IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684, p-ISSN: 2320-334X, Volume 23, Issue 5 Ser. I (Sep. – Oct. 2026), PP 38-45
www.iosrjournals.org

Moisture Resistance and Durability of Hot-Mix Asphalt Concrete Modified with a Blended Quarry Dust–Sugarcane Bagasse Ash Mineral Filler

C. A. Nworgu, E. O. Ekwulo and C. G. Otto
Department of Civil Engineering, Rivers State University, Nkpolu-Oroworukwo, Port Harcourt, Nigeria
**Corresponding Author: captain.otto@rsu.edu.ng; ORCID: 0000-0001-6855-6871*

Abstract
Premature moisture-induced failure of flexible pavements is a persistent problem in flood-prone regions such as the Niger Delta of Nigeria, where wearing courses are frequently submerged during the rainy season. This study evaluated the moisture resistance and durability of hot-mix asphalt (HMA) concrete in which the conventional mineral filler was partially replaced with a dual blend of quarry dust (QD) and sugarcane bagasse ash (SCBA). Marshall Mix design was used to establish the optimum binder content of a 60/70 penetration-grade bitumen, after which asphalt concrete specimens were produced with QD and SCBA blended in increments of 2–10% each by weight of aggregate. The best-performing blend, 6% QD combined with 2% SCBA, was subjected to full water submergence for 1, 2, 4, 7 and 14 days and assessed for retained Marshall stability, indirect tensile strength (ITS), tensile strength ratio (TSR) and swell index alongside unmodified control mixes. After 4 days of submergence, the modified mix retained 77.98% of its original Marshall stability against 71.88% for the control, and recorded a TSR of 76.44%, exceeding the 75% acceptance threshold of AASHTO T 283, whereas the control achieved only 57.42%. The dry ITS of the modified mix (2.25 MPa) was 45% higher than that of the control (1.55 MPa), and this advantage was sustained throughout the conditioning period. The one-day swell index of the modified mix (0.85%, with a mean daily increment of 0.30%) was substantially lower than that of the control (1.43%; 0.79% daily), and compared favourably with values reported in earlier submergence studies. The QD–SCBA blend is therefore recommended as a sustainable filler modification for asphalt pavements in moisture-prone environments.
Keywords: *sugarcane bagasse ash; quarry dust; moisture damage; retained Marshall stability; tensile strength ratio; swell index; hot-mix asphalt*

Date of Submission: 03-09-2026 Date of Acceptance: 13-09-2026

I. Introduction

Flexible pavements rely on bituminous mixtures in which mineral fillers—the fraction of fine aggregate passing the 0.075 mm sieve—fill voids, stiffen the binder mastic and improve the cohesion, stability and durability of the mix (Huang, 2004; Roberts et al., 1996). The fraction of filler finer than the asphalt film thickness blends with the binder to form a mastic that stiffens the mixture, while coarser particles behave as aggregate and contribute to inter-particle contact (Puzinauskas, 1969). Conventional fillers such as limestone dust, hydrated lime, Portland cement and quarry dust are, however, associated with high extraction and processing costs and with adverse environmental impacts at the point of mining and quarrying. These concerns have stimulated a sustained search for alternative fillers derived from agro-industrial by-products.

Sugarcane bagasse ash (SCBA), the residue obtained from the combustion of bagasse after juice extraction, is one such candidate. It is rich in silica and other mineral oxides, exhibits pozzolanic activity, and is abundantly available in sugar-producing and sugarcane-consuming regions (Chusilp et al., 2009; Cordeiro et al., 2009; Goyal et al., 2010). Reported chemical compositions show combined Al_2O_3, Fe_2O_3 and SiO_2 contents in the range of 70–74% (Goyal et al., 2010; Otuoze et al., 2012), which underpins its pozzolanic character. Laboratory studies have shown that replacing conventional fillers with SCBA at controlled proportions can improve Marshall stability, reduce air voids and enhance the moisture resistance of asphalt mixtures (Ahmed et al., 2018; Roberts et al., 1996), while also delivering environmental benefits through waste diversion and reduced raw-material consumption (Shafiq et al., 2020). Excessive SCBA contents have nevertheless been reported to induce brittleness and reduced cohesion, underscoring the need for careful proportioning (Ahmed et al., 2018).

Moisture damage remains one of the principal mechanisms of premature deterioration in asphalt pavements. It occurs when water penetrates the mixture and weakens adhesion at the binder–aggregate interface, and is influenced by binder and aggregate properties, mixture characteristics, construction practice, the nature of the displacing water and the dynamic action of traffic (Akhtar, 2018; Habeeb et al., 2012). The problem is particularly acute in the Niger Delta region of Nigeria, where seasonal flooding leaves road pavements submerged for days at a time, and where drainage provision is often inadequate on cost grounds (Igwe, *et al* 2016; Igwe & Ottos 2016; Igwe & Ottos 2017).

