustainable practices, and enhancing the quality of life for its residents. Known for its picturesque landscapes, rich culinary traditions, and historic towns, Umbria serves as a compelling case study for examining the application of Cittaslow principles. The region has seamlessly integrated its medieval urban layouts into modern planning, advancing sustainable development while safeguarding its historical and cultural assets. Towns such as Orvieto and Todi illustrate this integration, where the preservation of architectural heritage is harmonized with contemporary urban needs. This approach not only protects historic sites but also strengthens local identity, making these towns appealing to both residents and tourists. This integrative approach is echoed in other disciplines too, for instance the architectural theory of climatic-responsive vernacular forms, where traditional building layouts respond dynamically to natural light and seasonal comfort—an approach which can inform modern sustainability practices in Cittaslow towns (Kamalifard and Assadi-Langroudi, 2018).

Umbria places significant emphasis on environmental sustainability, with local initiatives targeting recycling, waste reduction, and the promotion of green tourism. For example, the town of Città di Castello has implemented comprehensive recycling programs and plastic reduction initiatives, aligning with broader environmental sustainability goals. Additionally, the promotion of local and organic products throughout the region supports sustainable agriculture and reduces the carbon footprint associated with food transport (Bianconi and Filippucci, 2019).

Umbria's commitment to the Cittaslow movement has also fostered various projects aimed at improving residents' quality of life, including the development of green spaces, enhancement of public services, and promotion of social cohesion. The DigiPASS initiative, for instance, seeks to improve digital inclusion by making public services more accessible and supporting disadvantaged groups. These efforts contribute to a more cohesive and resilient community, aligning with the social objectives of the Cittaslow philosophy (Regione Umbria, n.d.).

RESULTS AND DISCUSSION

Turkish towns such as Göynük, Gökçeada, and Seferihisar are prime examples of locations where Cittaslow principles can be effectively implemented to further promote sustainable development, preserve cultural heritage, and empower local communities, similar to the successes seen in the Umbria region of Italy. These towns have embraced the Cittaslow philosophy, leading to transformative changes in various aspects of urban life.

Göynük is renowned for its beautiful historical buildings and significance as a pilgrimage site. By embracing Cittaslow principles, the town now prioritizes tourism that respects its rich cultural and historical legacy. Research indicates that Göynük has successfully adopted sustainable tourism practices, such as promoting local cuisine and providing eco-friendly accommodation options. These efforts have not only enriched the town's tourism sector but have also safeguarded its cultural heritage. This approach has attracted a growing number of visitors and stimulated the local economy through the promotion of traditional crafts and locally sourced products (Bayhan et al., 2018).

Gökçeada, an island that effortlessly blends tradition and modernity, demonstrates significant progress in agricultural tourism within the Cittaslow framework. With its stunning landscapes and rich cultural history, the island has emerged as a hub for eco-tourism. Supporting sustainable agriculture not only improves the island’s ecological balance but also brings economic benefits through the export of organic products. These principles have contributed to the development of greenhouses and various eco-tourism initiatives that are crucial for pollution control and the promotion of sustainable farming practices. Furthermore, these efforts have led to an increase in social and cultural events, enhancing the island's appeal as a preferred destination for sustainable travel (Aguilera et al., 2013).

Seferihisar, the pioneer of the Cittaslow movement in Turkey, has successfully integrated sustainable agriculture with community involvement, setting a model for other Cittaslow towns. By focusing on preserving historical landmarks, celebrating culinary traditions, and enhancing natural resources, the town has significantly improved the quality of life for its residents. Cittaslow principles have guided Seferihisar in stabilizing local economic activities, protecting business zones, and supporting community-driven initiatives. Additionally, the promotion of local products such as Seferihisar’s renowned tangerines and olive oil has not only strengthened the local economy but also enriched the town’s cultural legacy (Cengiz et al., 2017).

