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Classification of Trinidad Oil Based Sands and Its Use in Pavement Engineering Applications

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Abstract* – The growing emphasis on sustainable infrastructure has spurred interest in repurposing waste and naturally occurring materials in pavement engineering. This research investigates the potential of oil-contaminated sand, which is in abundance in Trinidad for use as an alternative material for pavement layers. The study objectives were focused on classifying the untreated oil-contaminated sand sourced from Stollymers Quarry and subsequently enhancing its performance using waste/fine aggregate modifiers (limestone, recycled concrete, kiln dust, sharp sand). Laboratory testing included sieve analysis, direct shear, indirect tensile strength, elastic stiffness modulus, compaction, California bearing ratio, Marshall stability and flow. The results revealed a high friction angle, good cohesion and a maximum dry density of oil sand comparable to conventional materials. Untreated oil sand showed potential in subbase or capping layers but lacked durability for surface applications. In contrast, oil sand demonstrated improved mechanical properties when blended with fine aggregates at 10% replacement levels. The limestone modified blend showed significant enhancement to stiffness, moisture resistance, and tensile strength, yielding performance comparable to materials used in low-traffic roads. The study supports the reuse of oil sand in flexible pavement construction, contingent on contamination levels and stabilization techniques. A procedural framework is recommended to support the standardization of these unconventional materials.

***Keywords* - Oil Sand, aggregates, roads, pavement engineering, sustainability.**

I. Introduction

Oil sand, which is frequently referred to as tar sand, is a term that is commonly used to describe bituminous sand deposits that are high in bitumen or asphalt content and can be utilized to extract oil. These naturally occurring sands are low load-bearing materials due to the petroleum content in the soil [1]. Oil-contaminated sands (OCS) represent a significant environmental challenge and an underutilized resource in the construction industry. These sands, contaminated by hydrocarbons, possess altered geotechnical and physical properties, which, if carefully studied and managed, can offer sustainable solutions in pavement construction. The incorporation of oil sand into asphalt concrete compositions is emerging as a possible avenue for creating a more affordable pavement of similar performance.

The innovative reuse of OCS aligns with global sustainability goals by mitigating waste disposal issues and reducing the environmental impact of road building [2]. Existing research underscores the potential of treated and untreated OCS in various construction applications, highlighting key findings about their mechanical behavior, ecological safety, and practical performance [3, 4]. Studies, such as those by [5, 6], reveal that the presence of hydrocarbons influences the density, permeability, and shear strength of OCS, while others, like [3], show significant effects on plasticity and compaction properties.

Using the soil classification procedure, oil sands are generally categorized under the Unified Soil Classification System (USCS) as poorly graded sands with high plasticity, or "SP" and "SM" types, depending on clay content and gradation. This classification indicates a coarse-grained structure, often lacking particle size diversity, which impacts compaction and may reduce structural stability without blending with finer aggregates or binders. Together, these properties underscore the importance of tailoring oil sand mixtures to local traffic and climate conditions, as well as balancing stability with flexibility for optimal performance.

Zhou [7] examined the efficacy of the initial use of lean oil sand as both a base and surface material for gravel roads. The lean oil sand (LOS) roads decreased the dust generated by gravel roads. Aggregates of LOS exhibited some instability; however, specific proportions of gravel to lean oil sand exhibited elevated California Bearing Ratio (CBR) values. The use of oil sand on gravel can enhance surface hardness. This may lead to a roadway capable of accommodating increased traffic. The use of oil sand in tropical climates should be meticulously assessed. Vrtis and Romero [8] discovered that a temperature increase over 104 °C led to a decrease in the stiffness modulus of the sample. This indicates that excessive heating of the sample might adversely affect its mechanical characteristics.

