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STATISTICAL ANALYSIS OF ZEOLITE DOSAGE AND IMMERSION EFFECTS ON THE MOISTURE DURABILITY OF ASPHALT CONCRETE

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ABSTRACT

Laboratory studies of moisture damage in asphalt concrete are usually interpreted descriptively, which leaves the size and reliability of modifier effects unquantified. This paper subjects a 6 × 6 laboratory dataset (zeolite content of 0–10% by weight of mix; immersion for 0–7 days) to formal statistical analysis. Marshall stability, flow, bulk density, air voids and voids in mineral aggregate (VMA) were analysed together with the retained stability index (RSI) derived from stability. Two-way analysis of variance without replication, Tukey comparisons, a test for non-additivity, quadratic response-surface regression with bootstrap confidence intervals, slope and decay analysis, paired comparisons with effect sizes, correlation analysis, a Friedman rank test and a composite desirability function were applied. Zeolite content and immersion time both had large effects on stability (partial η^2 = 0.98 and 0.99), density, VMA and RSI; the effects on air voids were smaller (η^2 = 0.40 and 0.44) and interacted with dosage. Response-surface optima lay between 4.9% (air voids) and 7.8% (stability), and composite desirability peaked at 6% at every immersion time. Relative to the control, 6% zeolite raised stability by 37.2% and RSI by 12.9% on average and reduced flow, air voids and VMA by 16.3, 12.5 and 15.6%. Zeolite changed the level of stability but not its decay rate, whereas it reduced the rates of increase in flow, air voids and VMA, and doses of 8–10% lost this protection. The results quantify a dosage window of about 5.5–7% and show where the evidence is firm and where it needs replication.

Keywords: Asphalt Concrete; Zeolite; Moisture Damage; Analysis of Variance; Response Surface Methodology; Desirability Function; Retained Stability Index

1 INTRODUCTION

Moisture damage is among the principal causes of premature failure of flexible pavements, and its laboratory assessment typically relies on conditioned-versus-unconditioned comparisons of strength, such as retained Marshall stability or tensile strength ratio (Caro et al., 2008; Hicks, 1991; Omar et al., 2020). The Niger Delta of Nigeria, where heavy rainfall and poor drainage leave pavements submerged for days, has been the subject of a sustained series of laboratory studies at Rivers State University that evaluated modifiers against submergence using stability, flow, swell and durability indices (Igwe et al., 2016; Igwe & Amadi-Oparaeli, 2018; Igwe & Nyebuchi, 2017; Ottos & Nyebuchi, 2018;

Otto et al., 2020). Most of these studies, and most of the wider literature, present their results as curves and percentage differences. They seldom state how much of the total variation is due to the modifier and how much to exposure time, whether differences between dosages are larger than experimental noise, how precisely an optimum dosage is located, or whether a modifier alters the rate of deterioration as opposed to the starting level. Statistical validation of this kind has begun to appear in moisture-resistance work from the same region (Otto & Agi, 2026), and it is applied here to zeolite-modified asphalt concrete.

Zeolite is a hydrated aluminosilicate that has been used mainly as a warm-mix additive (Sengoz et al., 2013; Woszuk & Franus, 2016), and its effect on moisture resistance depends on dosage and conditions (Chomicz-Kowalska et al., 2021; Hasan et al., 2024). A companion paper reports the laboratory programme in which asphalt concrete containing 0–10% zeolite was immersed for 0–7 days and found a best overall response at 6% zeolite (Ndua et al., 2026, companion article under review). The present paper treats the same measurements as a designed experiment and asks six questions: (1) how is the variation in each property apportioned between zeolite content and immersion time; (2) which zeolite contents differ significantly; (3) where is the optimum zeolite content and how uncertain is it; (4) does zeolite change the *rate* at which properties deteriorate; (5) how large and how consistent is the benefit of the 6% mixture over the control; and (6) are the conclusions robust to the assumptions of the parametric methods?

2 DATA AND STATISTICAL METHODS

2.1 Experimental design and data

The data comprise a full factorial of six zeolite contents (0, 2, 4, 6, 8 and 10% by weight of mix) and six immersion times (0, 1, 2, 3, 4 and 7 days), giving 36 cells for each of five measured properties: Marshall stability, flow, bulk density, air voids and voids in mineral aggregate (VMA). The mixtures used a 60/70 penetration-grade bitumen at the optimum content of 5.0% and a 60:40 gravel–sand blend, and followed the Marshall procedure (Asphalt Institute, 2014; Roberts et al., 1996). The retained stability index, RSI = 100 S_t/S_0, was derived from stability. Because RSI equals 100% at day 0 for every mixture by definition, all RSI analyses use the five immersion times from day 1 to day 7. Swell index was measured for the control and 6% mixtures only (days 1–7) and is analysed in a paired comparison. Each cell holds a single value, so the design is unreplicated.

