

Elastic Stiffness and Indirect Tensile Strength Ratio of Palm Kernel Shell Ash–Oyster Shell Ash Modified Asphalt Concrete Under Full Moisture Conditioning

Enyi, Festus Weneka^{1*}, Igwe, E. A.¹, Otto, C. G.¹

¹Department of Civil Engineering,
Faculty of Engineering, Rivers State University,
Nkpolu-Oroworukwo, Port Harcourt, Nigeria

*Corresponding author: enyi.weneka@rsu.edu.ng
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Abstract

Moisture-induced damage is one of the leading causes of premature failure in asphalt pavements, and the search for sustainable filler materials that can delay stripping and stiffness loss remains an active research area. This study evaluates the elastic stiffness and indirect tensile strength ratio (ITSR) of asphalt concrete modified with blends of palm kernel shell ash (PKSA) and oyster shell ash (OSA) under full moisture conditioning. PKSA and OSA were combined at 0, 2, 4, 6, 8 and 10% by weight of filler in a 6 × 6 matrix, and Marshall specimens were prepared, conditioned by continuous water immersion for 0, 1, 2, 4, 7 and 14 days, and tested for tensile and compressive elastic modulus, indirect tensile strength (ITS) and ITSR. The unmodified mix recorded a dry tensile elastic modulus of about 0.77×10^3 MPa, rising to a maximum of about 1.14×10^3 MPa at 10% OSA with 0% PKSA, while progressive PKSA addition beyond 2% consistently reduced stiffness at every OSA level. After 14 days of immersion, the tensile modulus of the control mix fell to 0.34×10^3 MPa (a loss of over 50%), whereas the 10% PKSA–OSA blend retained 0.52×10^3 MPa over the same period. The ITSR of the control mix declined from 100% at day 0 to 65.6% at day 14, below the AASHTO T283 minimum of 80% beyond day 2, while the best-performing blend (2% PKSA, 2% OSA) sustained an ITSR of 85.9% after two days and the 10% PKSA–OSA blend recorded the highest 14-day ITSR of 69.7%. These findings confirm that low-to-moderate PKSA–OSA combinations, particularly around 2% PKSA with elevated OSA, measurably delay moisture-induced stiffness and strength loss relative to the unmodified control, supporting their use as sustainable, waste-derived alternatives to conventional mineral fillers in moisture-prone pavement environments.

Keywords: asphalt concrete; palm kernel shell ash; oyster shell ash; moisture damage; elastic modulus; indirect tensile strength ratio

1. Introduction

Asphalt pavements remain the dominant road-surfacing solution worldwide because of their cost-effectiveness, riding comfort and ease of maintenance, yet moisture-induced damage continues to be one of the most persistent threats to their long-term performance (Albayati & Ismael, 2025). When water infiltrates the asphalt mixture, it weakens the adhesive bond between the bituminous binder and the aggregate or degrades the cohesion of the mastic itself, producing stripping, loss of

stiffness, rutting and premature fatigue cracking (Wang et al., 2019; Omar et al., 2020). Because elastic stiffness and the indirect tensile strength ratio (ITSR) are among the most direct indicators of how a mixture's load-bearing capacity responds to water ingress, they are widely used to screen candidate filler materials before field trial (Radwan et al., 2025).

Conventional mineral fillers such as hydrated lime, cement and limestone dust have long been used to stiffen the mastic, reduce permeability and improve adhesion, thereby mitigating moisture damage (Xu et al., 2021; Tiwari et al., 2023). Their production, however, carries a non-trivial environmental cost in terms of resource depletion and carbon emissions, which has motivated growing interest in organic and waste-derived fillers such as lignin, biochar and agricultural or marine-shell ashes (Yaro et al., 2023; Jwaide et al., 2024). Palm kernel shell ash (PKSA), an abundant agro-industrial by-product in palm-oil producing regions, is rich in silica and residual carbon and has been reported to rival hydrated lime in moisture-damage resistance when used in dense-graded asphalt mixtures (Dergipark, 2024; Inyang et al., 2024). Oyster shell ash (OSA), a calcium-carbonate-rich marine by-product, has similarly been shown to stiffen asphalt mastic and improve Marshall properties when used as filler (Ajah & Michael, 2023; Rani et al., 2023).

