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CHARACTERIZING THE DURABILITY PROPERTIES OF SUBMERGED ASPHALT PAVEMENT SURFACING MODIFIED WITH ZEOLITE

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ABSTRACT

Asphalt surfacings in the Niger Delta region of Nigeria are frequently submerged because of intense rainfall and inadequate drainage, and the resulting moisture damage shortens service life. This study examined whether natural zeolite, used as a moisture-adsorbing modifier, improves the durability of submerged hot-mix asphalt (HMA) concrete. A 60/70 penetration-grade bitumen, river gravel and sand were blended 60:40 and designed by the Marshall procedure (optimum asphalt content 5.0%). Specimens containing 0, 2, 4, 6, 8 and 10% zeolite (by weight of mix) were immersed for 0, 1, 2, 3, 4 and 7 days. Stability, flow, bulk density, air voids and voids in mineral aggregate (VMA) were measured and used to derive the retained stability index (RSI) and a final durability index (FDI); swell index was determined for the control and 6% mixes. Immersion for seven days reduced the control stability from 12.78 to 7.48 kN (−41.5%) and increased flow, air voids and VMA. The 6% zeolite mixture gave the best overall performance: after seven days its stability was 10.49 kN (+40.2% over the control), flow was 22.3% lower, air voids 13.2% lower, VMA 17.5% lower, swell index fell from 1.64 to 1.21%, and RSI rose from 58.5 to 66.3%. The time for RSI to fall below 75% was extended from about 1.5 to 2.6 days. Doses of 8–10% were progressively less effective and produced excessive air voids after prolonged immersion. A 6% zeolite content is therefore recommended for asphalt surfacings exposed to flooding, although RSI after seven days of continuous soaking remained below 75%.

Keywords: Asphalt Concrete; Zeolite; Submergence; Moisture Damage; Retained Stability Index; Niger Delta; Durability

1 INTRODUCTION

Asphalt concrete is the dominant surfacing material for flexible pavements because it is flexible, economical and easy to maintain. Its long-term performance, however, depends as much on environmental exposure as on structural design. Moisture is among the most damaging agents: water reduces the adhesion between bitumen and aggregate and the cohesion of the binder film, causing stripping, raveling and loss of stiffness (Hicks, 1991; Kiggundu & Roberts, 1988). Moisture damage is a coupled thermodynamic, chemical, physical and mechanical process, and the void structure of the mixture governs how readily water is transported into it (Caro et al., 2008). Reviews of the topic agree that loss of

bitumen–aggregate adhesion is the principal cause of moisture damage and that poor drainage, which allows water to stand on the surface, aggravates its consequences (Albayati & Ismael, 2025; Hamzah et al., 2015; Omar et al., 2020).

These conditions describe the Niger Delta region of Nigeria, where high-intensity rainfall and inadequate roadside drainage leave pavements partly or wholly submerged for days at a time, so that many surfacings deteriorate well before their design life. Research at Rivers State University has documented this problem for several years. Igwe et al. (2016) examined how moisture affects the stiffness of asphalt concretes for low-volume roads, and Ottos and Nyebuchi (2018) studied the swell behaviour of heavy-traffic wearing courses under submerged conditions. A series of laboratory studies has since tested locally available modifiers against submergence damage, including polystyrene (Igwe & Amadi-Oparaeli, 2018), candle wax (Igwe & Nyebuchi, 2017; Otto & Akpila, 2020), shredded tyre chips (Otto et al., 2020), bamboo ash used as void filler (George et al., 2019) and polyethene as a partial replacement for bitumen (Ekwulo et al., 2021). More recent work has extended this approach to waste-derived fillers for moisture-resistant pavements in the Niger Delta (Otto, 2026) and has applied statistical validation to moisture-resistance data (Otto & Agi, 2026). Most of these modifiers act as hydrophobic additives or void fillers; none of them removes water from the mixture.