2.2 Analysis of variance

Each property was analysed by a two-way analysis of variance (ANOVA) without replication with an additive model, $y_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij}$, where α_i is the effect of zeolite content i and β_j that of immersion time j (Montgomery, 2017). With one observation per cell the residual mean square is the interaction mean square, so the main-effect F tests are conservative if a true interaction exists. The assumption of additivity was tested with Tukey's one-degree-of-freedom test for non-additivity (Tukey, 1949a). Effect size was expressed as partial $\eta^2 = SS_{effect}/(SS_{effect} + SS_{error})$, and residual normality was checked with the Shapiro–Wilk test (Shapiro & Wilk, 1965). Means of the zeolite levels were compared with Tukey's honestly significant difference (HSD) procedure using the residual mean square (Tukey, 1949b).

2.3 Response-surface regression

The dose–response relationship was described by a quadratic response-surface model with immersion time as a covariate (Box & Wilson, 1951; Myers et al., 2016),

$$y = \beta_0 + \beta_1 z + \beta_2 z^2 + \beta_3 t + \varepsilon \quad (1)$$

where z is zeolite content (%) and t is immersion time (days). The stationary point (optimum) is $z_{opt} = -\beta_1/(2\beta_2)$. Its 95% confidence interval was obtained from 2000 residual bootstrap resamples (Efron, 1979), and optima were also computed separately for each immersion time.

2.4 Rate of deterioration

For each zeolite content, properties were regressed linearly on immersion time, and heterogeneity of slopes among the six contents was tested by comparing models with and without a zeolite × time interaction (an F test on 5 and 24 degrees of freedom). Because strength loss is strongly non-linear in time, stability was also fitted by $\ln S = \ln S_0 - kt$, and the decay constants k of the control and 6% mixtures were compared with a t test on the difference of the fitted slopes.

2.5 Paired comparison, correlation, composite desirability and robustness

The control and 6% mixtures were compared across immersion times by paired t tests, with Wilcoxon signed-rank tests as a non-parametric check and Cohen's d_z as the effect size (Cohen, 1988; Lakens, 2013). Percentage changes were averaged over times, with 95% confidence intervals from the t distribution. Relations among properties were examined

with Pearson correlation coefficients over the 30 combinations of zeolite content and immersion time from day 1 to day 7. A composite desirability index was built by scaling each property to 0–1 over its observed range (larger-is-better for stability and density; smaller-is-better for flow, air voids and VMA) and taking the geometric mean of the five individual desirabilities (Derringer & Suich, 1980). Finally, Friedman's rank test with immersion times as blocks, together with Kendall's *W*, was used to check the zeolite effect without distributional assumptions (Friedman, 1937). All computations used Python with SciPy and statsmodels (Seabold & Perktold, 2010; Virtanen et al., 2020). The significance level was 0.05.

3 RESULTS

3.1 Descriptive pattern and partition of variance

Table 1: Mean of each property over the six immersion times, by zeolite content

Zeolite	Stability (kN)	Flow (mm)	Density (kg/m^3)	Air voids (%)	VMA (%)	RSI (%)[a]
Control	9.20	4.28	2353	4.76	18.57	66.4
2%	10.27	3.77	2364	4.50	16.08	74.9
4%	11.51	3.71	2378	4.36	15.88	75.0
6%	12.53	3.56	2387	4.16	15.66	75.0
8%	12.46	3.69	2379	4.45	15.96	74.6
10%	12.04	3.82	2376	4.91	16.07	75.0

Note. [a] Mean over days 1–7. Dose means for stability, flow, density and VMA were close to optimal at 6% (Table 3).

Table 1 shows the averaged dose–response. Stability, density and RSI increased from the control to a maximum around 6% (stability 12.53 kN) and declined at 10%, whereas flow, air voids and VMA reached minima at 4–6% and rose at 10%. The two-way ANOVA (Table 2; Figure 1) showed that zeolite content and immersion time were both significant for every property. Their relative importance differed by property. For stability, density and VMA the zeolite effect was very large (partial η^2 = 0.98, 0.96 and 0.97), and immersion time was equally important for stability (0.99) and density (0.95) but less so for VMA (0.68). Flow was affected by both factors to a moderate-to-large degree (η^2 = 0.78 and 0.69). Air voids showed the weakest effects (η^2 = 0.40 for zeolite and 0.44 for time) and the least significant *F* ratios (*p* = .019 and .010). The very high η^2 values for RSI arise because the residual variance after removing both factors is tiny; they should not be interpreted as precision beyond that of stability, from which RSI is computed.

