



UNDRAINED SHEAR STRENGTH BEHAVIOUR OF SAND-PALM KERNEL SHELL MIXTURES FOR BACKFILL APPLICATIONS

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ABSTRACT: Sand is a key material in civil engineering, particularly as a backfill for road foundation construction. Using unsuitable materials or poor construction methods in this layer can cause premature pavement failures such as rutting, cracking and potholes, reducing road lifespan, increasing maintenance costs and compromising safety. With global sand depletion posing environmental and economic challenges, alternative materials are needed to sustain infrastructure projects. One potential substitute is palm kernel shell (PKS), an agricultural by-product generated in large quantities by the palm oil industry. This study examined PKS particles (<2 mm) mixed with sand of similar size to evaluate their effects on undrained shear strength. Samples were prepared with PKS substitution ratios of 0%, 25%, 50%, 75% and 100% (by dry mass of sand) and tested using the standard direct shear test (60 mm × 60 mm) in accordance with BS 1377:1990. The results showed that PKS significantly influenced the shear behaviour of the mixtures. The 75S:25PKS specimen achieved a shear stress of 18.40 kPa, which was comparable to 100S (17.48 kPa), although the 100PKS specimen achieving the highest peak shear stress of 30.31 kPa. It also showed approximately 51% greater vertical displacement, showing better deformability and less sand consumption. Overall, partial replacement of sand with PKS improves shear strength performance and presents a sustainable and cost-effective alternative material for road foundation backfills. The findings highlight the potential of PKS to enhance geotechnical performance while promoting waste valorisation and environmental sustainability.

Keywords: Backfill, Sand, Palm Kernel Shell and Shear Strength

1. INTRODUCTION

Backfilling materials are essential in roadbase and embankment construction because its significantly influence load-bearing capacity, compaction characteristics, drainage behaviour, pavement durability and long-term structural stability. In road engineering, backfill refers to materials used to fill excavated spaces or support pavement structures, where commonly used materials include natural sand, crushed aggregates, quarry dust, recycled construction waste, industrial by-products and stabilized soils. Natural sand remains one of the most preferred backfill materials due to its favourable gradation, ease of compaction and adequate shear strength. However, the increasing demand for road and infrastructure development has accelerated excessive sand extraction from rivers, coastal zones and mining areas, causing depletion of natural sand resources, riverbank erosion, ecological imbalance, groundwater disturbance and environmental degradation [1,2].

Sand's versatility in offering strength and stability, combined with its high degree of durability, makes it advantageous for construction and allows it to endure and cope with a range of severe conditions and climates [3]. It is necessary to use sand in backfill because of its compacted structure, which makes it ideal for filling in gaps, levelling up surfaces and allowing compaction, all of which contribute to a solid foundation [4]. However, a recent UNEP report estimated that approximately 50 billion tonnes of sand and gravel are extracted globally each year, making sand the second most consumed natural resource after water [5]. This makes the extensive use of sand as a non-renewable raw material concerning, as it surpasses natural renewal rates. Additionally, sand mining and exploitation have disrupted environmental changes, leading to adverse effects on land, water, air, flora and fauna and the soil itself, including a shortage of sand [3,6].

Due to the continuing shortage of natural sand, the focus of current studies has switched from merely finding replacement materials to comprehending how these materials function in

engineering systems. The engineering performance of replacement materials in geotechnical applications like road embankments and backfill depends not only on their sustainability and availability but also on their particle characteristics, such as size distribution, shape, surface texture and packing behaviour, which control how individual particles interact with the overall backfill skeleton [7-9]. These micro-scale characteristics have a direct impact on backfill materials' permeability, shear strength, compaction efficiency and long-term structural stability [7,10]. As a result, potential sustainable substitute materials need to be considered for both their environmental advantages and their capacity to imitate or enhance the engineering behavior of traditional sand.