Zeolites are crystalline aluminosilicates with open channel systems that hold and release water reversibly (Breck, 1974). In asphalt technology they are best known as water-bearing warm-mix additives, which foam the binder and lower compaction temperatures (Kukiełka et al., 2014; Sengoz et al., 2013; Topal et al., 2014; Woszuk & Franus, 2016). Reports on their moisture performance are mixed and depend on dosage and production temperature. Hasan et al. (2024) found that a mixture with 6% zeolite showed the highest resistance to moisture susceptibility among the dosages tested, and Ahmadzadegan and Sarkar (2022) reported increases of roughly 21–70% in indirect-tensile parameters with nano-zeolite. By contrast, Chomicz-Kowalska et al. (2021) obtained lower tensile strengths in zeolite-bearing foamed mixtures and attributed this to production temperatures too low to release the zeolite water. These studies concern warm-mix technology and standard moisture conditioning. The use of zeolite as an *adsorbent* in hot-mix asphalt that is expected to stay under water for a prolonged period, which is the Niger Delta condition, has received little attention.

The aim of this study was therefore to improve the durability of submerged asphalt pavement surfacing, simulated in the laboratory, by modifying the mixture with zeolite. The specific objectives were to (i) determine the retained stability and retained stability index (RSI) of unmodified and zeolite-modified mixtures after 1–7 days of immersion; (ii) determine the swell index (SI); (iii) determine the final durability index (FDI); and (iv) quantify the improvement produced by zeolite additions of 2–10% by weight of mix. The RSI/FDI framework follows its use for flood-affected asphalt (Ali et al., 2011) and for submerged wearing courses at Rivers State University (Igwe & Nyebuchi, 2017).

Highlights

- Zeolite at 6% by weight of mix gave the best Marshall and durability response under 0–7 days of submergence.
- Seven-day stability of the 6% mix was 40% higher than the control, with lower flow, air voids, VMA and swell.
- Zeolite extended the time for RSI to drop below 75% from 1.5 to 2.6 days; RSI gains plateaued beyond 2%.
- Dosages of 8–10% increased air voids and flow after prolonged immersion, defining an upper limit near 6%.

2 MATERIALS AND METHODS

2.1 Materials

Table 1: Properties of the asphalt cement and aggregates

Material	Property	Result
Asphalt cement	Specific gravity	1.03
	Penetration at 25 °C, 100 g, 5 s (0.1 mm)	66.7 (grade 60/70)
	Saybolt-Furol viscosity at 60 °C, 50 ml (s)	69.3
	Softening point (°C)	49.3
Gravel	Bulk specific gravity (mean of 2.75 and 2.81)	2.78
Sand	Bulk specific gravity	2.66

All materials were purchased from local dealers in Port Harcourt, Rivers State. The binder was a 60/70 penetration-grade asphalt cement. Gravel was used as coarse aggregate, sand as fine aggregate and natural zeolite as the adsorbent. Binder tests comprised specific gravity, penetration at 25 °C, Saybolt-Furol viscosity and ring-and-ball softening point; aggregate tests comprised specific gravity and sieve analysis (Table 1). Gravel and sand were combined by the straight-line (graphical) method to give a 60:40 gravel-to-sand blend (Table 2; Figure 1). The blend lay inside the specification envelope at every sieve except the 0.075 mm sieve, where only 0.5% passed against a specified 3–8%.

Table 2: Aggregate blend (60% gravel : 40% sand) compared with the specification limits

Sieve (mm)	Gravel passing (%)	Sand passing (%)	Blend passing (%)	Specification limits (%)
19.1	100.0	100.0	100.0	100
12.7	91.1	100.0	94.7	76–92
9.52	43.3	100.0	66.0	64–79
4.75	8.6	99.7	45.0	40–60
1.18	2.7	87.4	36.6	23–37
0.425	1.8	21.2	9.6	7–20
0.300	1.8	10.6	5.3	5–13
0.075	0.6	0.3	0.5	3–8

Note. Blend = 0.60 × gravel + 0.40 × sand. The blend exceeds the upper limit at 12.7 mm by 2.7 points and falls below the lower limit at 0.075 mm.