Despite these encouraging single-filler results, few studies have systematically examined PKSA and OSA in combination, and fewer still have evaluated their elastic and tensile-strength response under full moisture conditioning that extends to 14 days of continuous immersion, a scenario more representative of prolonged rainfall or poor subsurface drainage than the short-term (24-48 hour) soaking regimes typically reported in the literature (Albayati & Ismael, 2025). This article addresses that gap by reporting the tensile and compressive elastic modulus, indirect tensile strength and ITSR of asphalt concrete blended with PKSA and OSA across a 6×6 dosage matrix (0-10% each) under a moisture-conditioning schedule of 0, 1, 2, 4, 7 and 14 days, with the goal of identifying blend proportions that best preserve stiffness and tensile strength retention under severe, prolonged moisture exposure.

2. Related Independent Published Work

A growing body of independent literature supports the use of shell- and husk-derived ashes as asphalt fillers, though most studies examine a single filler type rather than a blend. Ajah and Michael (2023) incorporated oyster shell ash alone into dense-graded asphalt concrete and reported that Marshall stability and indirect tensile properties improved up to an optimum OSA content before declining at higher dosages, a trend consistent with the OSA-driven stiffening observed in the present blended system. Rani et al. (2023) combined oyster shell ash with high-density polyethylene in porous asphalt and likewise found that OSA addition raised Marshall stability, attributing the improvement to the angular, calcium-rich particle morphology of OSA, which mirrors the mechanism proposed here for the OSA-dominant stiffness gains at low PKSA content. Kim et al. (2020) evaluated waste oyster shell powder as a mineral filler in hot-mix asphalt and confirmed its feasibility as a partial substitute for conventional limestone filler, reporting comparable or improved moisture-conditioned strength retention.

On the palm-derived side, Dergipark (2024) found that palm kernel shell ash could replicate or exceed the moisture-damage resistance of hydrated lime in dense-graded mixtures at low dosage, while Oktavia et al. (2024) reported that PKSA addition improved durability and Marshall values up to an optimum content beyond which performance declined, a pattern that closely parallels the single-filler PKSA trend recorded in the present study, where stiffness and ITS values decreased steadily once PKSA exceeded roughly 2%. Inyang et al. (2024) examined PKSA as filler in

reclaimed-asphalt-pavement mixtures and observed measurable improvements in micro-structural bonding and mechanical behaviour, while the Global Scientific Journal (2024) study on PKSA in conventional asphalt mixtures similarly reported an optimum dosage beyond which stability and strength properties deteriorated because of excessive fines increasing binder demand.

Relative to these single-filler studies, the present work extends the literature by evaluating PKSA and OSA in combination across a full dosage matrix rather than singly, and by conditioning specimens to 14 days of continuous immersion rather than the 1-2 day soaking windows common in most of the cited independent studies (e.g., Ajah & Michael, 2023; Kim et al., 2020). The results confirm the OSA-driven stiffening and PKSA-driven softening trends reported independently in the single-filler literature, but further show that blending a small, fixed proportion of PKSA (about 2%) with increasing OSA content offsets PKSA's stiffness penalty and yields ITSR values that remain measurably above the unmodified control even after prolonged immersion — a synergistic effect that has not been quantified in the reviewed single-filler studies. This is broadly consistent with the general observation of Muhmood et al. (2025) that moisture-damage resistance in hot-mix asphalt is most effectively improved when filler or additive systems are optimised jointly rather than in isolation.

3. Materials and Methods

3.1 Materials

The bitumen binder (60/70 penetration grade) was sourced from HCC Asphalt Plant, Emohua, Rivers State. Coarse aggregate (gravel) and fine aggregate (sand) were obtained from the Building Materials Market, Mile 3, Diobu, Port Harcourt. Palm kernel shells were sourced from a palm-oil processing plant along the Elele-Owerri expressway and calcined to ash, while oyster shells were obtained from waterside markets and similarly processed to ash. Potable water used for mixing and immersion conditioning was obtained from the Civil Engineering Laboratory, Rivers State University.