A substantial body of work by researchers at Rivers State University has documented and sought to mitigate this problem. Ottos and Nyebuchi (2018) characterised the swell behaviour of an asphalt wearing course designed for equivalent single axle loads greater than 10^6 under submerged conditions, reporting progressive, time-dependent swelling with a swell index of 1.49% after one day of soaking. Otto and Amadi (2020) showed in the laboratory that both moisture and traffic load frequency sharply reduce the fatigue life of submerged asphalt concrete, with a 21% reduction in fatigue after five days of soaking. Otto, *et al* (2020) demonstrated that modifying hot-mix asphalt with shredded tyre chips improved fatigue performance under submergence, while Otto and Akpila (2020) achieved comparable gains using candle wax as a waterproofing agent. Related studies established the cost-effectiveness of such modifications relative to unmodified mixtures under moisture exposure (Otto & Amadi-Oparaeli, 2020; Otto & Awarri, 2021), and, most recently, Otto and Okafor (2026) showed that a dual blend of waste engine oil and calcium carbide residue enhanced the moisture resistance of asphalt concrete. Complementary work in the same environment has examined recycled polyethylene void fillers (Igwe & Nyebuchi, 2017) and bamboo stem ash (Ekwulo & George, 2021). Also, Otto and Nworgu, (2026) has investigated the Marshall Mix Design properties of blended quarry dust–sugarcane bagasse ash. The study showed positive result. That study has led to the present research.

Despite this progress, previous submergence studies have largely investigated single modifiers. No prior study has evaluated the durability and moisture resistance of asphalt concrete containing a blended quarry dust–sugarcane bagasse ash (QD–SCBA) filler system. The present study addresses this gap by determining the retained Marshall stability, indirect tensile strength and tensile strength ratio, and swell characteristics of QD–SCBA modified hot-mix asphalt concrete relative to unmodified control mixes under full moisture submergence of up to 14 days.

II. Materials and Methods

2.1 Materials

The 60/70 penetration-grade asphalt cement was obtained from local dealers along the Oyigbo–Aba Expressway axis of Oyigbo Local Government Area, Rivers State, Nigeria. Coarse aggregate (gravel of varying sizes) and fine aggregate (river sand) were sourced from dealers at Mile 3 Market, Nkpolu-Oroworukwo, Port Harcourt. Quarry dust was obtained from Chipping Village, Oyigbo, Rivers State, while sugarcane bagasse was collected as consumer waste from fruit markets in Port Harcourt. The bagasse was thoroughly dried, burnt under controlled conditions and sieved through the 0.075 mm sieve to produce SCBA of filler fineness. Potable water was drawn from the Civil Engineering Laboratory of Rivers State University.

2.2 Characterisation of Constituent Materials

The constituent materials were classified and characterised in accordance with the applicable ASTM standards: specific gravity and sieve analysis of aggregates and fillers (ASTM C128; ASTM C136); and specific gravity (ASTM D70), penetration, viscosity (ASTM D4402) and softening point of the binder. The results are summarised in Table 1. The mean penetration of 66.7 (0.1 mm) at 25 °C classifies the binder as grade 60/70, which is widely regarded as suitable for hot-mix asphalt bases and wearing courses under heavy traffic in tropical climates.

Table 1. Properties of constituent materials

Material / property	Value	Test standard
Bitumen: specific gravity	1.02	ASTM D70
Bitumen: penetration at 25 °C (0.1 mm)	66.7 (grade 60/70)	Penetration test
Bitumen: Saybolt Furol viscosity at 60 °C (s)	69.3	ASTM D4402
Bitumen: softening point (°C)	49.5	Ring-and-ball test
Coarse aggregate (gravel): specific gravity	2.75	ASTM C128
Fine aggregate (sand): specific gravity	2.60	ASTM C128
Quarry dust: specific gravity	2.69	ASTM C128
SCBA: specific gravity	2.05	ASTM C128

The markedly lower specific gravity of SCBA (2.05) relative to quarry dust (2.69) reflects its porous, low-density ash structure and implies that, at equal mass replacement, SCBA occupies a proportionally greater volume within the mix—a property that contributes to its effectiveness in filling voids at modest dosages.