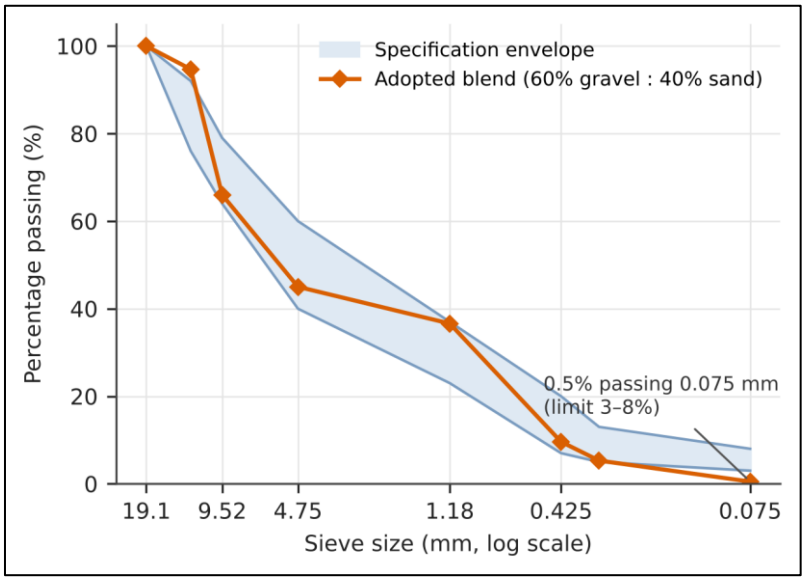


Figure 1: Gradation of the adopted aggregate blend relative to the specification envelope.

2.2 Mix design and specimen preparation

Specimens were prepared by the Marshall procedure (Asphalt Institute, 2014; Roberts et al., 1996). Asphalt contents from 4.0 to 6.0% in 0.5% steps were compacted with 75 blows on each face (6.5 kg rammer, 450 mm drop) into specimens 100 mm in diameter and about 64 mm high, each of about 1.2 kg. The optimum asphalt content was taken as the mean of the contents at maximum stability, maximum density and median air voids, and was 5.0%. Zeolite was added at 2, 4, 6, 8 and 10% by weight of mix after the heated aggregate and binder had been combined, and mixing continued for a further five minutes until homogeneous. Unmodified mixtures served as the control.

2.3 Immersion regime and measured properties

Compacted specimens of each mixture were immersed in water for 0, 1, 2, 3, 4 and 7 days to simulate flooding, giving 36 combinations of zeolite content and immersion time. At the end of each period specimens were conditioned in a water bath at 54 °C for about 15 minutes and loaded to failure to obtain Marshall stability (kN) and flow (mm). Mass in air, saturated-surface-dry mass and mass in water gave the bulk specific gravity, from which bulk density, air voids and

voids in mineral aggregate (VMA) were computed by the standard volumetric relationships. Each cell of the 6 × 6 experimental matrix was analysed as a single observation.

Three durability indices were derived. The retained stability index expresses stability after immersion as a percentage of the original stability:

$$RSI = (S_t / S_0) \times 100 \quad (1)$$

where S_t is the stability after t days of immersion and S_0 is the stability at zero days. The final durability index measures the rate of strength loss. It is evaluated as the sum of the interval loss rates,

$$FDI = \Sigma (S_i - S_{i+1}) / (t_{i+1} - t_i) \quad (2)$$

in kN per day. To allow mixtures of different initial strength to be compared, a normalised value FDI = $FDI / S^*_0 \times 100$ is also reported. The swell index is the relative increase in specimen volume on immersion,

$$SI = [(V_1 - V_0) / V_0] \times 100 \quad (3)$$

where V_0 and V_1 are the volumes before and after immersion. Swell index was measured for the control and 6% mixtures only. The improvement produced by zeolite (the mitigation or "healing" rate in this paper) was expressed as the percentage difference between the 6% mix and the control for each property, averaged over days 0–2 and over days 3–7.