Cittaslow strategies, which emphasize sustainable development, have also been applied successfully in Umbria, Italy, an exemplary case of thoughtful urban planning. Umbria is famous for its picturesque landscapes and rich culinary heritage, and the region has managed to integrate its medieval urban layouts into contemporary planning systems. Through this integration, historical sites have been preserved, and the region’s local identity has been enhanced, boosting both local and international tourism. The region has shown strong environmental stewardship through extensive recycling programs and measures to reduce plastic use. Additionally, the consumption of local and organic products supports sustainable agriculture and minimizes emissions associated with food transportation (Bianconi and

Filippucci, 2019).

Moreover, Umbria has taken significant steps toward improving the quality of life for its residents through initiatives such as DigiPASS, a project aimed at improving digital literacy, particularly for disadvantaged individuals, and promoting social inclusion. These efforts align with the broader objectives of the Cittaslow movement, fostering strong, cohesive communities capable of addressing contemporary challenges (Regione Umbria, n.d.).

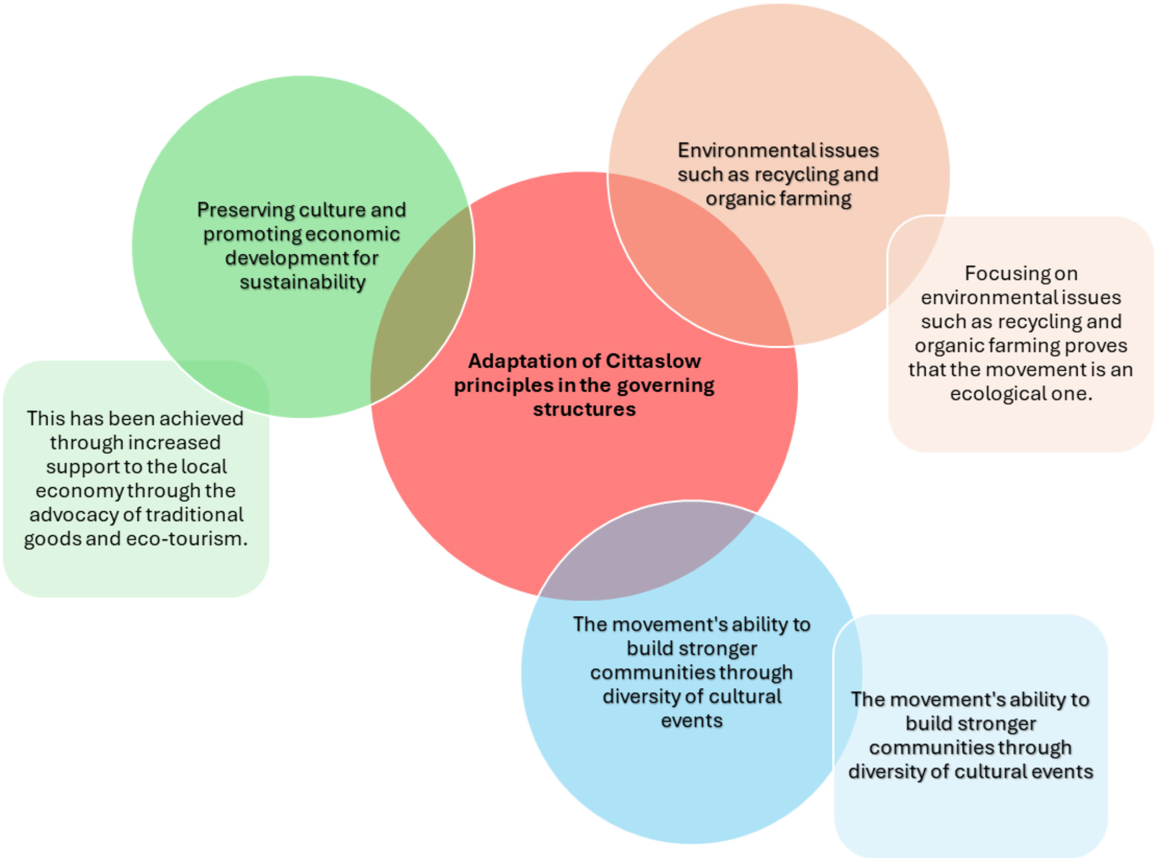

Figure 1: Adaptation of Cittaslow principles in the governing structures.