Research on innovative and beneficial waste material reuse is developing in response to the mounting issues of climate change and energy conservation. Numerous factors can affect the repurposing of waste materials such as accessibility, technical compatibility, financial benefits and environmental impact. Palm kernel shell (PKS) a waste by-product produced from palm oil processing activities, has gained interest as a sustainable engineering material. Improper disposal of this agricultural waste may contribute to environmental problems, including land contamination and increased greenhouse gas emissions. Therefore, appropriate waste management and material reutilization strategies are necessary to minimize its environmental impact [11]. The incorporation of PKS a partially processed material in backfill has gained increasing attention due to its lightweight nature, durability and environmental sustainability. Particle-scale interactions play a major role in the engineering performance of sand-PKS mixtures. PKS may more successfully interlock with sand particles when it gets processed to produce a more uniform gradation. These increases packing density, decreases empty areas and improves stress distribution within the backfill matrix. Studies have shown that such mixtures can improve compaction characteristics and shear strength while maintaining a relatively lower unit weight compared to conventional backfill materials [12,13].

PKS has been increasingly investigated as a sustainable alternative material in road and pavement applications due to its lightweight nature and ability to partially replace conventional aggregates in rigid pavement, asphalt concrete and geopolymer systems [14]. In addition, PKS has been shown to exhibit good mechanical performance when incorporated into engineering materials, making it suitable for lightweight construction and geotechnical applications [15]. Furthermore, the

integration of PKS into conventional materials such as sand can enhance particle interaction and packing efficiency, leading to improved compaction and mechanical behaviour. These improvements are essential in geotechnical structures such as backfill and pavement layers, where stability and load-bearing capacity are critical. Therefore, PKS presents a promising alternative material for sustainable construction, particularly in applications involving backfill and road base systems.

The novelty of this study lies in the integration of processed PKS with sand to develop a sustainable backfill material with improved particle interaction and reduced dependency on natural sand resources. Unlike previous studies that mainly focused on concrete or lightweight structural materials, this research specifically evaluates the engineering behaviour of sand-PKS mixtures for geotechnical backfill applications. The findings are expected to contribute to sustainable construction practices, reduce environmental impacts associated with sand extraction and agricultural waste disposal and provide alternative materials for future geotechnical engineering applications.

Finally, this paper is organized as follows. Section 2 present the research significance and objectives of the study. Section 3 outlines the experimental methodology adopted in the investigation. Section 4 discusses the results, while Section 5 summarizes the conclusions.

1.1 Research Background

Thus, the literature analysis of the research lays out the current study on sand extraction and PKS, which lead to pollution exposure and the depletion of natural resources.

1.1.1 Backfill

Backfilling is the process of filling in the excavations made around a foundation or structure. Backfill materials, including soil and gravel, are commonly compacted to improve stability and provide structural support. In addition, backfilling is often used to enhance foundation insulation and improve drainage performance. Therefore, backfilling is crucial to the building process after utility lines are installed and the foundation is poured. Backfilling may be a simple procedure or a complex one requiring certain instruments, depending on the project. The backfill material must be properly compacted in order to give a strong foundation [4]. As shown in Fig. 1, backfilling is a crucial step in the construction process, typically carried out in layers following the pouring of the foundation and the installation of utility lines.