2.3 Aggregate Blending and Optimum Binder Content

Gravel and sand gradations were combined by constrained optimisation (Excel Solver) to satisfy the dense-graded specification envelope, yielding a blend of 65.3% gravel and 34.7% sand. The optimum binder content (OBC) was established using the Marshall mix design method (ASTM D1559; Asphalt Institute, 1984). Trial mixes were prepared at binder contents of 4.0–6.0% in 0.5% increments, with three replicate specimens per content, and the OBC was taken as the arithmetic mean of the binder contents corresponding to maximum stability, maximum density and 4% air voids. At the OBC, the mix exhibited a stability of 24,160 N, flow of 3.35 mm, density of 2,413 kg/m³, air voids of 3.5%, VMA of 15.06% and voids filled with asphalt of 78%, all satisfying heavy-traffic design criteria (Asphalt Institute, 2007).

2.4 Preparation of Unmodified and QD–SCBA Modified Mixes

Aggregates were batched by weight and heated to a mixing temperature of 150–160 °C before introduction of the preheated binder at the OBC. Each specimen was compacted with 75 blows per face using a 6.5 kg rammer falling freely through 450 mm, representing heavy-traffic design conditions, and allowed to cool for 24 hours before demoulding. Modified specimens were prepared identically except that QD and SCBA were batched at varying proportions (2%, 4%, 6%, 8% and 10% each, in a 5 × 5 factorial blending matrix) and dry-blended with the aggregates before the binder was introduced, with three specimens per combination. Following Marshall testing of all blends, the combination yielding the best mechanical and volumetric performance 6% QD with 2% SCBA was adopted for the durability, moisture-resistance and swell investigations reported here.

2.5 Moisture Conditioning and Durability Testing

Specimens of the unmodified control mix and the optimal QD–SCBA mix were fully submerged in water for 1, 2, 4, 7 and 14 days to simulate the prolonged flooding experienced by Niger Delta pavements. Conditioned and unconditioned specimens were brought to 60 °C in a water bath for 30–35 minutes prior to testing, this being the destructive temperature specified for Marshall stability determination (Asphalt Institute, 1997). The retained Marshall stability (RMS), or retained strength index, was computed as:

$$RMS = (S_i / S_0) \times 100\% \qquad (1)$$

where S_i is the stability of the conditioned specimen after immersion time t_i and S_0 is the stability of the unconditioned specimen (ASTM D3744). The indirect tensile strength was determined in accordance with ASTM D6931 as:

$$\sigma_t = 2P / (\pi d l) \qquad (2)$$

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). The tensile strength ratio was obtained as the ratio of the conditioned to unconditioned tensile strengths (ASTM D4867; AASHTO T 283):

$$TSR = (\sigma_{tv} / \sigma_t^d) \times 100\% \qquad (3)$$

where σ_{tv} and σ_t^d are the tensile strengths of the conditioned and unconditioned specimens respectively. Swell was determined from the change in specimen volume before (V_1) and after (V_2) immersion (ASTM D4546), and the swell index expressed as the percentage volumetric change.

III. Results and Discussion

3.1 Effect of Moisture on Retained Marshall Stability

Table 2 and Figure 1 present the retained Marshall stability of both mixes over the 14-day submergence programme. Both mixes lost stability with increasing immersion duration, with the rate of loss decreasing over time, but the QD–SCBA modified mix retained a higher proportion of its strength at every conditioning interval.

Table 2. Retained Marshall stability of unmodified and QD–SCBA modified mixes

Immersion period (days)	Unmodified mix RMS (%)	QD–SCBA modified mix RMS (%)
0	100.00	100.00
1	92.38	95.49
2	80.05	86.01
4	71.88	77.98
7	59.14	70.28
14	47.71	52.65