3 RESULTS AND DISCUSSION

3.1 Response of the unmodified mixture to submergence

Submergence progressively weakened the control mixture (Table 3; Figure 2). Stability fell from 12.78 kN at day 0 to 9.89 kN after one day and 7.48 kN after seven days, a total loss of 41.5%, and more than half of that loss occurred in the first day. Flow rose from 3.75 to 4.79 mm (+27.7%), density fell from 2364 to 2340 kg/m^3, air voids rose from 4.51 to 5.06% and VMA from 18.01 to 19.34%. This pattern (loss of stability and density together with rising flow and voids) is the signature of stripping: water displaces binder from the aggregate surface, the aggregate skeleton loses effective cohesion and the mixture becomes more deformable and more open. It agrees with the descriptions of moisture-induced stiffness loss in Nigerian mixtures (Igwe et al., 2016) and of swelling under submergence (Ottos & Nyebuchi, 2018), and with the general mechanisms reviewed by Caro et al. (2008) and Omar et al. (2020).

Table 3: Marshall properties of the control and 6% zeolite mixtures during immersion

Property	Mix	Day 0	Day 1	Day 2	Day 3	Day 4	Day 7
Stability (kN)	Control	12.78	9.89	9.22	8.07	7.76	7.48
	6% zeolite	15.83	13.82	12.81	11.32	10.89	10.49
Flow (mm)	Control	3.75	3.92	4.02	4.53	4.68	4.79
	6% zeolite	3.32	3.52	3.56	3.59	3.67	3.72
Density (kg/m^3)	Control	2364	2360	2356	2353	2345	2340
	6% zeolite	2400	2397	2391	2389	2375	2370
Air voids (%)	Control	4.51	4.52	4.56	4.86	5.04	5.06
	6% zeolite	3.77	4.01	4.21	4.29	4.30	4.40
VMA (%)	Control	18.01	18.19	18.26	18.62	18.98	19.34
	6% zeolite	15.40	15.60	15.64	15.65	15.71	15.96

Note. Values for all six zeolite contents are plotted in Figures 2 and 3.