Table 2: Two-way ANOVA without replication: effects of zeolite content and immersion time

Property	$F_{zeolite}$	*p*	η^2_p	F_{time}	*p*	η^2_p	$F_{non\text{-}add}$	*p*	Shapiro–Wilk *p*
Stability (kN)	253.6	< .001	0.98	531.2	< .001	0.99	4.3	.048	.138
Flow (mm)	18.1	< .001	0.78	11.0	< .001	0.69	42.3	< .001	.547
Density (kg/m^3)	125.6	< .001	0.96	102.9	< .001	0.95	3.4	.079	.091
Air voids (%)	3.3	.019	0.40	3.9	.010	0.44	13.8	.001	< .001
VMA (%)	143.9	< .001	0.97	10.5	< .001	0.68	6.5	.018	.662
RSI (%)	369.9	< .001	0.99	2804.7	< .001	1.00	43.3	< .001	.001

Note. Degrees of freedom: zeolite 5, time 5, residual 25 (RSI: 5, 4 and 20). $F_{non\text{-}add}$ is Tukey's one-degree-of-freedom test for non-additivity (1 and 24 df; RSI 1 and 19). η^2_p = partial η^2.

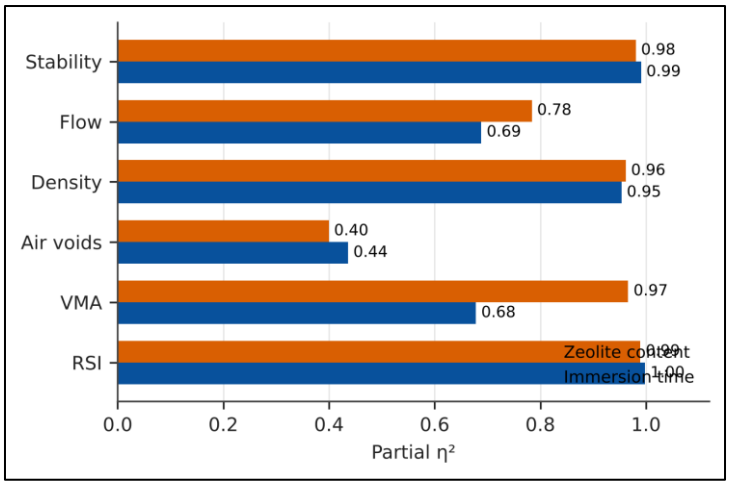


Figure 1: Partial η^2 of zeolite content and immersion time for each property (two-way ANOVA without replication).

3.2 Non-additivity and model adequacy

The additive model was adequate for density (non-additivity $p = .079$) and borderline for stability ($p = .048$), but there was significant interaction between zeolite content and time for VMA ($p = .018$) and highly significant interaction for flow, air voids and RSI (all $p \leq .001$; Table 2). Residuals were close to normal for stability, flow, density and VMA (Shapiro–Wilk $p > .09$), but not for air voids ($p < .001$) or RSI ($p = .001$; Figure 2). The air-voids residuals show the cause: a few cells, notably the 8 and 10% mixtures after seven days (5.22 and 6.81%), lie far above the rest. These cells reflect a real physical effect. High zeolite contents lose their protective effect during long immersion, so the dose–response differs at different times. The interaction means the main effects for flow, air voids and RSI describe averages and must be interpreted together with Figure 3 and Section 3.5. Because the unreplicated residual is the interaction term, the F tests for these properties are conservative.