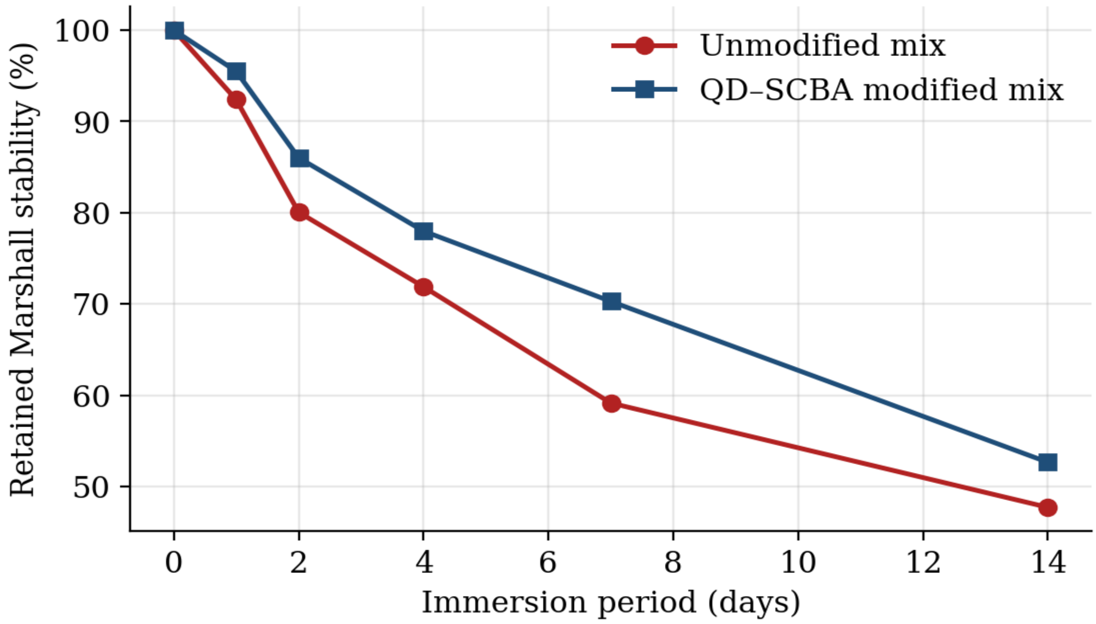

Figure 1. Effect of moisture on retained Marshall stability of unmodified and QD–SCBA modified asphalt concrete mixes

After 4 days of full submergence, the modified mix retained 77.98% of its original Marshall stability, against 71.88% for the unmodified control, an advantage of approximately 6.1 percentage points attributable to reduced internal voids and improved binder–aggregate adhesion imparted by the blended filler. The advantage widened to more than 11 percentage points at 7 days (70.28% versus 59.14%), before narrowing at 14 days as both mixes approached severe saturation. This gain considerably exceeds the 0.6% improvement in Marshall stability reported by Zainudin et al. (2016) when SCBA was used alone as a filler, indicating a synergistic effect of the dual QD–SCBA blend, and is consistent with the broader finding of Otto and Okafor (2026) that dual-blend modification systems outperform single modifiers in resisting moisture damage.

3.2 Effect of Moisture on Indirect Tensile Strength

The indirect tensile strength results are presented in Table 3 and Figure 2. In the unconditioned state, the modified mix developed an ITS of 2.25 MPa, some 45% higher than the 1.55 MPa of the control, demonstrating that the blended filler stiffens the mastic and improves the tensile capacity of the mixture even before moisture exposure. This advantage was sustained across the entire conditioning programme: at 4 days the modified mix retained 1.72 MPa against 0.89 MPa for the control, and even at 14 days its residual ITS (0.89 MPa) still exceeded the 4-day value of the unmodified mix.

Table 3. Indirect tensile strength of unmodified and QD–SCBA modified mixes

Immersion period (days)	Unmodified mix ITS (MPa)	QD–SCBA modified mix ITS (MPa)
0	1.55	2.25
1	1.25	2.11
2	1.01	1.84
4	0.89	1.72
7	0.69	1.33
14	0.52	0.89

