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Strength Development Index and Regression Analysis of Concrete Latex-Modified Asphalt Concrete under Prolonged Water Submergence

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Abstract

Moisture-induced damage is a leading cause of premature failure of asphalt pavements in the flood-prone Niger Delta, yet locally available polymer additives remain largely unexplored. This study evaluates concrete latex, a low-cost polymer emulsion sold in Port Harcourt building-materials markets, as a modifier for dense-graded asphalt concrete. Gravel, sand and asphalt cement (penetration 66.7) were blended and designed at an optimum binder content of 5%. Concrete latex was added at 0, 2, 4, 6, 8 and 10%, and specimens were submerged in water for 0, 1, 2, 3, 4 and 7 days before unconfined compressive strength (UCS) testing. The strength development index (SDI), retained strength, two-way analysis of variance and regression were used to interpret the results. Unconditioned UCS rose from 6.83 MPa for the control to a peak of 7.68 MPa at 6% latex (SDI = 0.124). After seven days the control retained 79.4% of its initial strength, compared with 89.5% and 89.9% for the 2% and 4% mixes and 83.3% for the 6% mix, giving SDI values of 0.15 to 0.19 for the 2–6% mixes. Latex content and immersion time were both highly significant ($p < 0.001$). Quadratic regression placed the optimum dosage near 7.6% for dry specimens but near 5.5% after seven days, and the 8% and 10% mixes lost strength sharply between days four and seven. A dosage of 4–6% is therefore proposed. Because each condition is represented by a single reported value, replicated testing and field trials are recommended.

Keywords: Concrete latex; asphalt concrete; Moisture damage; Unconfined compressive strength; Strength development index; Regression analysis.

1. INTRODUCTION

Hot-mix asphalt concrete is the dominant surfacing material for road networks worldwide, and its service life depends largely on how well the binder–aggregate system tolerates water. Moisture weakens the adhesive bond at the aggregate surface and softens the mastic, and the resulting stripping, ravelling and potholing then amplify rutting and fatigue distress [1], [2]. Molecular-scale studies show that water adsorbed on aggregate surfaces lowers the adhesion energy of the interface and can displace binder components from the mineral surface [3], and moisture failure is generally attributed to a combination of lost adhesion and lost cohesion [4]. For pavements that are periodically flooded or that sit on high water tables, resistance to prolonged immersion is therefore a primary durability requirement rather than a secondary check.

Polymer modification is the most widely used route to better moisture resistance, rutting resistance and fatigue life. Reviews of polymer-modified binders describe how elastomers such as styrene–butadiene rubber (SBR) and styrene–butadiene–styrene (SBS) form a swollen polymer network in the binder that raises stiffness and elastic recovery [5]–[7], although cost, ageing resistance and compatibility remain limitations [5], [8]. Latex-based delivery of SBS has been reported to give better rutting and fatigue resistance than particle-based SBS, at the price of reduced compatibility and storage stability at high dosage, and a dosage near 4 wt% was proposed as a sensible balance [9]. In mixtures, SBR and crumb rubber added by the wet process raised Marshall Stability, with an optimum SBR proportion of about 4% [10], and SBR/polypropylene blends improved moisture resistance relative to unmodified mixtures [4]. Natural rubber latex has also been reported to adhere well to aggregate and bitumen, although the water carried by the latex causes foaming during mixing [11] Waste plastics [12] and recycled polypropylene [13] have been explored as lower-cost alternatives that can raise stability and produce water-repellent surfaces. A common finding across these studies is that the benefit of a polymer rises to an optimum dosage and then declines, so the dosage has to be established experimentally for each material combination.

In Nigeria these concerns are acute. Failures along the Enugu–Port Harcourt expressway have been traced to clay-rich subgrade, missing drainage and heavy goods traffic that was not adequately considered in design [14]. Seasonal flooding in south-western Nigeria has been associated with 40–50% higher rehabilitation costs for flood-damaged roads [15], and recurrent flood washouts have been documented on the only major road into Wilberforce Island in the Niger Delta [16]. Rivers State combines high annual rainfall, low-lying terrain, shallow groundwater and heavy petroleum-sector traffic, so wearing courses there are exposed to water for long periods. Imported polymers such as SBS and SBR latex tend to be costly and are not routinely stocked in local markets, which limits their use in state and local government road programmes.