3.2 Material Characterization

The bitumen, aggregates and filler materials were characterised in accordance with the standards summarised in Table 1 prior to mixture production. Laboratory testing returned a bitumen specific gravity of 1.02, a penetration grade of 60/70, a Saybolt Furol viscosity flow time of 69.3 seconds and a softening point of 49.5 °C, confirming the binder's suitability for hot-mix asphalt production in accordance with the Asphalt Institute (2014) specification.

Table 1. Material characterisation tests and applicable standards.

Material	Property tested	Standard
Aggregate / filler	Specific gravity	ASTM C128 (2001)
Aggregate / filler	Sieve analysis / gradation	ASTM C136 (2001)
Bitumen	Specific gravity	ASTM D70 (2003)
Bitumen	Penetration	ASTM D5 (2017)
Bitumen	Viscosity (Saybolt Furol)	ASTM D88 (2019)
Bitumen	Softening point	ASTM D36 (2020)

Material	Property tested	Standard
Compacted mix	Indirect tensile strength	ASTM D6931 (2017)
Compacted mix	Indirect tensile strength ratio	ASTM D4867

3.3 Blending Schedule and Specimen Preparation

The optimum binder content (OBC) was first determined for the unmodified mix using the Marshall method (ASTM D1559) at bitumen contents of 4.0-6.0% in 0.5% increments, with the OBC taken as the average of the binder contents at maximum stability, maximum density and the median (4%) air-void limit. Aggregates were batched by weight and heated to 150-160 °C prior to blending with the preheated binder (Asphalt Institute, 2016). PKSA and OSA were then blended into the aggregate at the proportions shown in Table 2, each combination compacted with 75 blows per face using a 6.5 kg rammer falling from 450 mm (heavy-traffic design), in line with ASTM D6927. Three specimens were produced per combination.

Table 2. Blending matrix of palm kernel shell ash (PKSA) and oyster shell ash (OSA), percent by weight of filler.

PKSA (%)	OSA 2%	OSA 4%	OSA 6%	OSA 8%	OSA 10%
2	2:2	4:2	6:2	8:2	10:2
4	2:4	4:4	6:4	8:4	10:4
6	2:6	4:6	6:6	8:6	10:6
8	2:8	4:8	6:8	8:8	10:8
10	2:10	4:10	6:10	8:10	10:10

For moisture conditioning, compacted specimens were weighed in air and in water, then fully submerged in a controlled water bath for 0 (unconditioned baseline), 1, 2, 4, 7 and 14 days. Specimens were subsequently pre-heated at 60 °C, the destructive temperature specified by the Asphalt Institute (1997) for simulating worst-case in-service damage, before testing.

3.4 Determination of Elastic Modulus and Indirect Tensile Strength Ratio

Tensile and compressive elastic moduli were computed from the measured tensile and compressive strengths and corresponding strains, using standard elastic relationships incorporating Poisson's ratio for the compacted mixtures. Indirect tensile strength (ITS) was obtained from the failure load at diametral compression as:

$$\sigma_t = 2P / (\pi dl)$$

where σ_t is the tensile strength (MPa), P is the failure load (N), d is the specimen diameter (mm) and l is the specimen thickness (mm), following ASTM D6931. The indirect tensile strength ratio (ITSR) was then computed as the ratio of the tensile strength of the moisture-conditioned specimen (σ_{Tw}) to that of the unconditioned specimen (σ_{Td}), expressed as a percentage, in accordance with ASTM D4867:

$$ITSR (\%) = (\sigma_{Tw} / \sigma_{Td}) \times 100$$

An ITSR of at least 80% is the minimum threshold recommended by AASHTO T283 for acceptable moisture resistance and was used as the benchmark for interpreting results in this study.