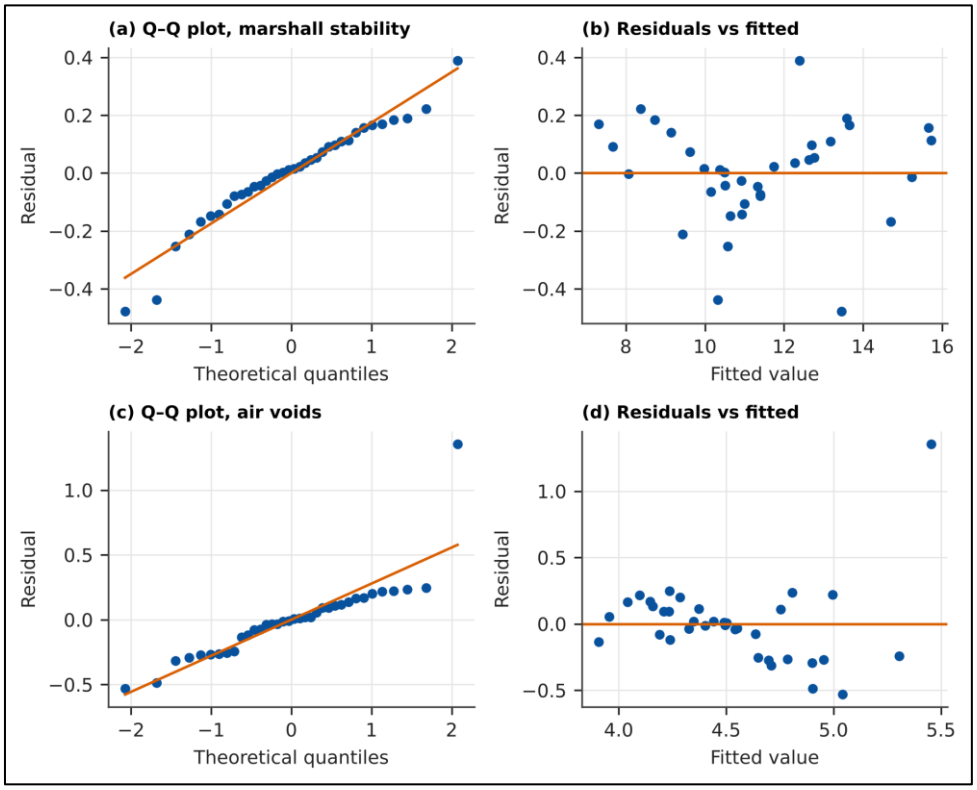


Figure 2: Residual diagnostics of the additive model for stability (a, b) and air voids (c, d). The air-voids residuals depart from normality and fitted values because of the 8–10% zeolite cells after seven days.

3.3 Comparison of zeolite contents

Table 3: Zeolite means over immersion times with Tukey grouping

Zeolite	Stability (kN)	Flow (mm)	Density (kg/m³)	Air voids (%)	VMA (%)
Control	9.20 e	4.28 a	2353 d	4.76 ab	18.57 a
2%	10.27 d	3.77 bc	2364 c	4.50 ab	16.08 b
4%	11.51 c	3.71 bc	2378 b	4.36 ab	15.88 bc
6%	12.53 a	3.56 c	2387 a	4.16 b	15.66 c
8%	12.46 a	3.69 bc	2379 b	4.45 ab	15.96 bc
10%	12.04 b	3.82 b	2376 b	4.91 a	16.07 b
HSD (5%)	0.366	0.255	4.8	0.647	0.395

Note. Means sharing a letter do not differ significantly (Tukey HSD, α = .05, 25 residual df). Letters run from the highest mean (a) downwards.

Table 3 groups the zeolite contents. For stability, the 6 and 8% mixtures formed the top group, the 10% mixture was significantly lower than both, and the control and 2% mixtures were lowest. Density was significantly highest at 6% alone. For flow and VMA the 6% mixture had the lowest mean, significantly better than the control and 10% mixture (and, for VMA, than 2%), but not distinguishable from 2, 4 and 8% for flow. The air-voids means overlapped almost completely: only 6 and 10% differed significantly. This agrees with the weak ANOVA result for air voids and reflects the time-dependent behaviour described above. Among dosages, 2–10% zeolite did not differ in RSI (Tukey HSD = 0.80 percentage points; all pairwise differences among 2–10% were below 0.5 points, $p > .5$), but all of them exceeded the control by about 8.2–8.7 points ($p < .001$), confirming that the RSI benefit saturates at the lowest dosage tested.

3.4 Response-surface models and optimum dosage

Table 4: Quadratic response-surface models with time covariate (Equation 1)

Property	R^2	β_1	β_2	p (β_2)	Optimum z_{opt} (%)	95% bootstrap CI	Range of z_{opt} by day (%)
Stability (kN)	0.835	0.8764	−0.05646	< .001	7.8	6.7–10.6	7.6–8.4
Flow (mm)	0.787	−0.2153	0.0177	< .001	6.1	5.7–6.7	5.6–7.2
Density (kg/m³)	0.929	9.488	−0.7091	< .001	6.7	6.3–7.2	6.5–7.3
Air voids (%)	0.555	−0.2314	0.02372	< .001	4.9	4.2–5.5	3.8–6.1
VMA (%)	0.844	−0.8567	0.06706	< .001	6.4	6.0–6.9	5.7–6.7

Note. Models were fitted to 36 observations; the F test of every model was significant ($p < .001$).