Concrete latex is a water-based polymer emulsion widely sold in Nigerian building-materials markets as a bonding agent and admixture for mortar and concrete repair. Polymer latexes of this kind form continuous films as water evaporates and are known to improve adhesion, impermeability and tensile behaviour of cementitious materials [17]. These film-forming and adhesive properties suggest that such a latex could act as a binder modifier in asphalt. To the authors' knowledge, however, its performance in asphalt concrete under prolonged water submergence has not been reported, and no data exist for Niger Delta materials. This is the gap addressed here.

From a sustainability perspective, extending pavement life even modestly reduces the repeated consumption of bitumen and aggregate, and the associated emissions, over the life cycle [18]. A locally sourced modifier that improves water resistance could therefore support more resource-efficient road maintenance, provided its dosage is optimised and its limits are understood. The objectives of this study were to (i) evaluate the effect of concrete latex content (0–10%) on the unconfined compressive strength (UCS) of asphalt concrete designed at the optimum binder content; (ii) quantify strength loss during water submergence for 0–7 days and the strength retained by each mix; (iii) express the benefit of the latex through a strength development index (SDI) and test the significance of latex content and immersion time using analysis of variance (ANOVA) and regression; and (iv) recommend a practical latex dosage for flexible pavements in the Niger Delta.

2. MATERIALS AND METHODS

2.1 Materials

All materials were purchased from local dealers at Mile 3 Market, Port Harcourt, Rivers State. The coarse aggregate was gravel, the fine aggregate was sand, the binder was asphalt cement, and the modifier was a

relevant commercially available concrete latex [CONFIRM: brand, polymer type and solids content, which are needed for reproducibility]. The aggregates were characterised by sieve analysis [19] and specific gravity [20], [21], and the binder by penetration [22], softening point [23] and viscosity. Gravel and sand were blended at a mass ratio of 0.60:0.40. Table 1 gives the gradations with the specification limits adopted for the mix, and Table 2 gives the material properties. Test procedures follow the cited ASTM and AASHTO standards; the Nigerian general specification for roads and bridges [26] is the local reference for bituminous wearing courses.

Table 1: Specification limits (ASTM C136) and blending of aggregates

Sieve (mm)	Specification Limit	% Passing Aggregate A (Gravel)	% Passing Aggregate B (Sand)	Mixture (0.60A+0.40B)
19.1	100	100.0	100.0	100.0
12.7	76 - 92	91.1	100.0	94.7
9.52	64 - 79	43.3	100.0	66.0
4.75	40 - 60	8.6	99.7	45.0
1.18	23 - 37	2.7	87.4	36.6
0.425	7 - 20	1.8	21.2	9.6
0.300	5 - 13	1.8	10.6	5.3
0.075	3 - 8	0.6	0.3	0.5

Table 2: Material Characterization of Aggregates and Asphalt Cement

Property	Asphalt Cement	Gravel	Sand
Specific gravity	1.03	2.78	2.66
Penetration	66.7	-	-
Viscosity (sec.)	69.3	-	-
Softening point (°C)	49.3	-	-

2.2 Mix design

Marshall specimens were prepared at binder contents of 4–6% by mass of mix and tested following AASHTO T245 [24] and ASTM D6927 [25. The mix was heated to a temperature of 160°C and poured into a mould and compacted with 75 blows at 150°C on both faces representing heavy traffic. The optimum binder content (OBC) was taken as 5% by considering the stability, flow, density and air-void results of all trial mixes together. Bulk density of compacted specimens was determined following ASTM D2726 [27]. Table 3 lists the properties of the unmodified mix at the OBC; the same binder content was used for every latex-modified mix.

Table 3. Marshall Properties of the unmodified asphalt concrete at the OBC (5%)

Marshall properties	Stability (KN)	Flow (mm)	Density (Kg/m^3)	Air Voids (%)	VMA (%)
Asphalt concrete	12.78	3.75	2364	4.509	18.013

2.3 Latex modification and moisture conditioning

Concrete latex was introduced at 0, 2, 4, 6, 8 and 10% by mass of mix. After heating of the aggregates and the addition of asphalt cement, the concrete latex was then added in between 2-10% by weight of the mix and

continuously stirred until there was homogeneity in the sample for another 5 mins.. The 0% mix served as the control. Specimens of every latex content were then submerged in water at room temperature 29°C for 0, 1, 2, 3, 4 and 7 days before testing, the 0-day condition representing unconditioned specimens. Three samples per condition were prepared, tested and average value taken and their mean values used in the report.