Using oil sand in asphalt mixtures offers notable environmental and economic advantages. Oil sands particularly oil-contaminated sands present an opportunity to reduce the environmental impact of waste disposal. For instance, [9] found that integrating treated oil sand waste as a sand replacement in concrete reduces porosity and heavy metal leaching, making it an environmentally preferable alternative to landfill disposal [9]. When adapted for asphalt use, such treated materials could help clean contaminated sites and improve soil quality, offering dual benefits of waste reduction and infrastructure development. Economically, oil sand is a cost-effective binder alternative in regions where it is naturally abundant. Rondón-Quintana et al. [10] concluded that natural asphalts like oil sand contribute to lower project costs due to their locally available sources and reduced processing needs, in contrast to fully synthetic binders. Moreover, oil sand's high asphaltene content can improve the durability and lifespan of asphalt pavements, which could lead to reduced maintenance costs over time.

This study aims to investigate the geotechnical and physical properties of OCS to establish a standardized classification system for their use in road construction projects. Additionally, the study will also investigate the performance of oil sand combined with various blends of fine aggregates to determine the optimal percentage of oil sand needed to produce a fine mastic mix suitable for patchwork.

II. Material And Methodology

A. *Classification of the Oil Contaminated Sand*

Tar sand deposits have been present in southwest Trinidad since 1930 [11]. The oil sand samples for the testing protocols were supplied by Stollmeyer's Oil Sand Quarry in Trinidad. Figure 1 highlights the visual comparison of a dark colored heavily contaminated soil sand to typical samples of fine aggregates used locally in road construction.

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

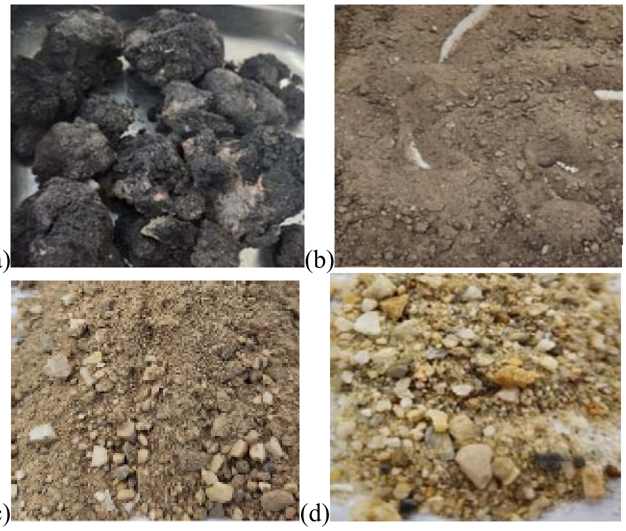

Fig. 1 Materials (a) contaminated oil sand (b) sand after oil is removed (c) limestone dust (d) sharp sand

The study materials are further characterized using the following test procedures:

- Gradation Analysis - ASTM C136 [12] determines the particle size distribution of fine and coarse aggregates. Interpolation is made for D_{10}, D_{30}, and D_{60}, which represent the particle diameters at which 10%, 30%, and 60% of the material passes through. The Coefficient of Uniformity (C_u) and Coefficient of Curvature (C_c) are estimated from particle dimensions.
- Density - ASTM D698 [13] determines maximum dry density of the compacted sample and optimum moisture content.
- California Bearing Ratio (CBR) - ASTM D1883 [14] evaluates the strength of materials for geotechnical use.

B. *Laboratory Prepared OCS Blended with Fine Materials*

This study developed fine mastic mixtures blended with fine conventional and waste materials (Figure 2). The main components of the mastic mixtures were natural aggregates: sand (SA), limestone dust (LS) and waste material; kiln dust (KD) and recycled concrete aggregate fines (RCA). No additional bitumen was added to the mixture. Table 1 gives the properties of the blending of the materials. The study specimens were prepared into cylindrical (100mm diameter by 63.5mm height) and rectangular (direct shear – 60mm length x 60mm width x 25mm height) geometries.

The assessment focused on volumetric and strength properties specifically:

- Density - ASTM D2726 [15]
  - Ensures adequate compaction which assists in reducing permeability and improves durability.
  - Affects load-bearing capacity and resistance to deformation and also evaluates air void content which helps in optimizing the material in designs to balance durability and flexibility.
- Stability & Flow - ASTM D6927 [16]
  - Measures the maximum load the asphalt specimen can withstand before failure and evaluates the mixture's flexibility.
  - Ensures adequate balance between stability, durability, and workability, thus helps predict pavement performance under traffic loads.