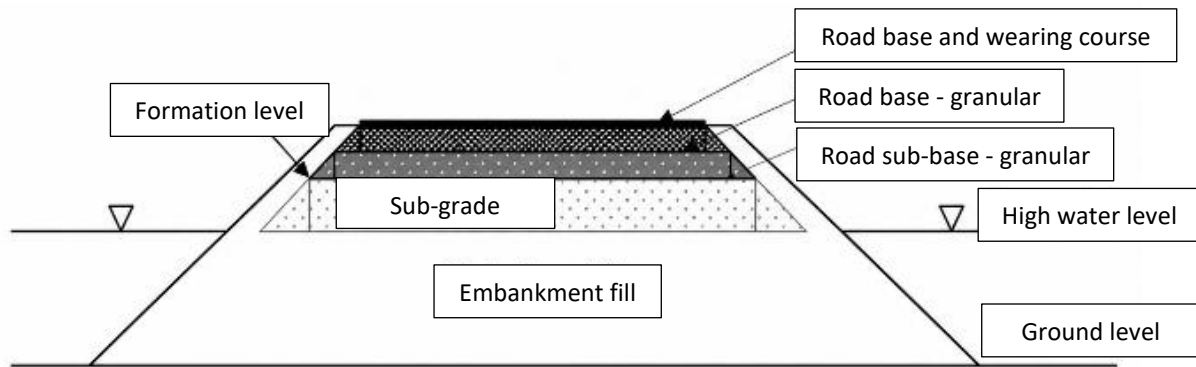


Fig. 1 Road embankment cross section (Kim & Salgado, 2018) [17]

Backfilling can be performed using a variety of methods, among them, trench compaction, flowable fill and water jetting are commonly highlighted. Of these, trench compaction is particularly suitable for geostructures such as embankments. This method has shown to be especially effective when used with sand-PKS mixtures.

Studies have shown that the incorporation of PKS into granular materials can improve load-bearing capacity and reduce overall unit weight, which is beneficial for minimizing settlement in both backfill and pavement applications such as road base layers [16]. When processed and blended with sand, PKS contributes to improved particle arrangement and enhances compaction efficiency. In addition, PKS-derived materials possess porous and irregular structures that enhance bonding and interaction within composite systems, leading to improved stability and durability [11,16]. The angular shape and rough surface texture of PKS also promote interlocking within the mixture, which enhances shear resistance and structural stability. These characteristics are desirable not only in backfill materials but also in road base applications where resistance to repeated loading is required.

1.1.2 Materials for backfill

The backfill material used in this study consists of a mixture of sand and processed PKS which serves a vital role in providing stability and support in construction applications. Backfill acts as an infill material that must adequately transfer loads and prevent excessive deformation beneath structures. In geotechnical engineering, the performance of backfill materials is heavily influenced by particle size distribution, surface texture and the interaction between particles. Properly processed PKS, when blended with sand, contributes to an improved gradation and mechanical interlocking within the mixture. This enhanced packing leads to more efficient compaction and increased resistance to shear loads, which is critical in backfilled zones that

experience dynamic loading conditions [18].

Sand is generally defined as a naturally occurring granular material that passes a sieve with approximate openings of 2 mm and is bounded by finer silt and clay particles on one side and larger gravel particles on the other. Standard classifications such as the Unified Soil Classification System (USCS), as illustrated in Fig. 2, provide a framework for categorizing soils with similar properties based on particle size and behaviour, which is essential when evaluating the suitability of materials for backfill applications. Despite similarities in purpose, different classification systems may vary slightly in cut-off limits due to diverse interpretations of particle behaviour and function [19]. Within this framework, the combination of sand with processed PKS creates a composite material that leverages the benefits of both components, the structural integrity of sand and the lightweight and rough-textured nature of PKS.



Fig. 2 Size differences between sand, gravel and silt (Atkinson, 2019) [19]

In this study, the incorporation of PKS into sand improves particle arrangement and reduces void spaces, resulting in enhanced density and more efficient load transfer. The rough and angular characteristics of PKS particles promote interparticle interlocking, which increases frictional resistance and contributes to improved shear strength and overall stability of the mixture. Recent studies have shown that PKS exhibits irregular morphology and porous surface characteristics that enhance mechanical interlocking and interfacial adhesion within composite materials, leading to improved stiffness, tensile strength and structural stability [20,21]. In addition, PKS incorporation has been found to improve deformation resistance and

strength characteristics of granular materials, making it suitable for applications such as backfill and pavement support layers as illustrated in Fig. 1. Therefore, the sand–PKS mixture used in this study provides a balanced combination of mechanical efficiency and environmental sustainability.

2. RESEARCH SIGNIFICANCE

This study contributes to sustainable geotechnical engineering by investigating the suitability of processed PKS as a partial replacement for sand in backfill applications. The research addresses critical environmental concerns associated with excessive sand mining and agricultural waste disposal while promoting sustainable material reuse. The incorporation of PKS is expected to improve particle interactions, packing efficiency and compaction characteristics of backfill mixtures while reducing overall material density. This study specifically evaluates the engineering performances of sand-PKS mixtures for backfill systems, providing valuable insight for sustainable construction and infrastructure development.