2.4 Unconfined compressive strength (UCS) test

UCS was measured on cylindrical specimens loaded axially to failure at a constant rate, following the principle of ASTM D1074 [28]. The submergence regime follows the moisture-conditioning principle behind AASHTO T283 [29], but is more severe in duration because specimens remain immersed for up to seven days.

2.5 Performance indices

Two indices were derived from the UCS data. The retained strength ratio, RSR = $(\sigma_7 / \sigma_0) \times 100$, expresses the strength after seven days of submergence (σ_7) as a percentage of the unconditioned strength (σ_0) of the same mix. The strength development index, SDI = $(\sigma_m - \sigma_c) / \sigma_c$, expresses the strength of a latex-modified mix (σ_m) relative to that of the unmodified control (σ_c) at the same immersion time. It adapts the SDI used for stabilised soils, in which σ_t and σ_u are the strengths of treated and untreated material, with the control asphalt concrete playing the role of the untreated material. A positive SDI indicates a strength gain from the latex.

2.6 Statistical analysis

The two factors, latex content (six levels) and immersion time (six levels), were analysed by two-way ANOVA at $\alpha = 0.05$. Because each cell holds a single value, an ANOVA without replication was used in which the interaction sum of squares serves as the error term [30]; this yields valid F-tests for the two main effects if any latex × time interaction is small, but it cannot test the interaction independently. Multiple regression was then used to model strength as $\sigma = b_0 + b_1L + b_2L^2 + b_3T$, where L is latex content (%) and T is immersion time (days). The quadratic term captures the rise-then-fall response to latex, and the stationary point $L = -b_1 / (2b_2)$ estimates the dosage giving maximum strength. The quadratic model was also fitted separately to the data of each immersion period to see whether the optimum dosage changes with time. For each mix, strength against time was fitted with a linear model, $\sigma = a + bT$, and a logarithmic model, $\sigma = a + b \cdot \ln(T + 1)$, and the coefficients of determination (R^2) were compared.

3. RESULTS AND DISCUSSIONS

3.1 Material properties and mix design

Table 1 shows that the blend met the specified limits at five of the seven control sieves but not at two. The percentage passing 12.7 mm (94.7%) slightly exceeded the upper limit of 92%, and the material passing 0.075 mm (0.5%) was far below the required 3–8%. This fines deficiency is typical of washed local sand and gravel used without added mineral filler. It matters for the interpretation of the results in two ways. First, it helps explain the high voids in mineral aggregate of the control (18.013%), since a mix lacking filler has a coarse, open skeleton and a less stiff mastic. Second, it probably makes the unmodified mix more sensitive to water than a fully compliant gradation, so part of the latex benefit reported below may be compensating for this deficiency and should not be extrapolated to well-graded, filler-bearing mixes without further testing.

The asphalt cement (penetration 66.7, softening point 49.3 °C, specific gravity 1.03) lies in the range expected of a 60/70 penetration grade, and the aggregate specific gravities (2.78 and 2.66) are typical of siliceous gravel and sand. At the OBC of 5%, the unmodified mix gave a Marshall stability of 12.78 kN, flow of 3.75 mm, density of 2364 kg/m^3 and 4.509% air voids (Table 3).

3.2 Effect of latex content on unconfined compressive strength

Table 4: Unconfined Compressive Strength of Concrete Latex Modified Asphalt Concrete Mixes under Moisture Submergence

Concrete Latex (%)	UCS (MPa) Immersion Days					
	0	1	2	3	4	7
0	6.83	6.39	6.18	5.69	5.52	5.42
2	6.98	6.76	6.62	6.43	6.32	6.25
4	7.16	6.87	6.76	6.58	6.49	6.44
6	7.68	7.26	7.03	6.76	6.55	6.40
8	7.43	7.06	6.90	6.67	6.52	6.05
10	7.37	7.04	6.87	6.63	6.42	5.95