TABLE I
MIX DESIGN PROPORTIONS

Mixture & Material	OCS	OS-SA	OS-LS	OS-KD	OS-RCA
	%				
OCS	100	90	90	90	90
SA	0	10	0	0	0
LS	0	0	10	0	0
KD	0	0	0	10	0
RCA	0	0	0	0	10

(a) (b)

Fig. 2 Study specimens (a) Cylindrical samples (b) direct shear samples

The performance testing is used to measure the properties of elastic stiffness, cracking and rutting susceptibility, and they are as follows (Figure 3):

- Direct Shear - ASTM D3080 [17], evaluate the shear strength and bond strength of asphalt material.
- Indirect Tensile Stiffness Modulus (ITSM) - BS EN 12697-26 [18], assesses the stiffness of asphalt mixtures, which is critical for evaluating their resistance to fatigue cracking and deformation.
- Indirect Tensile Strength (ITS) - ASTM D6931 [19], determines the tensile strength of asphalt mixtures, which helps evaluate their resistance to cracking. Tensile Strength Ratio (TSR).

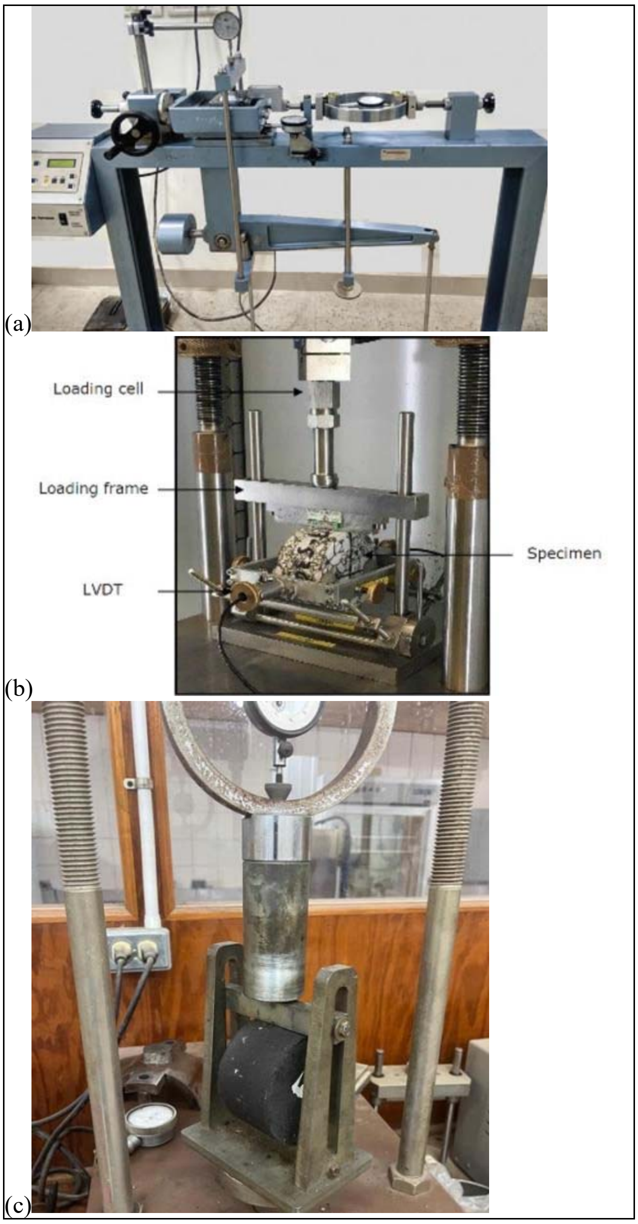

Fig. 3 Testing setup and devices (a) direct shear (b) ITSM (c) ITS

III. RESULTS

A. Material Physical Properties

The oil was extracted from the OCS sample using a centrifugal extractor and an organic solvent to ascertain the oil content. The average oil content was ascertained to be approximately 10 - 12%. This extracted oil content is lower than the 14.7% established by [20]. Nonetheless, the value is mostly comparable to the sample values presented by research [7, 8], except for the samples analyzed by [21] in Nigeria, which exhibited oil content of up to 40%. The washed oil sand, referred to as contaminated sand (CS), is further analyzed.