4. Results and Discussion

4.1 Elastic Modulus of Unconditioned (Dry) Specimens

Figure 1 presents the tensile elastic modulus of unconditioned specimens across the full PKSA-OSA matrix. The unmodified control (0% PKSA, 0% OSA) recorded a tensile modulus of about 0.77×10^3 MPa. At every OSA level, introducing a small proportion of PKSA up to about 2% consistently raised stiffness, with the highest overall value of approximately 1.14×10^3 MPa recorded at 0% PKSA combined with 10% OSA, confirming that OSA is the primary stiffening agent in the blend. Beyond 2% PKSA, the modulus declined progressively at every OSA level, indicating that excess PKSA overcrowds the filler fraction, increases the surface area requiring binder coating, and reduces the effective binder film thickness available for cohesive bonding. This behaviour mirrors the single-filler PKSA trend reported by Oktavia et al. (2024) and the Global Scientific Journal (2024) study, both of which identified an optimum PKSA dosage beyond which mechanical performance deteriorated.

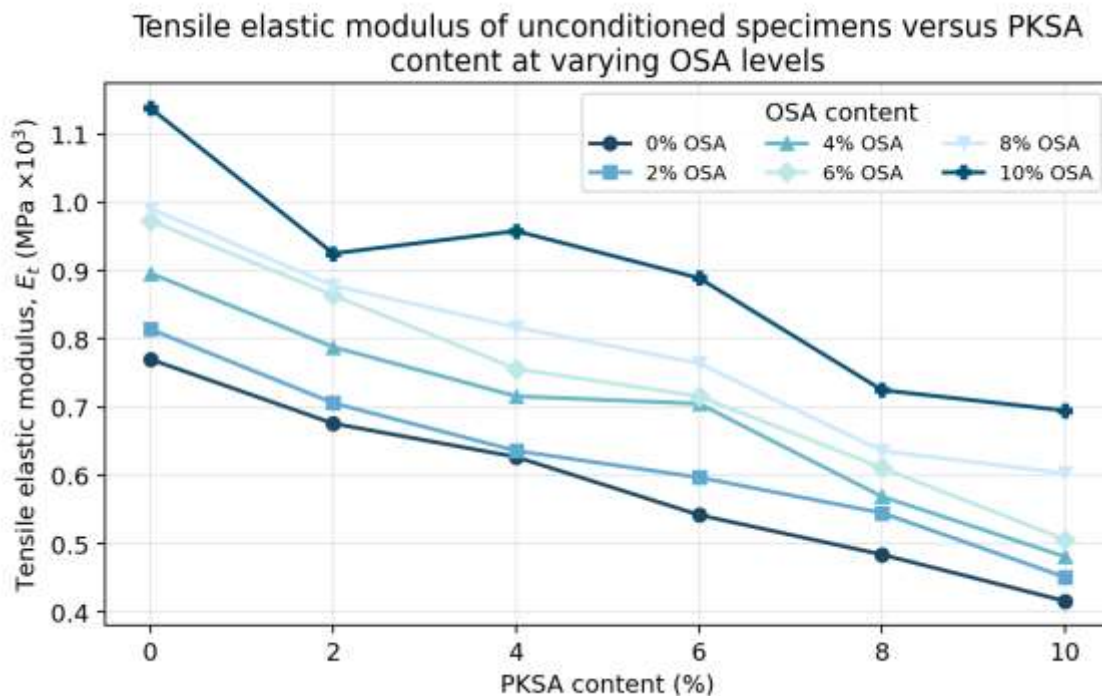


Figure 1. Tensile elastic modulus of unconditioned specimens versus PKSA content at varying OSA levels.

4.2 Elastic Modulus Under Full Moisture Conditioning

Figures 2 and 3 present the tensile and compressive elastic modulus, respectively, of the blended mixes across the six immersion periods (0-14 days). Both moduli decreased progressively with immersion time for every blend, confirming the expected loss of stiffness due to moisture ingress and weakening of the binder-aggregate bond (Sulejmani et al., 2019). The unmodified control exhibited the steepest decline, falling from about 0.73×10^3 MPa at day 0 to 0.34×10^3 MPa at day 14 in tension (a loss exceeding 50%), and from 0.43×10^3 MPa to 0.22×10^3 MPa in compression over the same period. In contrast, the 10% PKSA-OSA blend retained substantially

higher stiffness at every immersion age, recording 0.52×10^3 MPa in tension and 0.30×10^3 MPa in compression at day 14.