All five quadratic models explained a substantial share of the variation (R^2 from 0.56 for air voids to 0.93 for density), and in every case the quadratic term was significant ($p \leq .001$), which confirms a genuine interior optimum rather than a monotonic trend (Table 4; Figure 3). The estimated optima were 6.1% for flow (95% CI 5.7–6.7), 6.4% for VMA (6.0–6.9), 6.7% for density (6.3–7.2), 4.9% for air voids (4.2–5.5) and 7.8% for stability (6.7–10.6). The stability optimum is the highest and its interval is wide, because stability is almost flat between 6 and 8% (Table 3). The optima for flow, air voids and VMA became *lower* as immersion lengthened (flow from 7.2% at day 0 to 5.6% at day 7; VMA from 6.7% at day 4 to 5.7% at day 7), which is the same time-dependent loss of protection at high dosage seen in Section 3.2. Considered together, the property optima bracket 6% (4.9–7.8%), and the intervals for flow, density and VMA all include or neighbour 6%.

The composite desirability function integrates these competing optima (Figure 3f). Its mean over immersion times rose from 0.27 for the control to a maximum of 0.79 at 6% and then fell to 0.71 at 8% and 0.61 at 10%. The maximum was at 6% for every one of the six immersion times, including the seven-day condition in which the 8–10% mixtures deteriorate sharply. The composite criterion therefore supports a dosage of about 6% regardless of exposure duration, while the individual optima place the plausible window at roughly 5.5–7%.

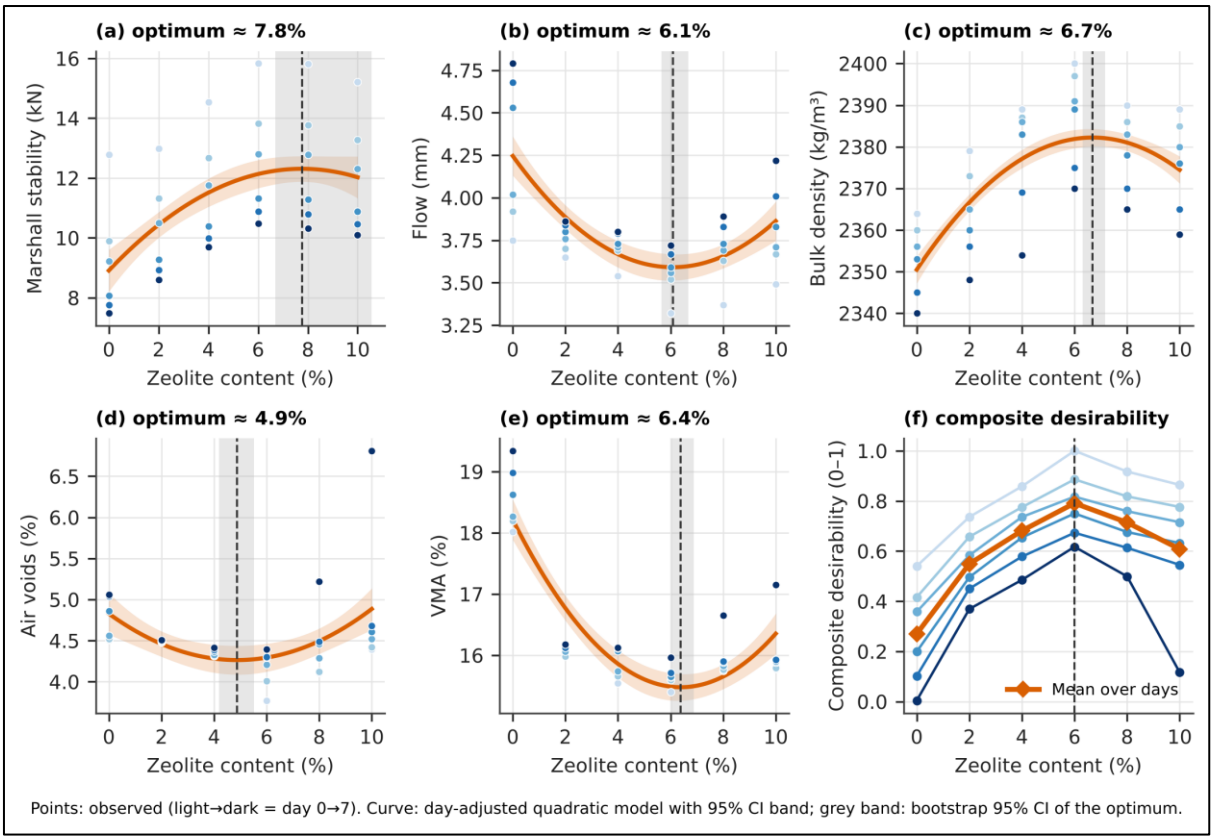


Figure 3: Quadratic response surfaces (day-adjusted) for (a) stability, (b) flow, (c) density, (d) air voids and (e) VMA, and (f) composite desirability, as functions of zeolite content. Points are observed values shaded by immersion time.