Figure 4 demonstrates the variation in particle sizes within the fine aggregates used in this study, while Table 2 summarizes the particle distribution metrics C_u and C_c. As per conventional geotechnical practices, a soil or aggregate would be said to be well-graded if $C_u > 4$ for sands or $C_u > 6$ for gravels, and C_c should be between 1 and 3. Limestone is seen to exhibit a dense-graded curve with a steep slope and wide particle size range, as is evident from its high C_u of 16.67. However, the fact that its C_c value is low means an irregular distribution of the intermediate particle sizes despite the wide range. RCA also exhibits a well-graded profile and its smooth continuous curve reveals an even representation of fines, intermediates, and coarse particles. Sharp sand, by comparison, is a more evenly graded material with an approximately horizontal curve, indicating that the size range is tighter with very few fines or coarse aggregates. Kiln dust, though finer dominant, is denser graded with $C_u = 7.50$ and $C_c = 1.01$, indicating a reasonably even spread of fine sizes. Oil sand's gradation curve is notably flatter and reflects poor gradation characteristics. According to the unified classification system, the study oil sand is classified as SM (silty sand). Gradation affects material properties like permeability, compaction, and stability.

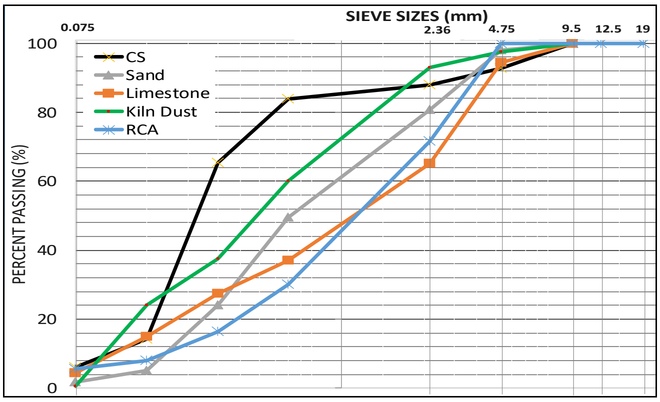

Fig. 4 Particle Size Distribution of Fine Aggregates

TABLE II

AGGREGATES PARTICLE SIZE DISTRIBUTION METRICS

Material	D_{60} (mm)	D_{30} (mm)	D_{10} (mm)	C_c	C_u
Limestone	2.0	0.36	0.12	0.54	16.67
RCA	1.75	0.6	0.18	1.14	9.72
Sand	0.75	0.32	0.18	0.75	4.17
Kiln Dust	0.60	0.22	0.08	1.01	7.50
Oil Sand	0.26	0.19	0.14	0.74	2.36

Table 3 illustrates that the densities of OCS and natural sand materials are comparable; however, upon the removal of the oil product, the density of the CS diminishes by 22%. The optimal moisture content (OMC) of the CS is significantly greater than that of sandy materials but lower than that of clay soils. Subsequent testing assessed the bearing capacity of the material via the CBR technique. Contrasting tendencies were noted between the soaked and unsoaked states of the OCS and CS samples. The moisture content in the saturated samples enhanced the strength relative to the OCS and other conventional construction materials. This behavior may be ascribed to the hydrophobic, binding, and water-resistant characteristics of the contaminants, a decrease in water-induced softening, and/or the preservation of inter-particle friction and structural integrity during immersion. OCS possesses the lowest specific gravity. This phenomenon is anticipated due to the presence of bitumen in OCS, which possesses a lower specific gravity (approximately 1.0 to 1.05) relative to the mineral particles found in natural sand (typically around 2.65) or clay (approximately 2.6 to 2.9). The bitumen either coats the mineral particles or fills the pores, thereby reducing the average specific gravity of the bulk material. These findings suggest that the elimination of oil contamination diminishes the mechanical capabilities of the material; yet the results may be equivalent to traditional construction materials such as clay and sand.