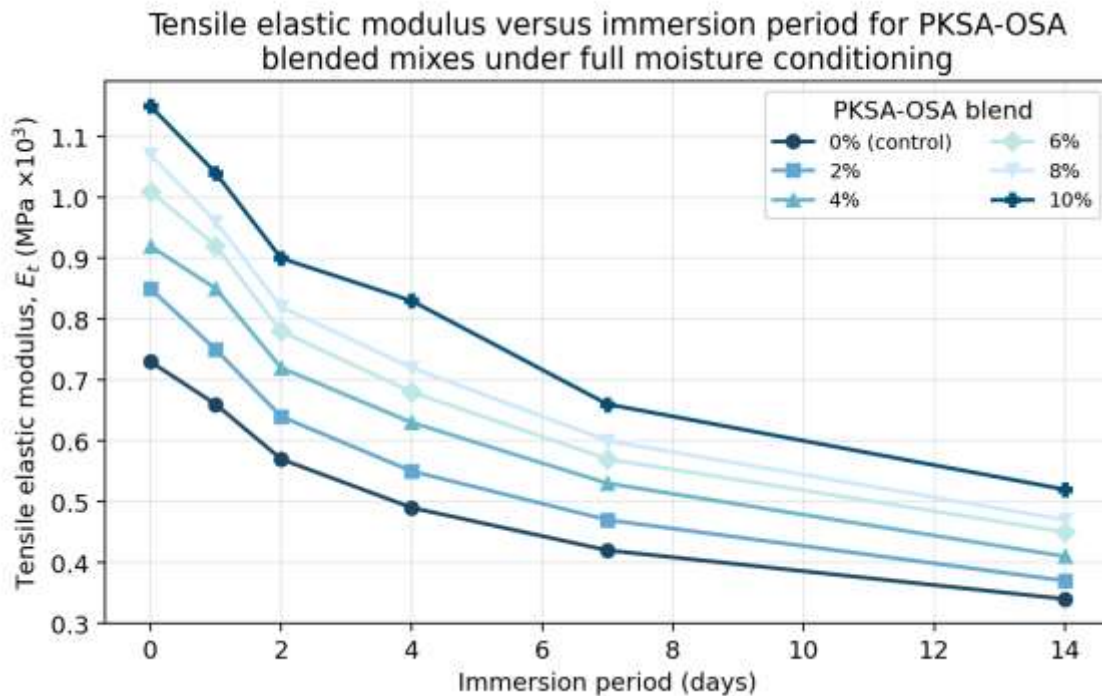


Figure 2. Tensile elastic modulus versus immersion period for PKSA-OSA blended mixes under full moisture conditioning.