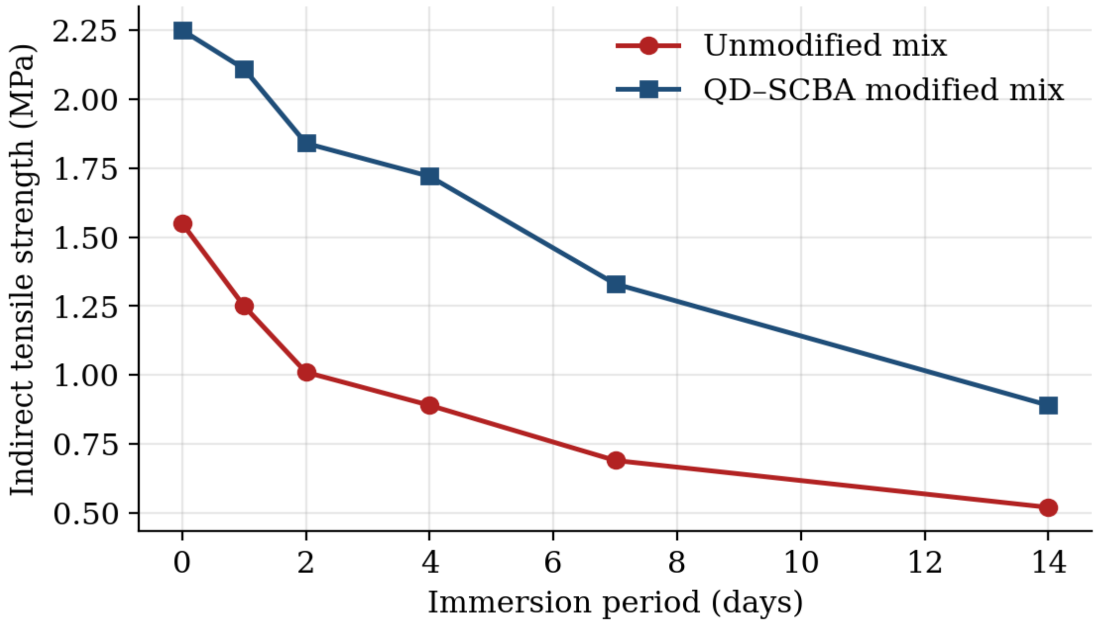

Figure 2. Effect of moisture on indirect tensile strength of unmodified and QD–SCBA modified asphalt concrete mixes

The tensile strength of an asphalt mixture is indicative of its resistance to fatigue, cracking and rutting. The progressive loss of ITS with immersion in both mixes confirms the degrading action of water on the binder–aggregate interface described by Habeeb et al. (2012), while the consistently higher curve of the modified mix in Figure 2 evidences the protective, densifying role of the QD–SCBA filler blend.

3.3 Effect of Moisture on Tensile Strength Ratio

The tensile strength ratios computed from Equation 3 are shown in Figure 3. After 4 days of submergence the modified mix recorded a TSR of 76.44%, above the 75% minimum acceptance threshold prescribed by AASHTO T 283, whereas the unmodified mix achieved only 57.42%. Indeed, the unmodified mix fell below the threshold within the first two days of submergence (65.16% at 2 days), while the modified mix remained compliant through the critical 4-day window, only declining below the criterion under the more extreme 7- and 14-day exposures (59.11% and 41.78% respectively).

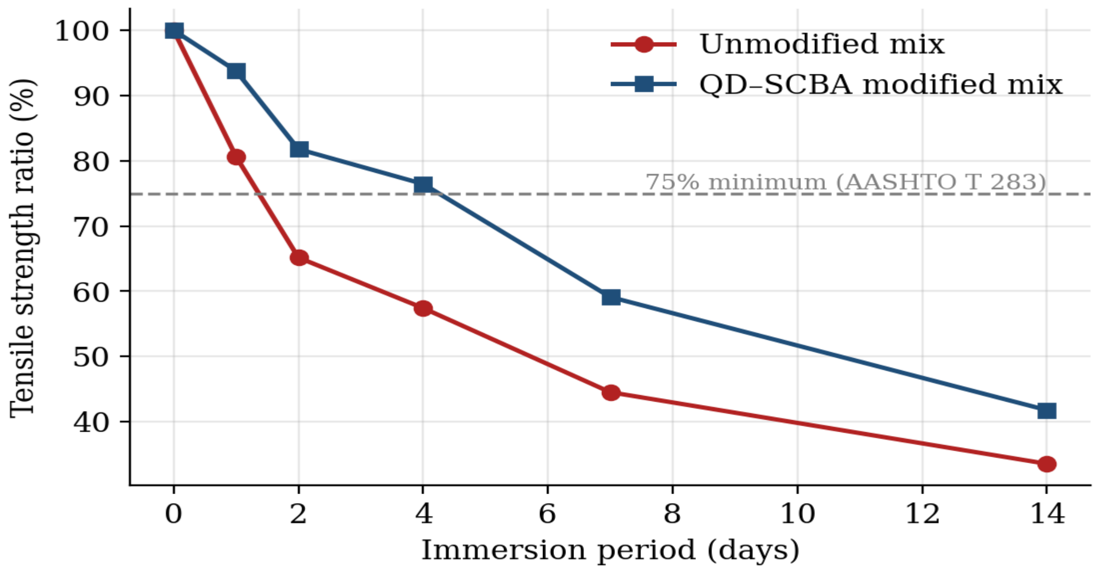

Figure 3. Effect of moisture on tensile strength ratio of unmodified and QD–SCBA modified asphalt concrete mixes, with the 75% acceptance threshold of AASHTO T 283

The TSR quantifies resistance to moisture-induced damage such as stripping; the markedly higher values for the QD–SCBA mix demonstrate that the blended filler densifies the mastic, restricts water ingress and preserves the tensile capacity of the mixture under prolonged wetting. The unmodified mix, by contrast, would be classified as moisture-susceptible and unsuitable for service in submergence-prone locations without remediation.