3. METHODOLOGY

This preparation follows the British Standard, which specifies particle size limits for the Direct Shear Test to ensure compatibility with the mould dimensions of 20 mm × 60 mm × 60 mm.

3.1 Methods

3.1.1 Materials

The backfill materials used in this study were sand and palm kernel shell (PKS). Both materials were oven-dried and sieved through a 2 mm sieve. Only particles passing the 2 mm sieve were used to ensure compatibility with the 60 mm × 60 mm × 20 mm direct shear box specified in BS 1377. Fig. 3 shows the sand and PKS used throughout the experimental testing.



Fig. 3 100% sand and 100% PKS

3.1.2 Sample mix design

Table 1 summarizes the five sand–PKS mixtures that were prepared: 100S, 75S:25PKS, 50S:50PKS, 25S:75PKS and 100PKS. These ratios were designed to assess how the engineering behaviour of the backfill material would change as the PKS amount increased.

Table 1. Sand-PKS mixture ratios

	SAMPLE	SAND	PALM KERNEL SHELL
1	100S	100	0
2	75S:25PKS	75	25
3	50S:50PKS	50	50
4	25S:75PKS	25	75
5	100PKS	0	100

3.1.3 Sample preparation

To produce a consistent mixture, the required quantities of sand and PKS were weighed in accordance with the specified mix ratios and well mixed. After that, the mixtures were carefully put into the shear box to reduce particle segregation.

3.1.4 Direct shear test apparatus

Direct shear testing was carried out in compliance with BS 1377: Section 7:1990 (Clause 4). A shear box, loading system, horizontal and vertical shear mechanism and digital control unit are part of the testing apparatus. Prior to testing, the apparatus was inspected and calibrated. The test apparatus is shown in Fig. 4.

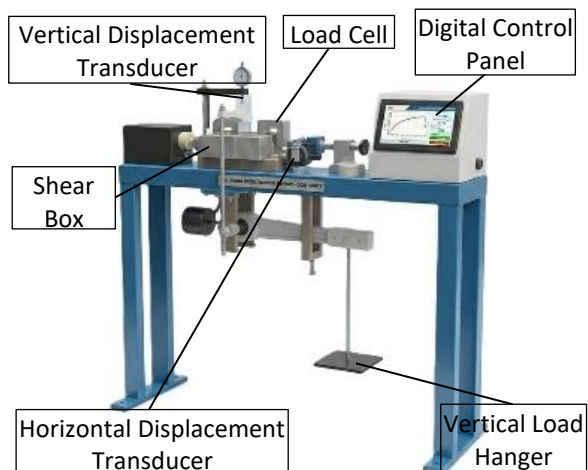


Fig. 4 Direct shear test machine used in the study

3.1.5 Direct shear testing procedure

As illustrated in Fig. 5, the shear box apparatus

was cleaned and assembled properly to ensure accurate testing conditions. After that, Fig. 6 shows the upper section of the shear box being carefully positioned and aligned with the lower section to ensure proper fitting of the apparatus.

Subsequently, as shown in Fig. 7, the bottom and top layer of plates was carefully placed in the shear box while minimizing disturbance to maintain the original condition of the sample. Then, Fig. 8 illustrates the loading cap being placed on top of the sample to distribute the applied normal load evenly across the specimen surface. Before starting the test, the apparatus alignment and levelling process were checked carefully, as shown in Fig. 9, to ensure that the horizontal shearing force would act uniformly during the test. Finally, as displayed in Fig. 10, the direct shear testing machine was operated using the digital control system at a constant loading rate of 0.5 mm/min with an applied normal load of 2.76 kPa. During the test, the shear load, vertical and horizontal displacement were continuously monitored and recorded until the specimen reached failure and the maximum shear stress obtained was used to determine the shear strength characteristics of the sample.