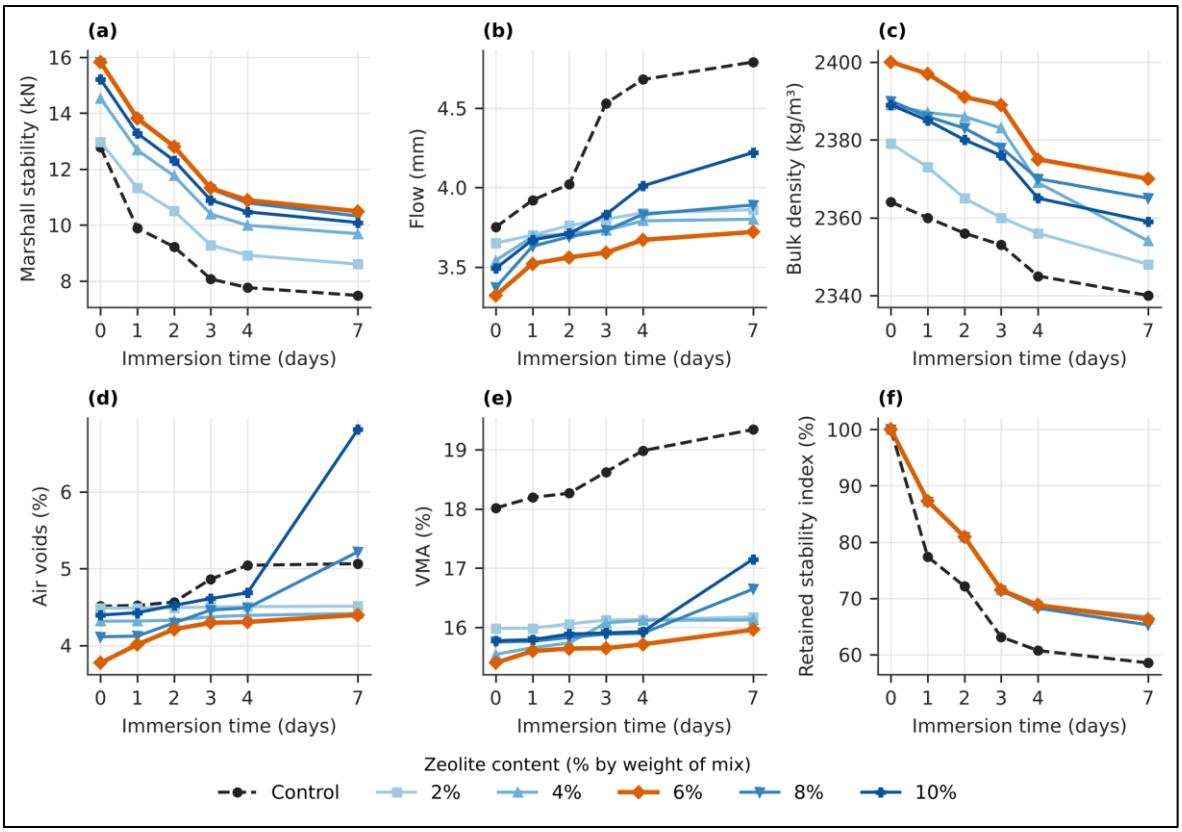


Figure 2: Variation of (a) stability, (b) flow, (c) density, (d) air voids, (e) VMA and (f) retained stability index with immersion time for the six zeolite contents.

3.2 Effect of zeolite content

At dosages up to 6%, zeolite improved every property relative to the control, and the improvement was largest at 6% (Figure 3). At day 0, stability rose from 12.78 kN (control) to 15.83 kN at 6% (+23.9%), density from 2364 to 2400 kg/m^3, and air voids fell from 4.51 to 3.77%. After seven days of immersion the benefits were larger in relative terms: stability 10.49 kN against 7.48 kN (+40.2%), flow 3.72 against 4.79 mm (−22.3%), density 2370 against 2340 kg/m^3 (+1.3%), air voids 4.40 against 5.06% (−13.2%) and VMA 15.96 against 19.34% (−17.5%). Stability, flow, density, air voids and VMA were each best at 6% at every immersion time, although the 8% mixture was almost identical in stability (for example 15.81 against 15.83 kN at day 0).

Beyond 6% the response reversed. Stability and density declined slightly, flow rose and air voids and VMA increased, and the reversal grew with immersion time. After seven days the 8 and 10% mixtures had air voids of 5.22 and 6.81% and flow of 3.89 and 4.22 mm, against 4.40% and 3.72 mm at 6%. A plausible reading, which these tests do not by themselves prove, is that moderate zeolite contents densify the matrix and hold moisture within the zeolite channels instead of at the binder–aggregate interface, whereas excess fine material absorbs binder, thins the binder film and opens the void structure, so that water penetrates more easily during long soaking. Part of the benefit may also be a filler effect: the blend contained only 0.5% material finer than 0.075 mm against 3–8% specified (Table 2), and zeolite supplies fines that the aggregate lacks. Related work at this university found that void-filling additives improved moisture resistance of asphalt concrete (Ekwulo et al., 2021; George et al., 2019), which is consistent with such a mechanism. Separating the adsorption and filler contributions would require a control with an inert filler added at the same dosage and microstructural evidence, and is recommended for further work.