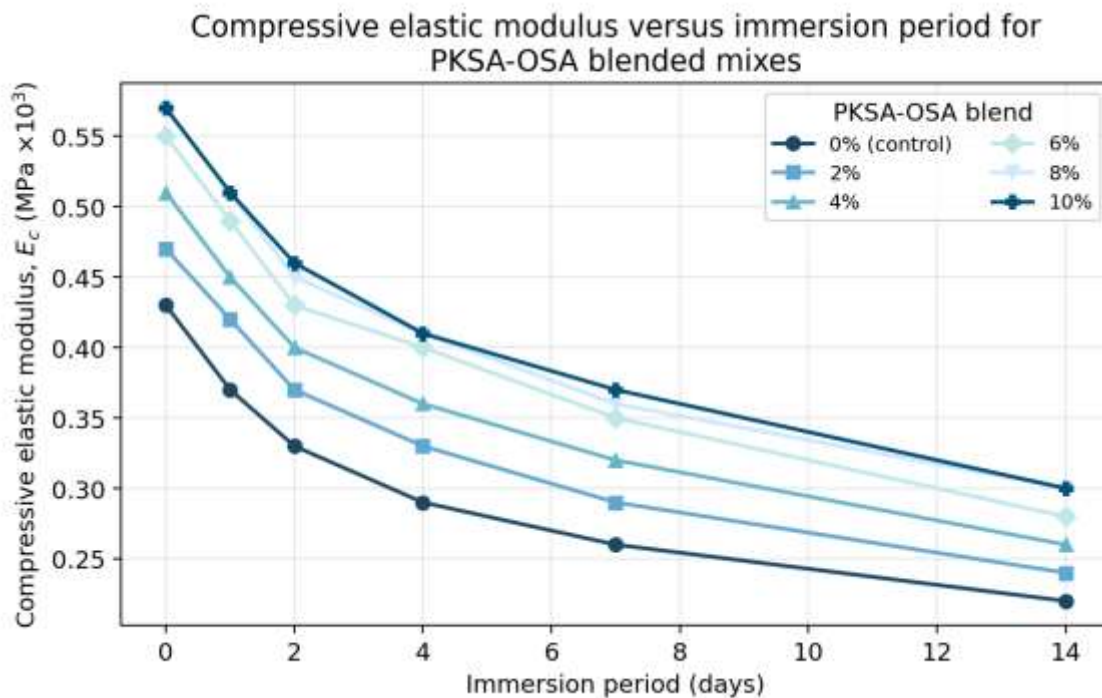


Figure 3. Compressive elastic modulus versus immersion period for PKSA-OSA blended mixes.

The consistently higher retained stiffness of the blended mixes relative to the control across all immersion periods indicates that the calcium-rich, angular OSA particles densify the mastic and reduce the pathways available for water ingress, an effect consistent with the moisture-conditioning behaviour reported for oyster-shell-modified mixtures by Kim et al. (2020) and Rani et al. (2023). The gradual convergence of the curves at 14 days, however, suggests that prolonged immersion progressively erodes the stiffness advantage conferred by the fillers, underscoring the importance of testing beyond the short 24-48-hour windows typically used in single-filler studies.

4.3 Indirect Tensile Strength of Unconditioned Specimens

Figure 4 shows the indirect tensile strength (ITS) of unconditioned specimens across the PKSA-OSA matrix. As with the elastic modulus, ITS increased with OSA content and decreased with PKSA content beyond about 2%, with the highest dry ITS of 3.18 N/mm² recorded at 10% OSA, 0% PKSA, compared with 2.54 N/mm² for the unmodified control. This confirms that the OSA-driven densification mechanism observed for stiffness also translates directly into tensile strength gains.