TABLE III

COMPARISON OF VARIOUS AGGREGATE MATERIALS

Material	Density (kg/m^3)	OMC (%)	Specific Gravity	Unsoaked CBR (%)	Soaked CBR (%)
OCS	1900	-	2.12	21	8
CS	1477	13	2.43	4	6
Clay	1605	20	2.71	4	2
Sand	1892	8.5	2.65	12	11

B. *Performance Evaluation of Modified OCS*

For surface course applications in low-volume road pavements, Marshall stability values are generally expected to exceed 6 kN to ensure adequate load-bearing capacity and resistance to plastic deformation. As depicted in Figure 5, none of the tested mixtures met this threshold, indicating substandard structural performance for surface layer application. Nonetheless, the incorporation of fine aggregate modifiers yielded measurable improvements in the Marshall stability of oil-contaminated sand (OCS) mixtures.

Relative to the unmodified OCS control mixture, which exhibited an average stability value of 3.5 kN, the limestone dust-modified mix demonstrated the highest stability at 4.6 kN, followed by the kiln dust (KD) modified mix at 4.1 kN. The superior performance of the limestone-modified mixture is attributed to the angularity and high surface roughness of the particles, which enhance mechanical interlock and aggregate cohesion. The improved performance of kiln dust may be related to its pozzolanic or cementitious properties, contributing to additional binding within the matrix upon compaction.

In contrast, modifications using recycled concrete aggregate and sharp sand resulted in reduced stability values when compared to the unmodified mix. This decline is likely due to incompatibility with the OCS matrix, lower particle interlock, or diminished adhesive bonding capacity, which collectively compromise the structural integrity of the compacted specimen.

The Marshall flow values revealed a contrasting trend. The RCA-modified mixtures exhibited the greatest resistance to deformation (lowest flow values), suggesting increased stiffness, while the SA-modified mixtures displayed the highest flow, indicative of insufficient structural restraint and lower resistance to shear deformation.

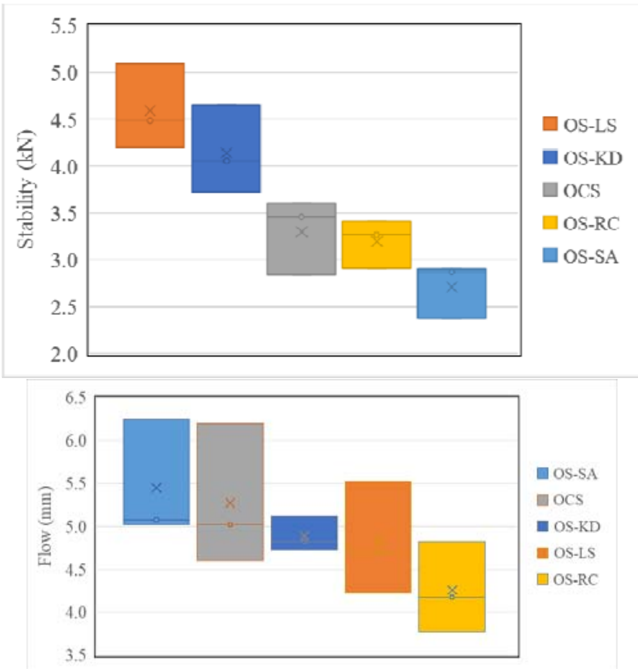

Fig. 5 Stability and Flow of modified OCS material

The Indirect Tensile Stiffness Modulus test was employed to evaluate the resilient stiffness characteristics of the modified oil sand mixtures under repeated loading a critical indicator of their load-spreading ability and structural integrity in flexible pavement systems. Conventional bituminous pavement layers typically exhibit ITSM values in the range of 1000-4000 MPa. For a well-compacted granular base, subbase and stabilized subgrade; the ranges are 300-600 MPa, 100-300 MPa and 50-300 MPa, respectively. In stark contrast, the modified mixtures investigated in this study demonstrated substantially lower stiffness moduli, ranging from 92 to 436 MPa, as illustrated in Figure 6. The unmodified oil-contaminated sand control mixture yielded a stiffness modulus of 129 MPa, ranking third among the test specimens.