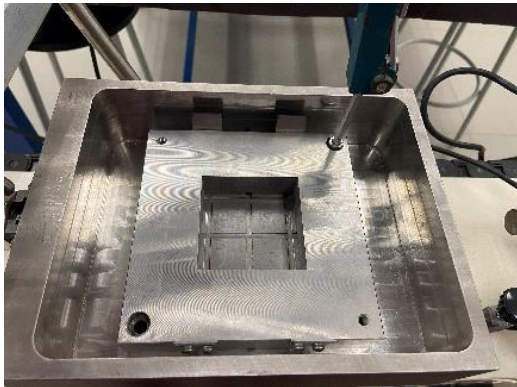


Fig. 5 Preparation and assembly of the shear box apparatus

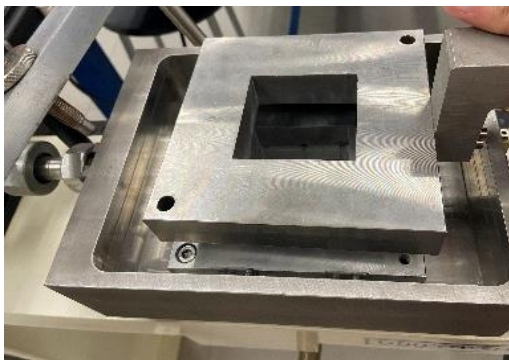


Fig. 6 Positioning and alignment of the upper shear box

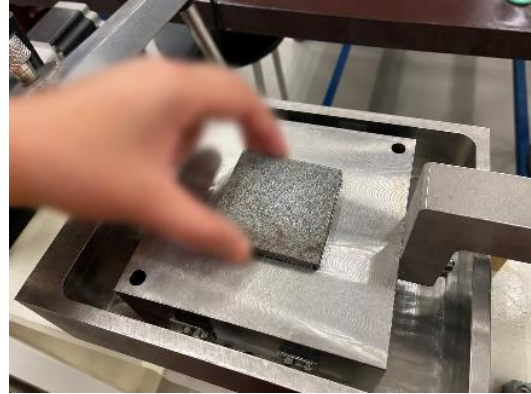


Fig. 7 Placement of bottom and top plates

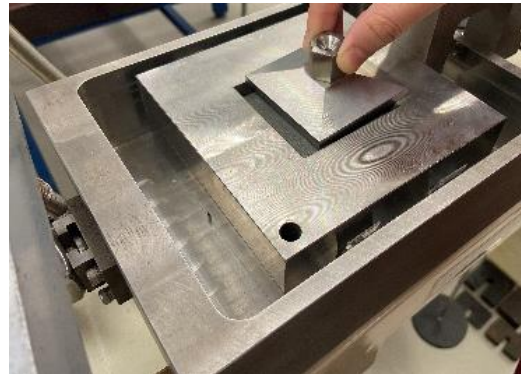


Fig. 8 Installation of the loading cap on the sample



Fig. 9 Levelling and alignment of the shear box system



Fig. 10 Digital control panel for monitoring and operating the direct shear test

4. DATA ANALYSIS AND DISCUSSIONS

4.1 Shear Stress (τ) versus Shear Strain (γ) Plots

The relationship between shear strain (γ) and shear stress (τ) for sand–PKS mixtures shown in Fig. 11. As is expected with frictional granular materials, all specimens showed a sharp rise in shear stress at low strain levels ($\gamma < 0.02$), followed by a gradual strain hardening. The shear strength increased from 17.48 kPa (100S) to 18.40 kPa (75S:25PKS) and then to 23.31 kPa (50S:50PKS) when PKS was added. These results indicate that the angular, rough PKS particles enhanced mechanical interlocking and interparticle friction while the asymmetrical sand skeleton maintained effective load transfer. However, the shear strength dropped to 12.24 kPa when the PKS content was increased to 75% because the disruption of the sand matrix mixtures weakened the force-chain network and allowed more particle movement during shearing [7,8]. The 100PKS mixtures, on the other hand, produced the highest shear stress (30.31 kPa), indicating that despite the material's increased compressibility and lower density, direct PKS–PKS interactions formed a stable frictional matrix. Overall, the findings show that a 50% PKS replacement offers the best compromise between improved structural stability, shear resistance and particle interlocking, whereas higher PKS contents need taking deformation characteristics into account for practical backfill applications [7,10].