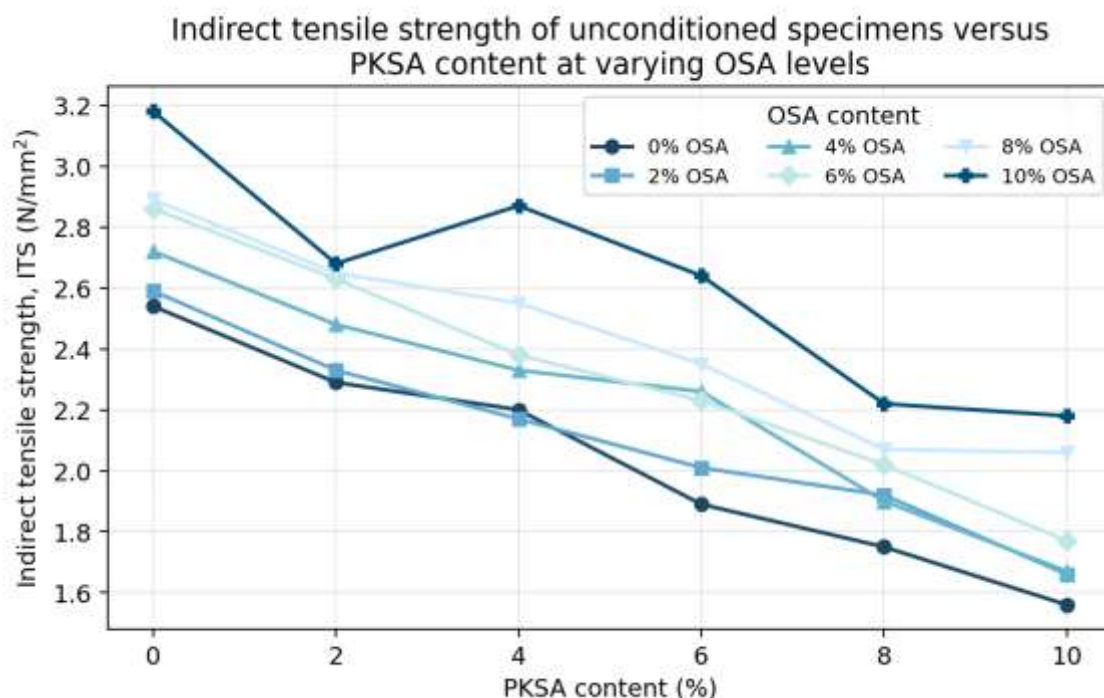


Figure 4. Indirect tensile strength of unconditioned specimens versus PKSA content at varying OSA levels.

4.4 Indirect Tensile Strength Ratio Under Full Moisture Conditioning

Figure 5 presents the ITSR of the blended mixes over the six immersion periods, benchmarked against the AASHTO T283 minimum of 80%. All mixes began at 100% ITSR by definition at day 0 and declined steadily thereafter. The unmodified control fell below the 80% threshold between days 2 and 4, reaching 85.9% at day 2 and 80.8% at day 4, before dropping further to 65.6% by day 14. The best-performing low-dosage blend (2% PKSA, 2% OSA) achieved the highest short-term ITSR of 85.9% at day 2, while the 10% PKSA-OSA blend achieved the highest ITSR at every

subsequent conditioning age, including 89.5% at day 2, 86.4% at day 4, 80.4% at day 7 and 69.7% at day 14, the last of which represents an improvement of 4.1 percentage points over the control at the same age.