3.4 Swell and Swell Index

Figure 4 presents the swell index of both mixes over the submergence programme, and Table 4 the corresponding values. After one day of soaking the unmodified mix exhibited a swell index of 1.43% with a mean daily increment of 0.79% over the programme, whereas the QD–SCBA modified mix swelled by only 0.85% with a mean daily increment of 0.30%. At the end of the 14-day exposure the cumulative swell of the modified mix (4.21%) was little more than half that of the control (7.91%).

Table 4. Swell index of unmodified and QD–SCBA modified mixes

Immersion period (days)	Unmodified mix SI (%)	QD–SCBA modified mix SI (%)
0	0.00	0.00
1	1.43	0.85
2	2.26	1.32
4	3.53	2.24
7	5.71	3.02
14	7.91	4.21

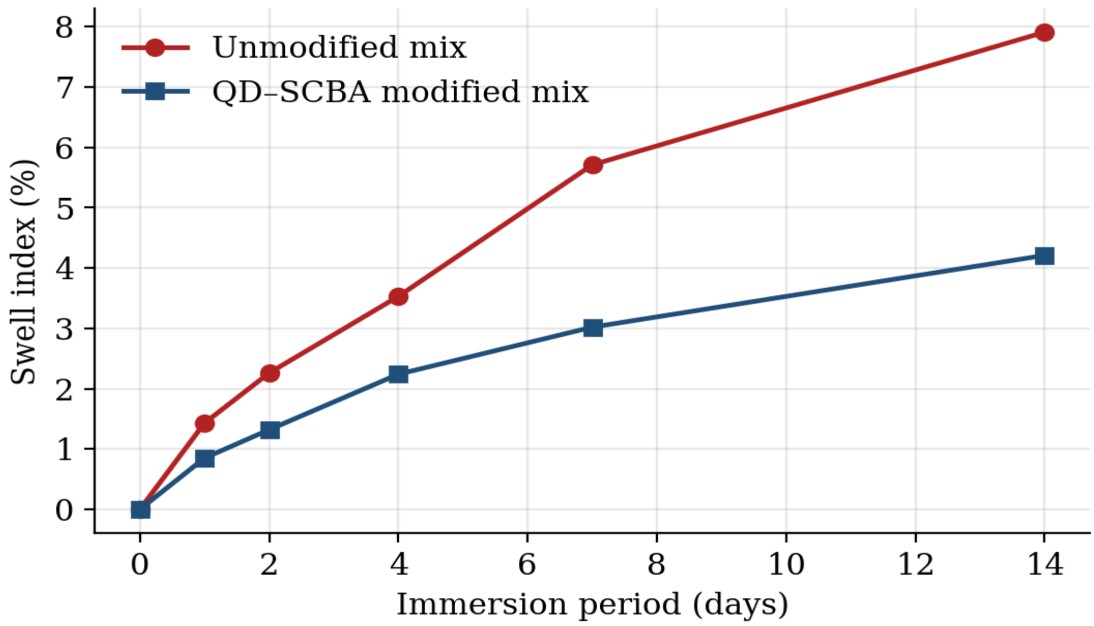

Figure 4. Swell index of unmodified and QD–SCBA modified asphalt concrete mixes subjected to full moisture submergence

In both mixes the swell index increased progressively with submergence duration, confirming the time-dependent swelling behaviour previously documented by Ottos and Nyebuchi (2018), who reported a swell index of 1.49% after one day of soaking and an average daily increment of 0.38% for a heavy-traffic wearing course. The one-day swell of the present modified mix (0.85%) and its daily increment (0.30%) both outperform those benchmark values, while the unmodified control (1.43%; 0.79%) behaved comparably to the unmodified mixes of the earlier study. The substantially lower swelling of the modified mix reflects the void-filling action of the blended filler, which increases density, reduces permeability and thereby limits moisture retention, the principal driver of stripping, deformation and premature failure in submerged pavements.

3.5 Practical Implications

Taken together, the four durability indicators show that partial replacement of conventional filler with a 6% QD + 2% SCBA blend materially improves the water resistance of hot-mix asphalt concrete. The findings extend the family of submergence studies conducted on Niger Delta pavements (Igwe *et al* 2016; Otto & Akpila, 2020; Otto, Igwe & Ekwulo, 2020; Ottos & Nyebuchi, 2018) by demonstrating, for the first time, the efficacy of a blended QD–SCBA filler system. Two practical points follow. First, because the TSR of even the modified mix falls below the 75% criterion beyond about four days of continuous submergence, adequate drainage should be provided wherever pavements may remain flooded for longer periods. Second, the use of SCBA converts an abundant urban agricultural waste into a value-added construction material, supporting circular-economy objectives while reducing the demand for quarried filler and the associated environmental burden of extraction.