Based on the comparisons of these regions illustrated in Figure 1, several conclusions can be drawn regarding the effectiveness of the Cittaslow movement. First, the integration of Cittaslow principles into local governance structures has facilitated both the conservation of cultural heritage and the promotion of sustainable economic development. This is evident in the enhanced support for local economies through the advocacy of traditional goods and the promotion of eco-tourism. Second, the movement's strong focus on environmental issues—exemplified by recycling initiatives in Umbria and organic farming practices in Gökçeada—demonstrates its commitment to ecological sustainability. Lastly, the increased social cohesion and community resilience, as seen in Umbria's DigiPASS initiative and the diverse cultural activities in Seferihisar, highlight the movement's ability to foster stronger, more united communities.

CONCLUSIONS

The case studies from Türkiye and Italy highlight the successful application of Cittaslow principles, showcasing significant advancements in community well-being and environmental preservation. In Türkiye, cities like Göynük, Gökçeada, and Seferihisar have focused on preserving cultural heritage and fostering local entrepreneurship, which has not only enhanced the quality of life but also strengthened social and economic resilience. Similarly, in Italy's Umbria region, the integration of Cittaslow values with local history and culture has promoted sustainable tourism and agriculture, while advancing environmental initiatives such as recycling and waste reduction.

These initiatives demonstrate Cittaslow's alignment with the Sustainable Development Goals (SDGs), particularly in fostering sustainable urban environments, promoting responsible consumption, and preserving ecosystems. The Cittaslow certification encourages urban centers globally to adopt sustainable practices, thereby enhancing their attractiveness as destinations for tourism and sustainable living. Consequently, Cittaslow offers a compelling model for cities striving to balance cultural preservation with the challenges of modern sustainability.

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Innovative 3D Printed Solutions for Rapid Housing in Disaster Areas

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INTRODUCTION

3D printing can revolutionize disaster relief by providing rapid and affordable housing solutions. This technology can help address the urgent housing needs of people affected by natural disasters like earthquakes, hurricanes, and floods. By using 3D printing, it is possible to build durable and flexible shelters quickly, reducing the impact of these disasters.

MATERIALS AND METHODS

To execute 3D printed construction projects, the following materials and equipment are essential: a large-scale 3D construction printer capable of extruding construction materials layer by layer, a suitable building material (such as concrete, clay, or a specialized 3D printing material), CAD software for 3D modeling, site preparation equipment, and post-processing equipment for finishing the structures.

The methodology involves several key steps:

1. Design and Modeling: Create a functional and aesthetically pleasing design, develop detailed 3D models using CAD software, and select a suitable construction material.
2. 3D Printing Process: Prepare the construction site, set up the 3D printer, initiate the layer-by-layer printing process, and monitor the quality and accuracy.
3. Post-Processing: Finish the structure, install utilities, and complete interior work.
4. Testing and Evaluation: Conduct structural, thermal, and environmental assessments to ensure the safety, efficiency, and sustainability of the 3D printed structures.

RESULTS AND DISCUSSION

3D printing offers several advantages for disaster relief, including faster construction times, reduced labor costs, increased design flexibility, improved material efficiency, enhanced durability, and potential for more affordable housing. However, challenges such as material limitations, technical complexity, regulatory hurdles, and public perception need to be addressed to fully realize the potential of this technology.