The inclusion of limestone dust as a fine aggregate modifier resulted in the highest stiffness modulus among all modified mixes, reaching levels comparable to those expected for base (> 300 MPa). These findings suggest that certain mineral fillers, particularly those with favorable morphological characteristics, can substantially improve the stiffness of oil sand-based mixtures.

The observed enhancement in stiffness performance for the limestone and recycled concrete (RC) modified mixtures is likely attributed to the angularity and rough texture of the constituent particles. These properties promote mechanical interlock and particle friction, thereby increasing load distribution efficiency and improving resistance to deformation. Conversely, mixtures modified with kiln dust and sharp sand showed marginal improvement relative to the control. This limited performance gain is presumed to result from their finer gradation and smoother particle surfaces, which contribute minimally to the structural framework and interparticle friction within the mix.

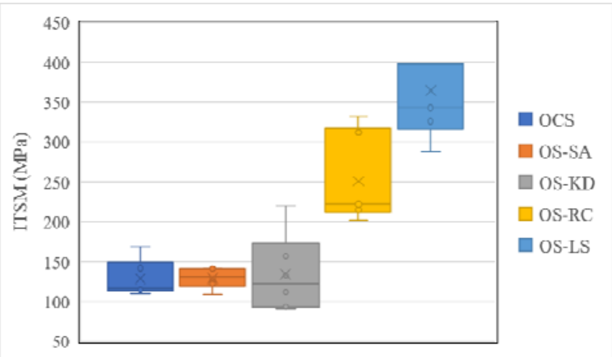

Fig. 6 ITSM of modified OCS material

The Direct Shear Test is a fundamental geotechnical method used to evaluate the shear strength characteristics of granular and cohesive soils. It quantifies resistance to shearing along a defined failure plane, typically reported in terms of the angle of internal friction (ϕ). Higher internal friction angles are indicative of greater interparticle friction and improved mechanical interlock, which collectively enhance the material's structural stability, particularly under compressive loading. Materials exhibiting internal friction angles exceeding 40° are classified as having excellent shear resistance typical of well-graded, angular aggregates such as crushed stone. Angles within the range of 30° to 40° suggest moderate shear strength, commonly observed in well-compacted silty sands. Conversely, friction angles below 30° are characteristic of low shear resistance materials, such as soft, fine-grained clays.

As presented in Figure 7, the unmodified Trinidad oil sand demonstrated superior shear strength performance, achieving an internal friction angle of 48°, which classifies it as a highly resistant granular material. Mixtures modified with recycled concrete (RC) exhibited a moderately reduced friction angle of 37.7°, indicating a decrease in shear resistance. Notably, all modified blends displayed lower friction angles compared to the unmodified oil sand, suggesting a general decline in shear strength with additive incorporation. This reduction in internal friction angle across modified mixtures may be attributed to the disruption of the original oil sand's compacted granular matrix. The introduction of non-cohesive or poorly graded modifiers likely interferes with the particle interlock mechanism, reducing overall shear resistance. In particular, higher dosages of additives may exacerbate this effect by diluting the cohesive and frictional integrity of the oil sand matrix, leading to diminished mechanical performance under shear loading.