3.5 Does zeolite change the rate of deterioration?

Table 5: Linear rate of change per day by zeolite content (slope of property on immersion time)

Property	0%	2%	4%	6%	8%	10%	F_{het}	p
Stability (kN)	−0.664	−0.600	−0.663	−0.732	−0.754	−0.702	0.09	.993
Flow (mm)	+0.163	+0.030	+0.032	+0.050	+0.066	+0.104	8.48	< .001
Density (kg/m^3)	−3.57	−4.43	−5.32	−4.64	−3.77	−4.55	1.18	.349
Air voids (%)	+0.095	+0.004	+0.016	+0.081	+0.160	+0.333	9.38	< .001
VMA (%)	+0.202	+0.030	+0.091	+0.070	+0.124	+0.188	5.85	.001

Note. F_{het} tests equality of the six slopes (5 and 24 df). Units are the property unit per day.

The linear slopes (Table 5) reveal two distinct modes of action. For stability and density the slopes did not differ among zeolite contents (F_{het} = 0.09, p = .993; F_{het} = 1.18, p = .349): the curves are essentially parallel, and zeolite raises the level of these properties without changing how fast they decline. In an exponential decay model for stability the decay constant was 0.070 day^{-1} for the control and 0.058 day^{-1} for the 6% mixture (Figure 4), a 17% lower rate, but with seven-day curves of six points the 95% intervals (0.013–0.126 and 0.020–0.095) overlap widely and the difference was not significant (t(8) = −0.49, p = .64). In contrast, the rates of increase in flow, air voids and VMA differed strongly among zeolite contents (F_{het} = 8.48, 9.38 and 5.85; $p \leq .001$). The control's flow increased at 0.163 mm per day against 0.030–0.050 mm per day for 2–6% zeolite. The air-voids slope was 0.095 % per day for the control, near zero for 2–4% (0.004–0.016), and then *larger* than the control at 8 and 10% (0.160 and 0.333). Moderate zeolite contents therefore slow the opening of the void structure during submergence, while excess zeolite accelerates it.

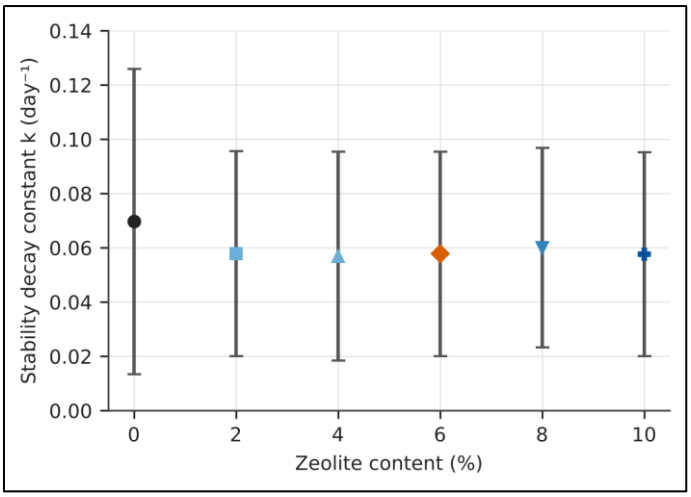


Figure 4: Exponential decay constant of stability (± 95% CI) by zeolite content. Overlapping intervals indicate that the decay rate is not distinguishable among mixtures with this sample size.

3.6 Control versus 6% zeolite

Table 6: Paired comparison of the 6% zeolite mixture with the control across immersion times

Property	Mean difference	95% CI	*t*	*p*	Cohen's d_z	Mean change (%)
Stability (kN)	3.33	2.95 to 3.71	22.52	< .001	9.2	+37.2
Flow (mm)	−0.718	−1.053 to −0.383	−5.51	.003	−2.3	−16.3
Density (kg/m^3)	34.0	30.7 to 37.3	26.34	< .001	10.8	+1.4
Air voids (%)	−0.596	−0.753 to −0.439	−9.74	< .001	−4.0	−12.5
VMA (%)	−2.91	−3.28 to −2.54	−20.16	< .001	−8.2	−15.6
RSI (%)	8.57	7.53 to 9.62	22.77	< .001	10.2	+12.9
Swell index (%)	−0.33	−0.52 to −0.14	−4.86	.008	−2.2	−31.2

Note. n = 6 immersion times (day 0–7); RSI n = 5 (day 1–7); swell index n = 5 (day 1–7). Differences are 6% minus control. Wilcoxon signed-rank p = .031 (n = 6) for the five measured properties, and .0625 for RSI and swell index (n = 5), the smallest values attainable.