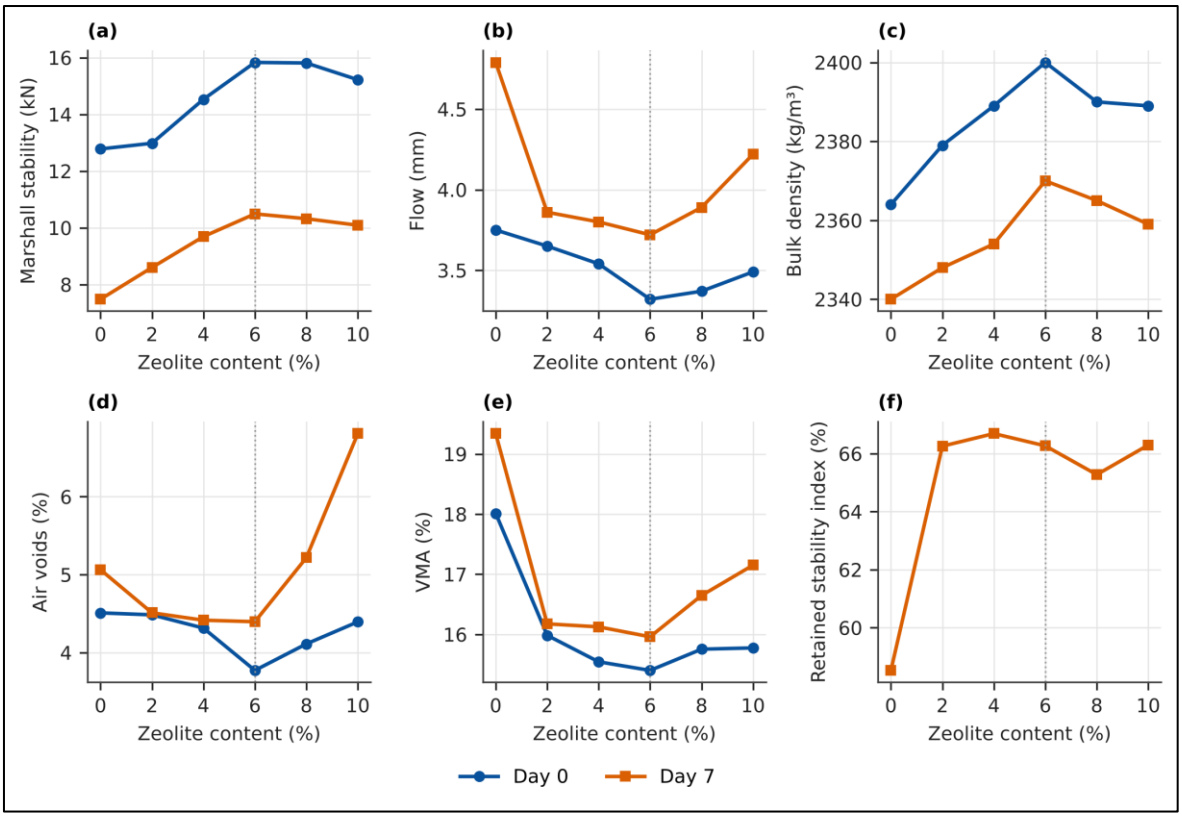


Figure 3: Variation of (a) stability, (b) flow, (c) density, (d) air voids, (e) VMA and (f) retained stability index with zeolite content at day 0 and day 7. The dotted line marks 6% zeolite.

3.3 Durability indices

Table 4: Retained stability index (RSI, %) and normalised final durability index (FDI) by zeolite content*

Zeolite	Day 1	Day 2	Day 3	Day 4	Day 7	FDI *(% of* S*$_0$ per day, summed)
Control	77.4	72.1	63.1	60.7	58.5	40.0
2%	87.2	80.9	71.5	68.7	66.3	32.1
4%	87.3	80.9	71.5	68.8	66.7	31.9
6%	87.3	80.9	71.5	68.8	66.3	32.0
8%	87.2	80.9	71.4	68.2	65.3	32.7
10%	87.3	80.9	71.6	68.8	66.3	32.0

Note. RSI = 100% at day 0 for all mixtures by definition. FDI* was calculated from the stability data with Equation 2.