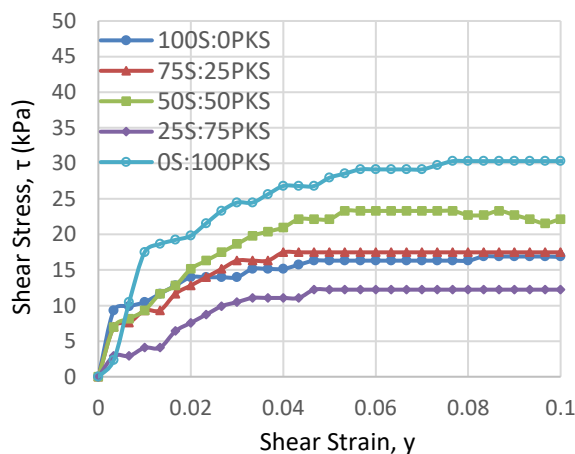


Fig. 11 Shear Stress–Shear Strain Behaviour of Sand–PKS Mixtures for Different Mixing Ratios

4.2 Vertical Displacement versus Horizontal Displacement Plots

The interaction between vertical displacement (δv) and horizontal displacement (δh) for the sand–

PKS mixtures can be seen in Fig. 12. At small horizontal displacement, all specimens showed minimal vertical displacement, which gradually increased as shearing continued. The 50S:50PKS showed moderate deformation, suggesting that PKS increased deformation performance, while the asymmetrical sand arrangement successfully reduced particle movement [7,10].

Table 2. Shear Stress Result of Sand with Varying PKS Substitution

SAMPLE	RATIO (S:PKS)	PEAK SHEAR STRESS, τ (kPa)
1	100S	17.48
2	75S:25PKS	18.40
3	50S:50PKS	23.31
4	25S:75PKS	12.24
5	100PKS	30.31

Nevertheless, 25S:75PKS showed the highest vertical displacement (0.894 mm), indicating that too much PKS disturbed the sand's arrangement, decreased confinement and caused more particle rearrangement during shearing [7,8]. Direct PKS–PKS interactions presented a quite stable deformation response, even though 100PKS also showed notable displacement (0.845 mm). On the other hand, because of sand's stiffness and resistance to deformation, the sand-dominated mixtures which are 100S and 75S:25PKS, showed the lowest vertical displacements. Overall, increasing PKS content enhanced deformability, while a balanced 50S:50PKS mixture provided the best compromise between deformation control and shear performance.

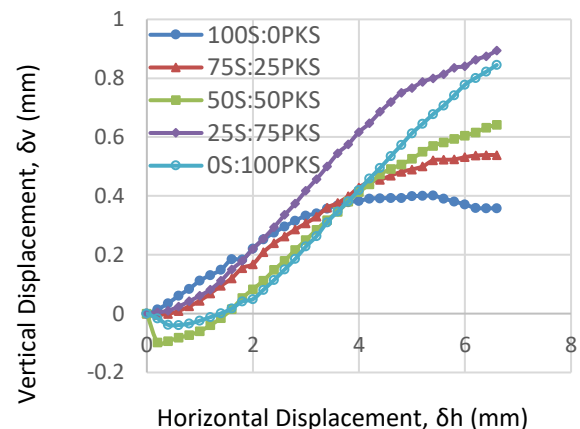


Fig. 12 Relationship between Vertical and Horizontal Displacements for Different Mixing Ratios

Table 3. Vertical Displacement of Sand with Varying PKS Substitution

SAMPLE	RATIO (S:PKS)	Vertical Displacement, δv (mm)
1	100S	0.358
2	75S:25PKS	0.539
3	50S:50PKS	0.642
4	25S:75PKS	0.894
5	100PKS	0.845