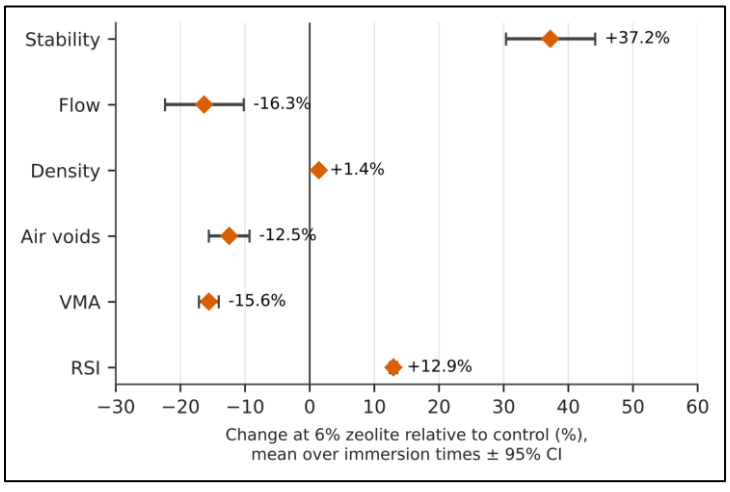


Figure 5: Percentage change produced by 6% zeolite relative to the control, averaged over immersion times, with 95% confidence intervals.

The 6% mixture outperformed the control in every comparison (Table 6; Figure 5). Mean stability was higher by 3.33 kN (+37.2%; 95% CI 2.95–3.71 kN), flow was lower by 0.72 mm (16.3%), air voids by 0.60 percentage points, VMA by 2.91 percentage points and RSI higher by 8.6 points (+12.9%). All paired t tests were significant ($p \leq .003$) and the swell index was also lower (p = .008); the Wilcoxon tests reached the smallest p values possible with six or five pairs. The

standardised effects ($|d_z|$ from 2.3 to 10.8) are extremely large, but they are large because the differences are consistent across immersion times, not because the samples are large, and with only five or six pairs their precision is low. The practically important finding is the consistent direction and the interval estimates in percentage terms: stability gains of roughly 24% at day 0 and 40% at day 7, and flow, air-voids and VMA reductions between 11 and 22% (Figure 5).

3.7 Relationships among properties

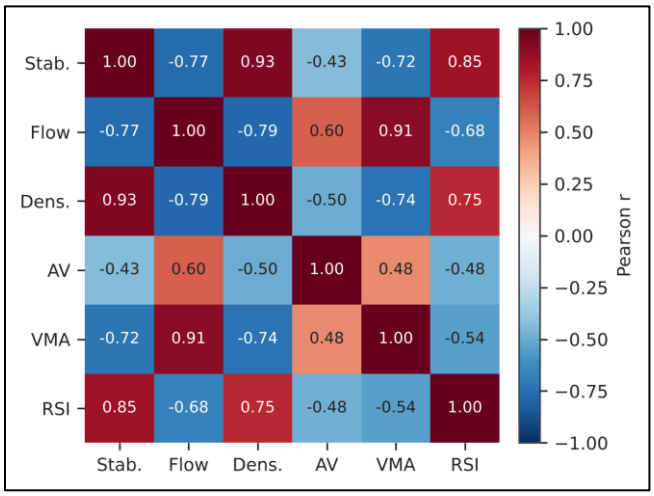


Figure 6: Pearson correlation matrix of the five measured properties and RSI (30 combinations of zeolite content and immersion time, days 1–7). Stab. = stability; Dens. = density; AV = air voids.

Strong correlations linked the properties that depend on binder–aggregate adhesion and packing (Figure 6). Stability correlated with density (r = 0.93) and with RSI (r = 0.85), and flow with VMA (r = 0.90); flow was negatively related to density (r = −0.79) and to stability (r = −0.77), all with p < .001. Air voids were the least well correlated with the other properties ($|r|$ from 0.43 to 0.60) because their dose–response and time response are non-monotonic (Section 3.2). Two practical consequences follow. First, density, which is cheap to measure, is a good screening indicator of stability retention (r = 0.93); second, air voids carry information that the Marshall variables do not and should be monitored separately when high zeolite contents are used.

3.8 Robustness to distributional assumptions

Table 7: Friedman test of the zeolite effect (immersion times as blocks)

Property	χ^2_F (5 df)	p	Kendall's W
Stability (kN)	30.0	< .001	1.00
Flow (mm)	25.3	< .001	0.84
Density (kg/m^3)	28.2	< .001	0.94
Air voids (%)	25.0	< .001	0.83
VMA (%)	25.9	< .001	0.86
RSI (%)	19.5	.002	0.78

Note. n = 6 blocks (immersion times); RSI uses the five times from day 1 to day 7. W = 1 indicates identical ranking of the zeolite levels at every immersion time.