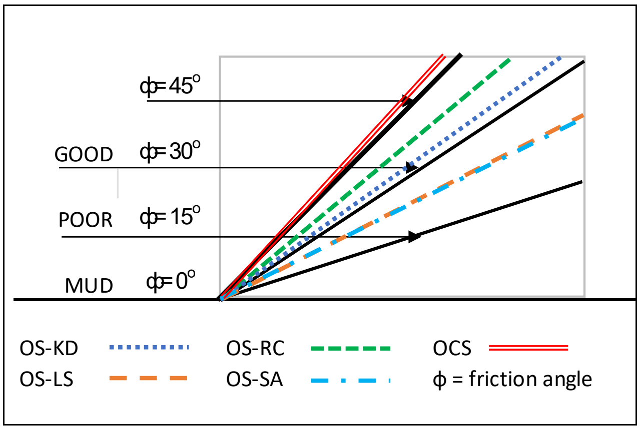

Fig. 7 Direct shear friction angle properties of study materials

The Indirect Tensile Strength results under both dry and wet conditioning are illustrated in Figure 8. For surface course bituminous mixtures, ITS values typically range from 0.7 to 1.5 MPa, as per industry standards. However, the oil-sand modified asphalt mixtures evaluated in this study exhibited significantly lower ITS values, averaging approximately 0.28 MPa. Among the various additive combinations assessed, the mixture incorporating 10% limestone filler yielded the highest ITS value of 0.53 MPa, corresponding to a 156% increase relative to the unmodified oil sand control mixture, which registered an ITS of 0.34 MPa. The mix amended with recycled concrete aggregate (RCA) also demonstrated modest performance enhancement, attaining an ITS of 0.36 MPa.

Conversely, the remaining modified blends failed to show appreciable improvements in tensile strength, suggesting suboptimal performance in terms of cracking resistance, fatigue life, and durability under moisture ingress. Across all mixtures, a reduction in tensile strength was observed under wet conditioning compared to dry, indicating a susceptibility to moisture-induced damage. This behavior aligns with established mechanistic understanding, wherein water disrupts the adhesive bond between binder and aggregate, thereby reducing cohesive strength within the asphalt matrix.

Moisture sensitivity was further quantified using the Tensile Strength Ratio (TSR), defined as the ratio of wet ITS to dry ITS. As shown in Figure 8, TSR values for all modified mixtures were lower than that of the unmodified control, with the exception of the limestone-modified blend, which achieved the highest TSR of 0.95. This suggests that limestone fillers contribute to enhanced moisture resistance, likely due to its fine gradation and improved binder-aggregate interaction under wet conditions.

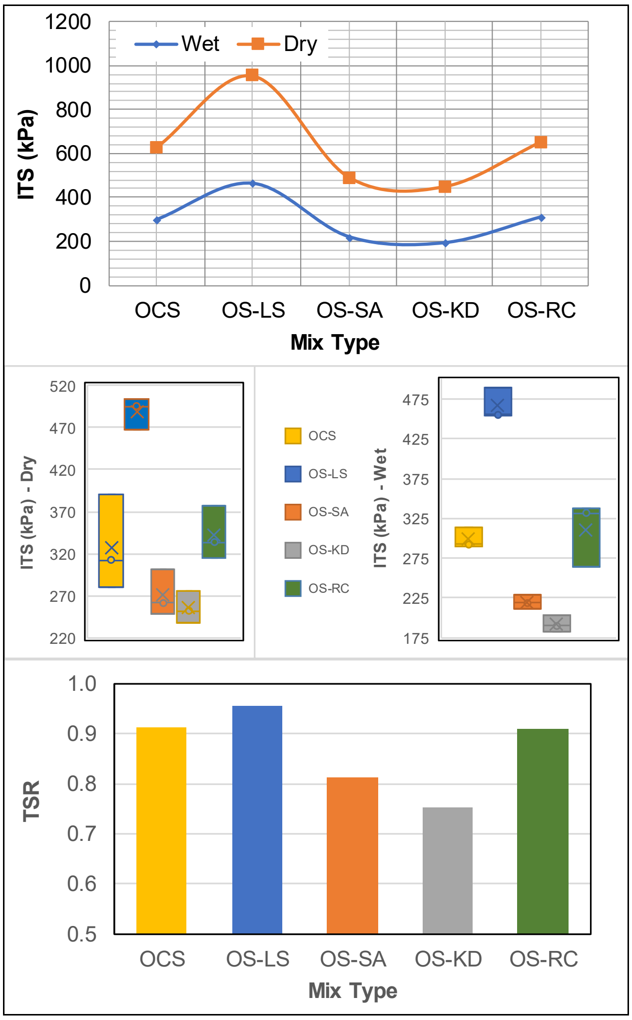

Fig. 8 ITS and TSR of modified OCS material

C. Key Observations and Summary

Table 3 summarizes the performance ranking of five modified oil sand (OS) mixtures across six different laboratory tests used to assess the effects of modifiers on Density, Stability, Flow, Tensile Strength Ratio, Indirect Tensile Stiffness Modulus and Internal Friction Angle. Rankings are from 1 (best) to 5 (worst), and the overall rank reflects average performance across all tests. The key observations from the ranking are:

- Oil Sand + Limestone Dust consistently ranked 1st or 2nd in almost all categories, including Density, Stability, TSR, and ITSM, securing the top overall rank (1st). This suggests limestone dust is the most effective modifier, significantly improving both mechanical and moisture resistance properties.
- Oil Sand + Recycled Concrete achieved a balanced performance with mid-to-high rankings across most parameters, especially in ϕ (2nd) and ITSM (2nd). Its overall rank is 2nd, indicating that recycled concrete is a viable secondary modifier with stiffness and frictional benefits.
- Unmodified Oil Contaminated Sand had a mixed performance; it had the highest internal friction angle but low rankings in stiffness and density. It placed 3rd overall, suggesting that while it possesses good shear resistance naturally, it lacks mechanical strength and durability.
- Oil Sand + Kiln Dust showed moderate performance, ranking well in density (2nd) and stability (2nd), but poorly in TSR (5th) and ϕ (3rd). Its overall rank ties for 3rd, indicating some improvement in structural performance, though poor moisture sensitivity limits its desirability.
- Oil Sand + Sharp Sand performed poorly across most parameters, with the lowest rankings in stability, flow, and ϕ. It ranked 4th overall, showing that sharp sand is the least effective modifier, possibly due to poor interlock or incompatibility.

TABLE III
SUMMARY AND RANKING OF MIXTURES

Test	Mix Type and Ranking				
	OCS	**OS-LS**	**OS-SA**	**OS-KD**	**OS-RC**
Density	4	1	3	2	5
Stability	3	1	5	2	4
Flow	4	2	5	3	1
TSR	2	1	4	5	3
ITSM	4	1	4	3	2
ϕ	1	4	5	3	2
OVERALL RANK	**3**	**1**	**4**	**3**	**2**

IV. Conclusions

This study critically evaluated the classification and engineering suitability of oil-contaminated sand (OCS), sourced from Stollymers Quarry, for potential use in pavement applications. The unmodified material, characterized by approximately 12% oil content by mass, was found to be a poorly graded fine sand with unique mechanical properties that diverge significantly from those of conventional pavement materials. The presence of bituminous oil substantially enhances the cohesion and angle of internal friction, indicating a strengthening effect. However, this strength is highly sensitive to moisture and temperature variations, and chemical washing of the material resulted in considerable reductions in both strength and density highlighting the oil's pivotal role in the material's behavior. Despite these enhancements in shear strength, unmodified OCS exhibited inherently low stability, high flow, and poor rutting resistance, rendering it unsuitable for high-performance pavement layers such as base or surface courses. It also displayed low indirect tensile strength (ITS), which further limits its applicability in demanding traffic scenarios. Nevertheless, it performed comparably to sharp sand under soaked California Bearing Ratio (CBR) conditions, suggesting viability for use in subbase or capping layers, especially in areas with aggregate scarcity.

To enhance the engineering properties of OCS, a range of fine aggregate modifiers were introduced. Among these, a 10% addition of limestone fines significantly improved the material's stability, flow characteristics, moisture resistance, stiffness, and resistance to rutting and cracking. Notably, modifier type, particle size, and dosage were found to strongly influence the extent of improvement, with sharp sand particularly enhancing rutting resistance. The modified oil sand mixtures demonstrated performance improvements suitable for low-traffic road applications, though still falling short of the performance standards associated with conventional hot mix asphalt (HMA).

In conclusion, OCS can be classified as a modified marginal material whose performance can be markedly enhanced through targeted modification strategies. While unmodified OCS is limited in structural applications due to low stability and gradation issues, its reuse in substructural pavement layers offers environmental and economic advantages. Moreover, modification with fine aggregates, particularly at optimal replacement levels such as 10%, can elevate its suitability for light-duty pavement infrastructure. Future research should prioritize curing times, field trials, hybrid blend formulations, and long-term durability assessments to validate laboratory findings and support broader implementation in pavement engineering.

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