4.3 Shear Stress versus Normal Stress Plots

Fig. 13 shows a linear increase in shear stress with increasing normal stress for all S:PKS ratios, indicating compliance with the Mohr–Coulomb failure criterion. The 75S:25PKS mixture demonstrated the best-balanced engineering performance, although the 100PKS specimen showed the highest shear strength. At this ratio, the angular PKS particles improved interparticle friction, maintaining the continuous sand skeleton and making shear resistance similar to 100S, $\tan \phi = 6.42$ and 6.76 , respectively. Higher PKS amounts, on the other hand, reduced stiffness and stability in the continuous load-transfer network, even though PKS particles contributed more. In order to achieve a realistic balance between shear strength, structural stability and a sustained reduction in the use of sand, the 75S:25PKS combination is the ideal ratio.

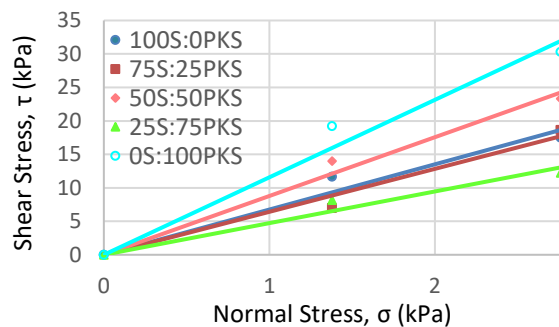


Fig. 13 Effect of Sand–PKS Mixing Ratio on Shear Stress–Normal Stress Relationship

4.4 Phi-angle versus Palm Kernel Shell Percentage Plots

The graph illustrates the relationship between PKS percentage and the internal friction angle (ϕ). Between 100S (81.58°) and 75S:25PKS (81.14°), the friction angle was almost the same, suggesting that

the sand matrix's frictional behaviour remained unchanged by minimal PKS replacement.

Table 4. Gradient of Sand with Varying PKS Substitution

SAMPLE	RATIO (S:PKS)	$\tan \phi$
1	100S	6.76
2	75S:25PKS	6.42
3	50S:50PKS	8.78
4	25S:75PKS	4.73
5	100PKS	11.57

Due to increased particle interlocking, the value increased slightly at 50S:50PKS (83.50°), but it dropped to 78.06° at 25S:75PKS, indicating that too much PKS disrupted the rigid sand skeleton and reduced effective particle interactions. Despite having the highest friction angle which is 85.05° , the 100PKS specimen's engineering performance should also take density, compressibility and material homogeneity into account. Overall, the 75S:25PKS combination is the most practical ratio since it uses less sand by substituting PKS while maintaining shear performance comparable to 100S.

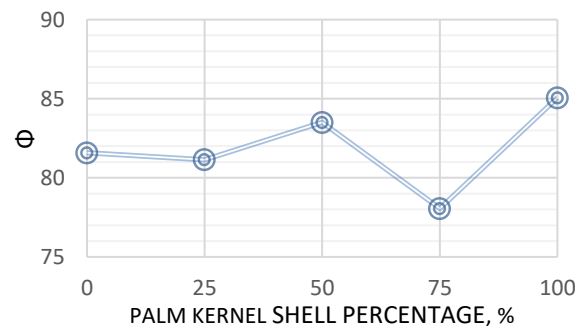


Fig. 14 Relationships between Palm Kernel Shell Percentage and phi-angle

5. CONCLUSIONS

In conclusion, the study has shown that PKS has the potential to partially replace sand in backfills used to create road foundations. Among the mixtures investigated, the 75S:25PKS ratio is recommended for practical applications, as it maintained shear performance comparable to 100S while improving deformability and reducing natural sand consumption. Higher PKS proportions, however, have a lower load-bearing capability, which may restrict their use in structural applications where great shear resistance is necessary. Future research

should evaluate the long-term performance of the optimum 75S:25PKS mixture, particularly its settlement behaviour, durability under repeated loading and environmental exposure, as well as its performance through large-scale field trials before practical implementation.

6. ACKNOWLEDGEMENTS

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