IV. Conclusions

Based on the laboratory investigation, the following conclusions are drawn. First, the QD–SCBA modified asphalt mix retained 77.98% of its original Marshall stability after 4 days of full submergence, compared with 71.88% for the unmodified mix, an improvement in moisture resistance that surpasses the gains reported for SCBA used alone. Second, the modified mix developed an unconditioned indirect tensile strength of 2.25 MPa which is 45% above the 1.55 MPa of the control and maintained this advantage across all conditioning periods. Third, the modified mix achieved a tensile strength ratio of 76.44% after 4 days of submergence, satisfying the AASHTO T283 minimum of 75%, whereas the unmodified mix (57.42%) failed the criterion within two days of exposure. Fourth, the modified mix reduced moisture-induced swelling by approximately 40–47% across the programme, recording a one-day swell index of 0.85% against 1.43% for the control, and outperforming values reported in earlier submergence studies. A blend of 6% quarry dust and 2% sugarcane bagasse ash by weight of aggregate is therefore recommended for asphalt surfacing in moisture-prone areas, alongside the provision of adequate drainage where pavements may remain submerged for more than two days. Further research on SCBA blended with other waste fillers under different traffic conditions is recommended.

References

[1]. Ahmed, A., Ali, H., & Saleem, M. (2018). Performance evaluation of sugarcane bagasse ash as a filler in asphalt concrete. *International Journal of Pavement Research and Technology, 11*(4), 393–401. https://doi.org/10.1016/j.ijprt.2018.01.003

[2]. Akhtar, H. (2018). Effect of water submergence on the characteristics of bituminous mixes using reclaimed asphalt pavement. *European Journal of Biophysics, 6*(1), 1–6.

[3]. American Association of State Highway and Transportation Officials. (2014). *Standard method of test for resistance of compacted asphalt mixtures to moisture-induced damage* (AASHTO T 283-14). AASHTO.

[4]. American Society for Testing and Materials. (2017). *Standard test method for indirect tensile (IDT) strength of asphalt mixtures* (ASTM D6931-17). ASTM International.

[5]. American Society for Testing and Materials. (2021). *Standard test methods for one-dimensional swell or collapse of soils* (ASTM D4546-21). ASTM International.

[6]. American Society for Testing and Materials. (2022). *Standard test method for effect of moisture on asphalt mixtures* (ASTM D4867/D4867M-22e1). ASTM International.

[7]. American Society for Testing and Materials. (2022). *Standard test method for Marshall stability and flow of asphalt mixtures* (ASTM D6927-22). ASTM International.

[8]. Asphalt Institute. (1984). *Mix design methods for asphalt concrete and other hot-mix types* (MS-2). Asphalt Institute.

[9]. Asphalt Institute. (1997). *MS-4: The asphalt handbook* (7th ed.). Asphalt Institute.

[10]. Asphalt Institute. (2007). *MS-2: Asphalt mix design methods* (7th ed.). Asphalt Institute.

[11]. Chusilp, N., Jaturapitakkul, C., & Kiattikomol, K. (2009). Utilization of bagasse ash as a pozzolanic material in concrete. *Construction and Building Materials, 23*(11), 3352–3358. https://doi.org/10.1016/j.conbuildmat.2009.05.002

[12]. Cordeiro, G. C., Toledo Filho, R. D., & Fairbairn, E. M. R. (2009). Use of ultrafine sugar cane bagasse ash as mineral admixture for concrete. *ACI Materials Journal, 106*(5), 485–492.

[13]. Ekwulo, E. O., & George, G. (2021). Effect of bamboo ash on moisture damage in hot mix asphalt concrete. *American Journal of Engineering Research, 10*(5), 92–98.

[14]. Goyal, A., Hattori, K., Ogata, H., & Ashraf, M. (2010). Processing of sugarcane bagasse ash and reactivity of ash-blended cement mortar. *Transactions of the Japanese Society of Irrigation, Drainage and Rural Engineering, 77*, 243–251.

[15]. Habeeb, A. O., Olabambe, A. A., & Oladipupo, S. O. (2012). Investigation of the geotechnical engineering properties of laterite as sub-grade and base material for road construction in Nigeria. *Civil and Environmental Research, 2*(8), 23–31.

[16]. Huang, Y. H. (2004). *Pavement analysis and design* (2nd ed.). Pearson Prentice Hall.