Latex content had a non-monotonic effect on UCS at every immersion period (Figure 1). At day 0, strength rose from 6.83 MPa (0%) to 6.98, 7.16 and 7.68 MPa at 2, 4 and 6% latex, then fell to 7.43 and 7.37 MPa at 8 and 10%. The 6% mix therefore exceeded the control by 12.4%, and even the 10% mix exceeded it by 7.9%. The same inverted-U shape with a peak at 6% persisted from day 0 to day 4. At day 7 the peak moved to 4% (6.44 MPa), with the 6% mix marginally lower (6.40 MPa); a difference of 0.6% is well within normal specimen variability, so the two mixes should be regarded as equivalent after a week of submergence. Averaged over all six immersion periods, mean UCS was 6.01, 6.56, 6.72, 6.95, 6.77 and 6.71 MPa for 0, 2, 4, 6, 8 and 10% latex, so the 6% mix was 15.7% stronger than the control overall.

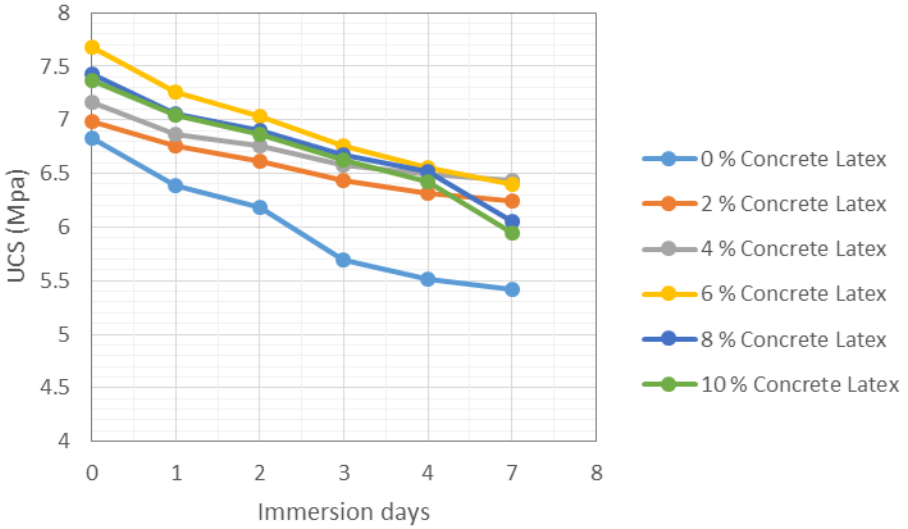


Figure 1. UCS against concrete latex content for each immersion period.

3.3 Effect of immersion time and strength retention

Immersion reduced UCS in every mix, but the pattern of loss differed with latex content (Table 5). The control lost 6.4% of its strength in the first day and a further 13.6% between day 1 and day 4, then levelled off, losing only 1.8% between day 4 and day 7. Its total loss was 20.6% (1.41 MPa), so it retained 79.4% of its initial

strength. The 2% and 4% mixes lost only 10.5% and 10.1% overall, and their absolute losses (0.73 and 0.72 MPa) were about half that of the control. The 6% mix lost 16.7% (1.28 MPa).

Table 5. Strength loss and retained strength ratio (RSR) after submergence

Concrete Latex (%)	Loss 0–1 d (%)	Loss 1–4 d (%)	Loss 4–7 d (%)	Total loss 0–7 d (%)	Absolute loss (MPa)	RSR (%)
0	6.4	13.6	1.8	20.6	1.41	79.4
2	3.2	6.5	1.1	10.5	0.73	89.5
4	4.1	5.5	0.8	10.1	0.72	89.9
6	5.5	9.8	2.3	16.7	1.28	83.3
8	5.0	7.6	7.2	18.6	1.38	81.4
10	4.5	8.8	7.3	19.3	1.42	80.7

The 8% and 10% mixes behaved differently from the others. Between day 1 and day 4 they lost 7.6% and 8.8%, comparable with the 6% mix, but between day 4 and day 7, when every other mix was close to stable, they lost a further 7.2% and 7.3%. Their total losses (18.6% and 19.3%, or 1.38 and 1.42 MPa) ended almost equal to those of the control.