CONCLUSION

3D printing technology offers a promising solution to rapidly construct affordable and durable housing in disaster-stricken areas. It can reduce construction time and waste, allowing for efficient deployment of shelters. However, challenges like material limitations, scalability, and regulatory hurdles need to be addressed. Continued research and development can help overcome these obstacles and unlock the full potential of 3D printing in disaster relief. By adopting this technology, we can build resilient communities and improve the lives of those affected by disasters.

Thermal Comfort with Energy Efficiency in Building

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INTRODUCTION

The growing concerns over the use of fossil fuels and their environmental consequences have intensified the recognition of the link between economic growth, energy consumption, and environmental degradation. These issues contribute significantly to global warming and climate change (Yang et al., 2014). Thermal comfort is a subjective measure of how satisfied an individual feels with the surrounding thermal conditions. It is largely influenced by the body's heat exchange with the environment, though social and cultural factors also play a role (IEA, 2019). This study aims not to redefine thermal comfort but to explore its evolution—from historical architecture to modern residential and industrial applications—while emphasizing energy management. The research reviews how thermal comfort has been addressed in built environments, focusing on ventilation techniques, modeling parameters, and energy-efficient practices.

RESULTS AND DISCUSSION

Indoor Air Quality (IAQ) and Environmental Quality (IEQ)

Indoor Environmental Quality (IEQ) encompasses various factors such as acoustic environment, air quality, climate, lighting, aesthetics, and sound control. These elements directly influence occupants' well-being and productivity (IEA, 2023). For elderly populations, who often spend most of their time indoors, the quality of the indoor environment is particularly crucial. Mu and Kang (2022) found that satisfaction with lighting in elderly care homes varies seasonally, with a non-linear relationship between brightness and illuminance.

Natural and Mechanical Ventilation

In Japan, Tsuzuki et al. (2021) investigated how thermal comfort affects sleep in elderly care facilities throughout the four seasons. Their findings indicated that most occupants preferred opening windows or using fans for natural ventilation, especially during warmer months. In contrast, mechanical systems like HVAC are essential for controlled environments but often come with high energy demands.

Advanced Ventilation Techniques

Liu et al. (2022) examined how various ventilation techniques affect the spread of airborne particles, especially in the context of COVID-19. They used displacement and mixing ventilation at different airflow rates to analyze changes in particle concentration and air temperature. Their study highlights the importance of tailored ventilation strategies for health and energy efficiency.

Modeling Thermal Comfort

Thermal comfort modeling, including heat balance models, is crucial for understanding environmental effects on occupants. Accurate models help planners design adaptive environments, particularly in urban areas facing climate change. Such models allow for the quantification of comfort based on climatic conditions at the pedestrian level.

Nature-Inspired Design Alignment

The techniques reviewed align closely with principles of nature-inspired design. As noted by Kamalifard and Assadi-Langroudi (2018), traditional Iranian architecture effectively uses passive strategies to enhance indoor thermal comfort. Their study highlights how light, space, and human behavior interact in vernacular forms, emphasizing occupants' adaptation to natural cycles of temperature and daylight. Applying such nature-based strategies in modern architecture—such as central courtyards, shaded zones, and light-controlled domains—can enhance thermal comfort while reducing reliance on artificial energy. Nature-inspired design promotes a symbiotic relationship between building occupants and their environment. Incorporating lessons from vernacular architecture, such as managing daylight and airflow, aligns with sustainable and resilient building practices. These strategies support the goals of modern energy-efficient design while reconnecting human behavior with environmental rhythms.

CONCLUSION

This study reviewed various approaches to achieving thermal comfort while maintaining energy efficiency. From traditional ventilation methods to advanced modeling and nature-inspired solutions, multiple strategies exist to improve comfort without sacrificing sustainability. Emphasis should be placed on designing spaces that adapt to seasonal and daily climatic changes, optimizing natural ventilation, and promoting occupant awareness of environmental interaction. Such strategies not only improve well-being but also contribute to a more sustainable future.

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