[17]. Igwe, E. A., Ekwulo, E. O., & Otto, C. G. (2016). Moisture effect on stiffness of asphalt concretes for low volume roads: Comparative study of Asphalt Institute and Witczak 1-40D models. *International Journal of Constructive Research in Civil Engineering.* 2 (4) 1-8.

[18]. Igwe, E. A., & Nyebuchi, D. A. (2017). Improving durability of asphalt pavement wearing course submerged in water using candle wax as water proofing agent: An assessment using RSI, FDI and SDI. Int. J. Concr. Technol, 3(2), 1-10.

[19]. Igwe, E. A., Ottos, C. G., & Ekwulo, E. O. (2016). The role of candle wax as non-bituminous modifier in material re-characterization of bituminous concretes used synonymously for flexible pavement-study on voids and flow. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), 13(5), 74-81.

[20]. Igwe, E. A., & Ottos, C. G. (2016). Investigating the effect of air voids content in fatigue life of hot mix asphalt mixtures: case study of rubberized asphalt concrete. International Journal of Innovative Science, Engineering & Technology, 3(5), 56-64.

[21]. Igwe, E. A., & Ottos, C. G. (2017). Increasing durability of bituminous pavements using hydro carbon void fillers produced from recycled polyethylene wastes (RPEW). J. Sci. Eng. Res, 4(12), 24-30

[22]. Otto, C. G., & Akpila, S. B. (2020). Performance analysis of candle wax modified asphalt pavement wearing course submerged in moisture. *International Journal of New Technology and Research. 6(11), 15-17.*

[23]. Otto, C. G., & Amadi, C. P. (2020). Laboratory investigation of the effect of traffic load frequency and moisture on the fatigue life of asphalt concrete pavement. International Journal of Trend in Research and Development 7(4), 205-208

[24]. Otto, C. G., & Amadi-Oparaeli, K. I. (2020). Cost-effectiveness of waste polythene bag modified asphalt concrete submerged in moisture. *International Journal of New Technology and Research. 5(6), 1-8.*

[25]. Otto, C. G., & Awarri, W. A. (2021). Comparative cost-effectiveness of modified asphalt concrete submerged in moisture as related to fatigue performance. *IOSR Journal of Mechanical and Civil Engineering 18(2), 49-54.*

[26]. Otto, C. G., Igwe, E. A., & Ekwulo, E. O. (2020). Fatigue performance of asphalt pavement wearing course in submerged condition modified with shredded tyre chips. *International Journal of Scientific and Engineering Research 11(11), 167-172.*

[27]. Otto, C. G., & Okafor, I. A. (2026). Evaluating moisture resistance of asphalt concrete using a dual blend of waste engine oil and calcium carbide residue. *IOSR Journal of Mechanical and Civil Engineering 23(1), 87-94.*

[28]. Otto, C. G., & Nworgu, C. A. (2026). Marshall Mix Design Properties of Asphalt Concrete Incorporating Quarry Dust and Sugarcane Bagasse Ash as Partial Mineral Filler Replacement. *Kronika Journal 26(7), 341-353.*

[29]. Ottos, C. G., & Nyebuchi, D. A. (2018). Swell behaviour of asphalt pavement wearing course with ESAL > 10^6 under submerged conditions. *International Journal of Trend in Research and Development, 5*(2), 242–245.

[30]. Otuoze, H. S., Amartey, Y. D., Sada, B. H., Ahmed, H. A., Sanni, M. I., & Suleiman, M. A. (2012, July). Characterization of sugar cane bagasse ash and Ordinary Portland Cement Blends in Concrete. In 4th West African Built Environment Research (WABER) Conference (pp. 1231-1237).

[31]. Puzinauskas, V. P. (1969). Filler in asphalt mixtures. *The Asphalt Institute Research Report 69-2.*

[32]. Roberts, F. L., Kandhal, P. S., Brown, E. R., Lee, D. Y., & Kennedy, T. W. (1996). *Hot mix asphalt materials, mixture design and construction* (2nd ed.). NAPA Education Foundation.

[33]. Shafiq, N., Hussein, A. A. E., Nuruddin, M. F., & Al Mattarneh, H. (2018, June). Effects of sugarcane bagasse ash on the properties of concrete. In Proceedings of the institution of civil engineers-engineering sustainability (Vol. 171, No. 3, pp. 123-132). Thomas Telford Ltd.

[34]. Zainudin, M. Z. M., Khairuddin, F. H., Ng, C. P., Che Osmi, S. K., Misnon, N. A., & Syaripuddin, M. (2016, April). Effect of sugarcane bagasse ash as filler in hot mix asphalt. In Materials science forum (Vol. 846, pp. 683-689). Trans Tech Publications Ltd.