3.4 Strength development index

Table 6 and Figure 2 give the SDI of each latex mix at each immersion time. All values are positive, so every latex content improved strength relative to the control at every stage. At day 0 the SDI ranged from 0.022 (2% latex) to 0.124 (6%). For the 2%, 4% and 6% mixes the SDI increased as immersion progressed, for example from 0.048 to 0.188 for the 4% mix between day 0 and day 7, because the control deteriorated faster than the modified mixes. The benefit of the latex is therefore larger in wet than in dry conditions, which is the behaviour expected of a moisture-resistance modifier. The 6% mix had the highest SDI from day 0 to day 4 (peak 0.188 at day 3), whereas at day 7 the 4% mix was highest (0.188). The SDI of the 8% and 10% mixes rose to 0.181 and 0.163 at day 4 but then fell to 0.116 and 0.098 at day 7, mirroring the late strength loss in Table 5. Averaged over the six immersion periods, the mean SDI was 0.097, 0.123, 0.159, 0.130 and 0.120 for 2, 4, 6, 8 and 10% latex, so the 6% mix gave the largest overall gain.

Table 6. Strength development index (SDI) of latex-modified mixes relative to the control

Concrete Latex (%)	SDI						
	Immersion Days						
	0	1	2	3	4	7	Mean
2	0.022	0.058	0.071	0.130	0.145	0.153	0.097
4	0.048	0.075	0.094	0.156	0.176	0.188	0.123
6	0.124	0.136	0.138	0.188	0.187	0.181	0.159
8	0.088	0.105	0.117	0.172	0.181	0.116	0.130
10	0.079	0.102	0.112	0.165	0.163	0.098	0.120

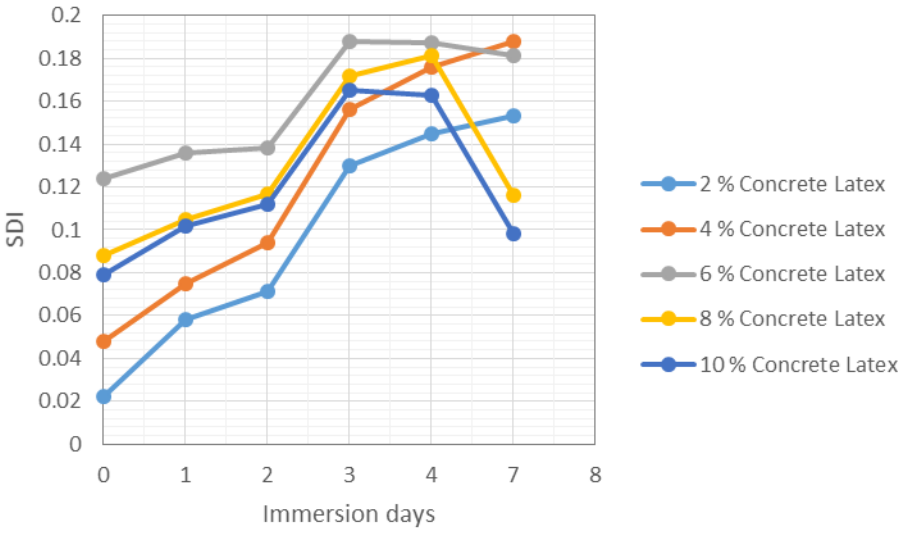


Figure 2. Strength development index against concrete latex content for each immersion period.

3.5 Analysis of variance

Table 7 summarises the two-way ANOVA. Both factors were highly significant: latex content, $F(5, 25) = 33.38$, $p < 0.001$, and immersion time, $F(5, 25) = 55.88$, $p < 0.001$. Immersion time accounted for 59.3% of the total variation in UCS, latex content for 35.4% and the residual for 5.3%. The dominance of the time effect shows how severely submergence degrades strength in this family of mixes, while the large latex share shows that modification can offset a substantial part of that loss. Because the error term is the latex × time interaction, a real interaction would inflate it and make the tests conservative; the interaction is evidently present to some degree, as the different loss patterns in Section 3.3 and the improvement in regression fit reported below both indicate, but the small residual share supports treating the two main effects as reliably established. Replicated specimens would be needed to test the interaction itself.