The rank-based test confirmed that the zeolite effect was significant for all properties without any normality assumption (Table 7). Agreement was perfect for stability (W = 1.00; the ranking of the six contents was identical at every immersion time) and high for density (0.94), VMA (0.86), flow (0.84), air voids (0.83) and RSI (0.78). The significance of the air-voids result under this test (p < .001), where the parametric test was weakest, shows that the ordering of dosages is consistent across times even though the magnitudes interact with time.

4 DISCUSSION

Four findings stand out. First, the experiment quantifies how much of the variation each factor explains. For stability, density and VMA, zeolite content accounted for a large share and was as influential as seven days of submergence, which

is the practical meaning of the large partial η^2 values. The modifier is therefore not a marginal adjustment but a first-order design variable under flooding. Second, the location of the optimum is determined by statistical evidence, not by visual inspection: quadratic terms were significant for all properties, the stationary points bracket 6%, and the composite criterion peaks at 6% at every exposure time. The optimum is, however, not a point but a window of about 5.5–7%, and for the worst-case seven-day condition the optimum shifts downward (5.6% for flow and 5.7% for VMA). This asymmetry (a gentle penalty for under-dosing and a steeper one at 8–10% after prolonged immersion) argues for a dosage target of about 6% and against casually exceeding it.

Third, the rate analysis separates two mechanisms. Zeolite lifts the stability and density curves by a near-constant amount (parallel decay), whereas for flow, air voids and VMA it reduces the *rate* of deterioration at moderate dosages and loses that advantage above about 6%. The RSI result is consistent with the first mechanism: all zeolite contents retained about 8.5 points more of their initial strength than the control, with no further gain above 2%, even though absolute stability continued to rise to 6–8%. A designer concerned only with retained fraction might therefore choose a lower dosage, while one concerned with the absolute margin above the stability limit under flooding would choose about 6%. These interpretations match the pattern of modifier studies on submerged Niger Delta mixtures in which gains in retained strength and swell were found, but without formal rate analysis (Igwe & Amadi-Oparaeli, 2018; Igwe & Nyebuchi, 2017; Otto et al., 2020). Fourth, the interaction detected for flow, air voids and RSI shows that conclusions drawn from one immersion time alone may mislead: a dosage that is best at day 0 is not necessarily best at day 7, and testing across times, as done here, is essential for submerged pavements.

The analysis has limits. The design is unreplicated, so the residual term mixes interaction with experimental error, the *F* tests for non-additive properties are conservative, and tests based on six time points have limited power and imprecise effect sizes. Residual non-normality in air voids and RSI was handled by rank-based confirmation rather than by transformation, which could be examined further. The results come from one binder, one aggregate source and one zeolite, and the dataset contains the stability, flow, density, air voids and VMA values only; swell index was available for two mixtures. The aggregate blend was also deficient in fines passing 0.075 mm, so some of the zeolite effect may be a filler effect, as discussed in the companion paper. Replication (at least three specimens per cell), an inert-filler control and a mixed-effects model with specimen as a random effect would give firmer inference and direct estimates of experimental error.

5 CONCLUSIONS

- Zeolite content and immersion time were both highly significant for stability, flow, density, VMA and RSI; partial η^2 exceeded 0.95 for stability and density. The effects on air voids were smaller and interacted with dosage.
- Quadratic response surfaces had significant curvature for all properties. Their optima (air voids 4.9%, flow 6.1%, VMA 6.4%, density 6.7%, stability 7.8%) bracket 6%, and composite desirability was highest at 6% at every immersion time.
- Zeolite raised stability and density by a near-constant amount without significantly changing their decay rate, but at moderate dosage (2–6%) it reduced the rates at which flow, air voids and VMA deteriorated; at 8–10% zeolite air voids rose faster than in the control.
- Relative to the control, 6% zeolite increased stability by 37% and RSI by 13% on average and reduced flow, air voids and VMA by 16, 12 and 16% (all $p \leq .003$).
- The RSI benefit was fully realised at 2% zeolite; further dosage improved absolute stability but not retained fraction.
- Replicated experiments with an inert-filler control are needed to confirm the dosage window of about 5.5–7% and to separate adsorption from filler effects.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare no competing interests.

Author contributions

Data and laboratory investigation: E. A. Igwe; statistical analysis and drafting: C. G. Otto.

Data availability

The 6 × 6 experimental matrices analysed here are reported in the dissertation from which this work was prepared and are available from the corresponding author on request.

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