The RSI of the control declined from 77.4% after one day to 58.5% after seven days (Table 4; Figure 2f). The 6% mixture retained more of its strength at every age: 87.3% after one day and 66.3% after seven. Taking 75% as a commonly used minimum retained-strength criterion, the control fell below it after about 1.5 days and the 6% mixture after about 2.6 days, so zeolite extended the time to reach this level by roughly 1.2 days. Two features of Table 4 deserve emphasis. First, the RSI gain was already complete at 2%: all five zeolite mixtures had seven-day RSI between 65.3 and 66.7%, well above the control (58.5%) but not different from each other. The additional stability that 4–6% zeolite provides is therefore an increase in the *absolute* strength of the mixture, not in the *fraction* retained. Second, the normalised FDI* confirms this pattern: it fell from 40.0 for the control to 31.9–32.7 for all modified mixtures. The seven-day RSI of the 6% mixture is still below 75%, so zeolite modification slows moisture damage rather than preventing it, which is consistent with the modest but real gains reported for other additives under prolonged submergence (Igwe & Nyebuchi, 2017; Otto et al., 2020).

Swell index (Figure 4) increased with immersion for both mixtures, reaching 1.64% for the control and 1.21% for the 6% mixture after seven days, a reduction of 26%; at the earlier ages the reduction ranged from 25 to 47%. Smaller swelling means less volumetric expansion of the binder–aggregate system and is consistent with better preservation of

adhesion. The same direction of effect was reported when polystyrene was added to Niger Delta mixtures (Igwe & Amadi-Oparaeli, 2018).

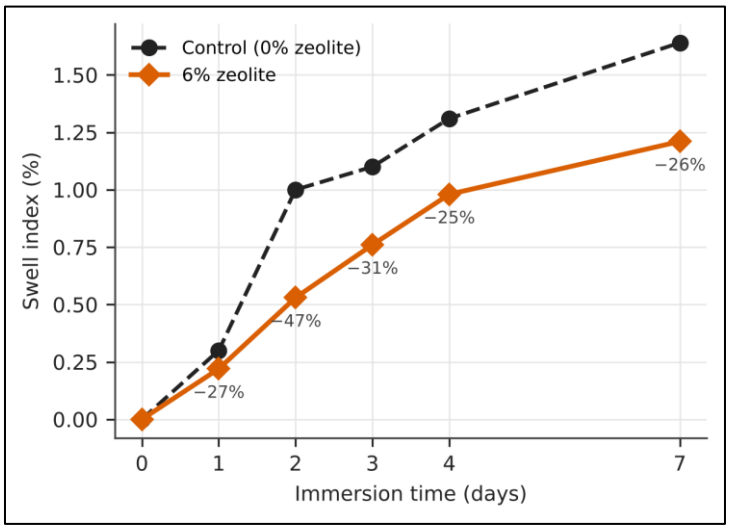


Figure 4: Swell index of the control and 6% zeolite mixtures during seven days of immersion (percentage reductions relative to the control are annotated).

3.4 Compliance with design limits after seven days

Table 5: Properties after seven days of immersion compared with the acceptance limits adopted in this study

Zeolite	Stability (kN)	Flow (mm)	Density (kg/m^3)	Air voids (%)	VMA (%)	RSI (%)	Limits met
Control	7.48 ✗	4.79 ✗	2340	5.06 ✗	19.34	58.5 ✗	2/6
2%	8.60	3.86	2348	4.51	16.18	66.3 ✗	5/6
4%	9.69	3.80	2354	4.42	16.12	66.7 ✗	5/6
6%	10.49	3.72	2370	4.40	15.96	66.3 ✗	5/6
8%	10.32	3.89	2365	5.22 ✗	16.65	65.3 ✗	4/6
10%	10.09	4.22 ✗	2359	6.81 ✗	17.15	66.3 ✗	3/6
Limit	≥ 8	2–4	2300–2500	3–5	≥ 15	≥ 75	—

Note. ✗ = outside the limit. Limits are those adopted for heavy-traffic asphalt concrete in the source study; the 75% RSI value is a commonly used minimum for retained strength and is normally applied after a much shorter conditioning period than seven days.