Table 7. Two-way ANOVA (without replication) for UCS

Source	Sum of squares	df	Mean square	F	p-value
Latex content	3.178	5	0.636	33.38	< 0.001
Immersion time	5.319	5	1.064	55.88	< 0.001
Residual (interaction)	0.476	25	0.0190	–	–
Total	8.972	35	–	–	–

3.7 Regression models

The regression of UCS on latex content and immersion time across all 36 observations gave $\sigma = 6.500 + 0.2591L - 0.01961L^2 - 0.1616T$, with $R^2 = 0.878$, adjusted $R^2 = 0.866$ and a root-mean-square error of 0.185 MPa; every coefficient was significant at $p < 0.001$. On average, each additional day of submergence therefore lowered UCS by 0.162 MPa at a given latex content. The marginal gain from latex, $0.2591 - 0.0392L$ MPa per percentage point, is positive up to the stationary point $L^* = 6.60\%$ and negative beyond it. Adding the $L \times T$ and $L^2 \times T$

terms raised R^2 to 0.898 (adjusted 0.881), a modest gain that confirms a real but secondary dependence of the latex effect on immersion time.

Fitting the quadratic model separately to each immersion period (Table 8) shows that the optimum dosage is not fixed. The fitted optimum fell steadily from 7.6% at day 0 to 5.5% at day 7, and the curvature coefficient b2 became more negative from −0.0124 to −0.0304, meaning that the penalty for over-dosing grows with the duration of submergence. The day-0 value of 7.6% lies between the tested dosages of 6% and 8%, where the measured strengths were 7.68 and 7.43 MPa, so it should be read as an indication that the true dry optimum may lie slightly above 6% rather than as a precise figure; each fit uses three parameters on six points.

The time dependence of each mix was also modelled (Table 9). Linear fits were significant for every mix (p = 0.0125, 0.0089, 0.0163, 0.0074, 0.0003 and 0.0001 for 0 to 10% latex). The fitted rate of loss was 0.203 MPa/day for the control but only 0.104 and 0.098 MPa/day for the 2% and 4% mixes, about half; it rose again to 0.178, 0.189 and 0.199 MPa/day for the 6%, 8% and 10% mixes, approaching the control. The logarithmic model fitted better than the linear model for the control and the 2–6% mixes (R^2 = 0.953–0.985 against 0.799–0.863), consistent with rapid early loss that levels off, whereas for the 8% and 10% mixes the linear model fitted as well or better (R^2 = 0.974 and 0.983 against 0.969 and 0.957), consistent with loss that is still continuing at day 7. The fitted equations apply only within the 0–7 day range tested, and the 8% and 10% mixes in particular should not be extrapolated beyond it.

Table 8. Quadratic regression of UCS on latex content, $\sigma = b_0 + b_1L + b_2L^2$, for each immersion period

Immersion (days)	b_0	b_1	b_2	R^2	Fitted optimum L (%)	Best tested dosage (%)
0	6.750	0.1890	−0.01237	0.797	7.64	6
1	6.383	0.2073	−0.01424	0.913	7.28	6
2	6.197	0.2183	−0.01531	0.963	7.13	6
3	5.771	0.2970	−0.02170	0.946	6.84	6
4	5.619	0.3103	−0.02366	0.928	6.56	6
7	5.536	0.3327	−0.03040	0.854	5.47	4

Table 9. Regression of UCS on immersion time for each mix

Concrete Latex (%)	Linear intercept (MPa)	Linear slope (MPa/day)	R^2 linear	R^2 logarithmic	Logarithmic slope (MPa per ln unit)
0	6.579	−0.2025	0.823	0.953	−0.7411
2	6.854	−0.1038	0.850	0.974	−0.3778
4	6.994	−0.0977	0.799	0.969	−0.3662
6	7.451	−0.1782	0.863	0.985	−0.6475
8	7.306	−0.1887	0.974	0.969	−0.6402
10	7.276	−0.1987	0.983	0.957	−0.6667

3.8 Mechanisms and comparison with the literature

The rising limb of the response, up to 6% latex, is consistent with the film-forming behaviour of polymer latexes. As the mixture is heated and its water evaporates, the polymer particles coalesce into a film that can bridge the binder and the aggregate surface and form a polymer network within the mastic, raising cohesion

and stiffness [9], [10]. A continuous film also reduces the access of water to the aggregate–binder interface, which is where adsorbed water lowers adhesion energy [3] and where moisture damage starts [4], and polymer films have been shown to give water-repellent asphalt surfaces [13], [17]. This explains why the modified mixes lost strength more slowly than the control, and why the 2% and 4% mixes lost the least, since a thin, well-dispersed film is probably enough to protect the interface. Surface-energy studies likewise link better water resistance to a higher work of adhesion between binder and aggregate [31].