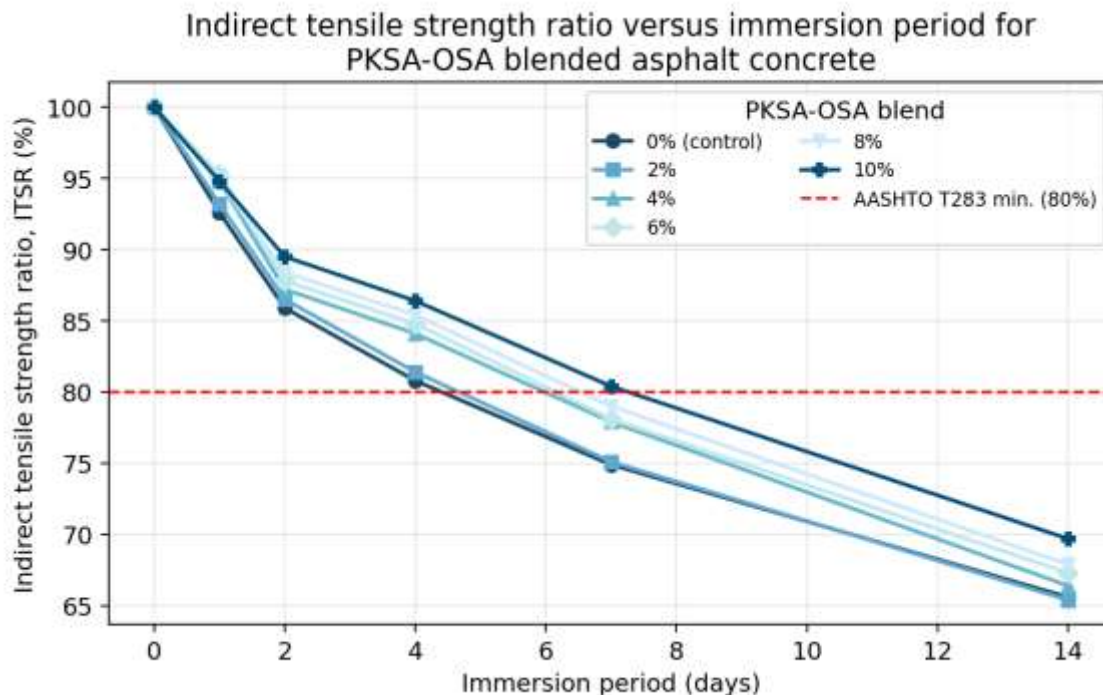


Figure 5. Indirect tensile strength ratio versus immersion period for PKSA-OSA blended asphalt concrete.

These results indicate that while none of the mixes, including the modified blends, retain ITSR above the 80% threshold beyond 7 days of continuous immersion, the OSA-rich blends consistently delay the point at which the threshold is crossed and retain a meaningfully higher strength ratio at every conditioning age relative to the unmodified control. This is consistent with the durability improvement reported for oyster shell ash by Ajah and Michael (2023) and reinforces the interpretation, offered by Radwan et al. (2025), that higher retained ITSR under prolonged conditioning reflects stronger adhesive bonding between filler, binder and aggregate rather than a simple short-term surface effect.

4.5 Comparative Validation Against Independent Literature

Table 3 summarises how the elastic modulus and ITSR trends recorded in this study compare with previously published, independently conducted research. The consistent agreement across studies, despite differences in filler type, dosage and conditioning duration, supports the mechanistic interpretation that calcium-rich, angular fillers such as OSA improve moisture resistance primarily through densification and improved filler-binder adhesion, while excessive fine, porous fillers such as PKSA increase binder demand and reduce moisture resistance when used alone at high dosage.

Table 3. Comparison of elastic modulus and ITSR trends with independent published studies.

Parameter	Present study trend	Independent literature	Agreement
Tensile / compressive elastic modulus	Increases with OSA; decreases with PKSA alone; reduces with immersion	Moisture conditioning reduces stiffness via stripping (Sulejmani et al., 2019); calcium-rich fillers improve stiffness (Ajah & Michael, 2023)	Strong
Indirect tensile strength (dry)	Increases with OSA; decreases with PKSA beyond ~2%	PKSA improves ITS only up to an optimum dosage (Oktavia et al., 2024; Global Scientific Journal, 2024)	Strong
ITSR (moisture-conditioned)	Improves with OSA; declines with immersion time for all blends	Higher ITSR indicates stronger adhesive bonding (AASHTO T283; Radwan et al., 2025)	Strong
Blended (PKSA+OSA) vs single-filler systems	2% PKSA + high OSA offsets PKSA's stiffness penalty	Optimised, jointly-modified filler systems outperform single-filler systems (Muhmood et al., 2025)	Consistent

5. Conclusion

This study evaluated the elastic modulus and indirect tensile strength ratio of asphalt concrete modified with combined palm kernel shell ash and oyster shell ash under full moisture conditioning extending to 14 days. Oyster shell ash was found to be the dominant stiffening and strengthening agent, raising both dry and moisture-conditioned modulus and ITS values, while palm kernel shell ash improved performance only up to about 2% before becoming detrimental when used at higher dosage. Blending a small, fixed proportion of PKSA with increasing OSA content offset PKSA's stiffness penalty and produced ITSR values that remained consistently above the unmodified control at every immersion age, with the 10% PKSA-OSA blend retaining the highest ITSR (69.7%) after 14 days of continuous immersion, compared with 65.6% for the control. Although no blend sustained the AASHTO T283 80% ITSR threshold beyond 7 days of continuous immersion, the results demonstrate that PKSA-OSA blending meaningfully delays and moderate's moisture-induced stiffness and strength loss, supporting its potential as a sustainable, waste-valourising alternative to conventional mineral fillers for asphalt pavements in moisture-prone environments. Future work should extend testing to field-representative freeze-thaw and cyclic wet-dry conditioning, and should incorporate microstructural analysis (SEM, FTIR) to directly characterise the filler-binder interaction mechanisms proposed here.

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