After seven days of immersion the control failed on stability (7.48 kN), flow, air voids and RSI. The 2, 4 and 6% mixtures satisfied all five Marshall and volumetric limits and failed only the 75% RSI minimum, whereas the 8% mixture failed on air voids and the 10% mixture on both flow and air voids. Among the compliant dosages, 6% gave the highest stability and density and the lowest flow, air voids and VMA, so it is the best compromise among the dosages tested. Because the 75% RSI value is normally applied after a short conditioning period, the seven-day RSI shortfall should be read as a statement about extreme submergence and not as failure under standard conditioning.

3.5 Mitigation rates

For stability, flow, air voids, VMA and RSI the mitigation was larger in the later period (Table 6); the stability gain, for example, rose from about 34% over days 0–2 to about 40% over days 3–7, and the flow reduction doubled from 11 to 22%. The density gain stayed at about 1.4–1.5%. Zeolite therefore protects most when exposure is prolonged and the risk of damage is greatest, which is the case for the flood-prone settings that motivate the study.

Table 6: Mean change produced by 6% zeolite relative to the control (%)

Property	Days 0–2	Days 3–7	Beneficial direction
Stability	+34.2	+40.3	increase is beneficial
Flow	−11.0	−21.6	decrease is beneficial
Density	+1.5	+1.4	increase is beneficial
Air voids	−11.8	−13.2	decrease is beneficial
VMA	−14.4	−16.9	decrease is beneficial
RSI	+12.5	+13.3	increase is beneficial

Note. RSI is compared over days 1–2 and 3–7 because it equals 100% at day 0.

3.6 Limitations

The results are laboratory-scale and based on one binder, one aggregate source, one zeolite and one dataset per condition. Zeolite mineralogy and particle size were not characterised, swell index was determined only for the control and 6% mixtures, and no microstructural evidence (for example SEM or XRD) was collected to confirm the proposed adsorption mechanism. Conditioning was by static immersion; traffic loading, drainage dynamics, temperature cycling and ageing were not simulated, so field performance may differ.

4 CONCLUSIONS

Zeolite-modified asphalt concrete was investigated under 0–7 days of submergence. The main conclusions are:

- Submergence degraded the control mixture progressively: after seven days stability fell by 41.5% and flow, air voids and VMA increased, consistent with stripping.
- A zeolite content of 6% by weight of mix gave the best combination of stability, flow, density, air voids and VMA at all immersion times. After seven days it improved stability by 40% and reduced flow, air voids and VMA by 22, 13 and 17%, respectively.
- Zeolite raised the seven-day retained stability index from 58.5 to 66.3% and reduced seven-day swell index from 1.64 to 1.21%. RSI gains were already reached at 2% zeolite and did not increase further with dosage, but the absolute stability continued to rise to 6%.
- Dosages of 8–10% performed progressively worse than 6% after prolonged immersion, with air voids of 5.2–6.8% and flow of 3.9–4.2 mm at seven days. Zeolite should not exceed about 6%.
- Zeolite slows but does not eliminate moisture damage: after seven days of continuous soaking the 6% mixture still retained less than 75% of its original stability.

It is recommended that 6% zeolite be considered for asphalt surfacings in flood-prone parts of the Niger Delta, together with adequate drainage. Further work should include replicated specimens, an inert-filler control, characterisation of the zeolite, indirect tensile strength-ratio testing and field trials.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The authors declare no competing interests.

Author contributions

Conceptualisation, investigation and drafting: M. A. Ndua; supervision and review: E. A. Igwe and A. L. Oba.

Data availability

The experimental matrices on which the figures and tables are based are given in the dissertation from which this article was prepared and are available from the corresponding author on request.

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