Beyond the optimum, several mechanisms could account for the weaker and less durable response of the 8% and 10% mixes. A higher dosage carries more water into the mix and promotes foaming during mixing, which leaves micro-voids [11]; excess polymer can exceed the compatibility limit of the binder and plasticise rather than reinforce it [9]; and the surfactants that stabilise commercial latex emulsions are hydrophilic and may provide pathways for water uptake once the latex content is high. The last explanation is a hypothesis that needs scanning electron microscopy, infrared spectroscopy or water-absorption tests to confirm. The companion Marshall volumetric measurements on the same mixes, reported separately, are consistent with it: air voids at day 7 rose to 5.217% and 6.810% for the 8% and 10% mixes, against 4.396% for the 6% mix.

The overall picture agrees in direction with earlier work on elastomer-modified asphalt. A dosage of about 4% was proposed for SBS latex [9] and found optimal for SBR in mixtures [10], which falls inside the 4–6% window found here, and the improvement in moisture resistance mirrors that reported for SBR/polypropylene blends [4]. The studies cited measured different properties, mostly Marshall stability, rutting and moisture-damage indices, so the comparison is qualitative. Against an agency threshold of 80% retained strength, which is widely used with AASHTO T283 [29], the control (79.4%) fell just short while every modified mix passed (80.7–89.9%), although a seven-day immersion test is not equivalent to the T283 tensile strength ratio and the comparison is indicative only.

3.9 Practical implications and limitations

For flexible pavements in the Niger Delta the results support a latex content of 4–6%. A content of 6% gives the highest strength when the pavement is dry or briefly wetted and the largest mean SDI (0.159), whereas 4% gives the highest retained strength (89.9%) and the lowest absolute loss (0.72 MPa) under prolonged submergence and is equal in strength to the 6% mix at day 7. Corridors that flood for long periods favour the lower dosage, and dosages of 8% and above should be avoided because they cost more, add no benefit after a week of submergence and show accelerating loss. Latex modification does not replace good drainage and subgrade design, which remain the main control on flood damage [14], [16]. In sustainability terms, the retained strength may extend wearing-course life and reduce repeated material use [18], but latex is itself a manufactured polymer, and a life-cycle assessment would be needed to confirm a net benefit.

The findings are subject to several limitations. Each condition is represented by a single value, so differences of a few percent, such as those between the 4% and 6% mixes at day 7, cannot be resolved. A single latex product was used and its composition is unconfirmed. The blend lacked mineral filler, which may exaggerate both the moisture sensitivity of the control and the benefit of the latex. Only compressive strength was measured, and only under seven days of immersion at laboratory conditions without ageing or traffic loading.

CONCLUSIONS

The effect of concrete latex on the unconfined compressive strength of asphalt concrete under water submergence was investigated for latex contents of 0–10% and immersion periods of 0–7 days. The main conclusions are as follows.

1. Concrete latex raised the dry UCS up to 6% content, from 6.83 MPa for the control to 7.68 MPa (+12.4%, SDI = 0.124), and strength fell to 7.43 and 7.37 MPa at 8% and 10%.
2. Submergence reduced the strength of every mix. After seven days the control retained 79.4% of its initial UCS, against 89.5% and 89.9% for the 2% and 4% mixes, 83.3% for the 6% mix, and 81.4% and 80.7% for the 8% and 10% mixes.
3. The SDI was positive for all mixes and grew with immersion time for the 2–6% mixes, reaching 0.15–0.19 at day 7, so the benefit of the latex is greater in wet than in dry conditions. The 8% and 10% mixes lost strength sharply between days 4 and 7, and their SDI fell to 0.116 and 0.098.
4. Latex content and immersion time both had highly significant effects ($p < 0.001$), with immersion time explaining 59.3% and latex content 35.4% of the variation in UCS.
5. A quadratic regression model with immersion time ($R^2 = 0.878$) placed the overall optimum at 6.6% latex. The fitted optimum fell from 7.6% for dry specimens to 5.5% after seven days, and strength loss followed a logarithmic law for the 0–6% mixes but was nearly linear for the 8% and 10% mixes.
6. A latex content of 4–6% is recommended, with 6% favoured for strength and 4% for prolonged submergence. Replicated testing, tensile and durability tests, and field trials are needed before the latex is adopted in practice.

Declaration of Conflicting Interests

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