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Performance Study on Laterite Road Base Stabilised with Emulsions Incorporating Biochar

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Abstract: This study explores the utilisation of biochar as an innovative and sustainable additive to emulsions for stabilising laterite road base material in pavements, with the environmental benefit of sequestering atmospheric carbon and stable form storing. A diverse range of design mixtures for the treated road base material with the proposed biochar–emulsion binder was developed for experimental validation and subsequent steps encompassed an array of laboratory tests to scrutinise the engineering attributes of the mixtures. The tests were selected to assess various properties such as unconfined compressive strength, tensile strength, resilient modulus, flexural modulus, fatigue life, and deformation characteristics. To gain practical insights from real-world conditions, two field trials were also conducted to evaluate the performance of the stabilised road base. The findings revealed that a design mix incorporating 5% biochar and 6% emulsion delivered an average unconfined compressive strength (UCS) of 1.5 MPa, which adheres to the standard UCS range for cemented lightly bound base course material. The optimal ratio of biochar to emulsion was identified as 1:1.6, which delivered a higher resilient modulus value than did the minimum stipulated by the literature for average daily traffic in the first year of design. As the temperature rose, the stabilised laterite base exhibited a reduction in its flexural modulus; however, it demonstrated minimal susceptibility to fluctuations in frequency. The deformation observed in the wheel-tracking tests for mixtures of the optimum biochar-to-emulsion ratio was less than 1 mm, which is remarkably lower than the maximum requirement outlined in the literature (i.e., 15 mm). Furthermore, visual inspection post-testing detected minimal cracking. These findings indicate that the integration of biochar and emulsion in the construction of road pavements is a promising technique that could contribute to carbon sequestration and climate change mitigation without sacrificing pavement performance. The successful field trials provided further evidence of the feasibility of this novel technique.

Keywords: road base material; road construction; pavements; stabilisation; emulsion; biochar

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1. Introduction

In the domain of road pavements, traditional Portland Cement (PC) has been the predominant chemical stabiliser for road base materials to improve material mechanical properties. However, the continual reliance on PC as a chemical stabiliser has the potential to magnify the environmental impacts associated with its production. These encompass increased carbon dioxide emissions by more than 7%, significant energy consumption, depletion of raw materials, and considerable landscape degradation [1]. This has prompted the pursuit of innovative and efficient nontraditional binders that can stabilise road materials for pavements, whilst concurrently reducing the environmental footprint.

Recent years have witnessed the rise of polymer emulsions as nontraditional binders for soil stabilisation in road construction and applications. An emulsion, a system comprising two immiscible liquids in which one is dispersed in the other, offers versatility in chemical formulations, enabling the treatment of a variety of soil types. When compared to the calcium-based stabilisers (e.g., PC), polymer-stabilised materials demonstrate more flexible behaviour, require a shorter curing period, and necessitate less quantity for effective results [2,3]. Furthermore, polymer emulsions, due to their nontoxic nature and lower carbon emissions, pose fewer environmental concerns, aligning with global efforts to mitigate climate change [4]. One promising avenue to augment the use of polymer emulsions and further reduce climate change impacts involves the integration of biochar, a sustainable additive.

Biochar, a porous, carbon-rich material, is derived from the thermochemical conversion of biomass, which often includes biological waste such as industrial wastewater, bovine manure, algae, wastewater sludge, and seaweed [5,6]. The conversion process of biochar incorporates a variety of techniques such as pyrolysis, torrefaction, flash carbonization, hydrothermal carbonisation, and gasification. These techniques all share a common element of applying heat (ranging from 350 to 700 °C) in a low-oxygen setting [6,7]. The potential of biochar for carbon sequestration has been widely acknowledged, positioning it as an important tool in mitigating climate change [7,8]. This carbon sequestration potential stems from the biochar's inherent properties, solidified through the process of pyrolysis. During pyrolysis, organic material is subjected to high temperatures in an oxygen-free environment, converting the biomass into a stable form of carbon. This transformation not only prevents the emission of carbon dioxide into the atmosphere but also effectively locks the carbon into biochar, which could potentially result in a net reduction of over 800 kg of CO_2 per tonne of feedstock, as illustrated by Gupta et al. [8]. When used as a construction material, biochar essentially acts as a carbon sink, potentially sequestering carbon for hundreds of years within the built structure. In the realm of road construction, biochar is primarily utilised in flexible asphalt pavements to produce bioasphalt and modify asphalt binders, thereby reducing carbon emissions [9–13]. The inherent properties of biochar, including high stability, large surface area, and aromatic structure, contribute significantly to enhancing the mechanical properties of asphalt bitumen [6]. It is crucial to acknowledge that not all forms of biochar are suitable for road applications due to the potential release of harmful components. Specifically, biochar derived from industrial wastewater and wastewater sludge must be approached with caution, as these sources often contain high levels of heavy metals that can leach into the soil [14]. On the contrary, organic-based biochar that is free from harmful components or demonstrates low concentrations of hazardous substances is generally considered a safer option for soil amendment. Therefore, it is imperative to carefully consider the source and properties of biochar before utilizing it in soil applications. However, in the context of research, using biochar as an additive with emulsions for chemical stabilisation of road base materials is currently limited and warrants further exploration. The stable chemical structure and high carbon content of biochar are postulated to be capable of forming robust covalent bonds with the modified emulsion. This potent combination could potentially provide substantial bond strength with aggregate whilst preserving an adequate degree of flexibility for the treated road base and concurrently contribute to reducing the greenhouse impact.

The current paper intends to investigate the feasibility of integrating biochar into emulsions to advance its application as an environmentally friendly binder for the stabilisation of road base material in pavement infrastructures. The research conducted involved devising an assortment of design mixes tailored specifically to the proposed road base material, with a particular focus on the lateritic aggregate, typically found in tropical and subtropical climates. The design mixes were predominantly developed for the experimental assessment, and an array of laboratory tests was conducted to explore the engineering properties of the formulated mixtures. The primary focus of these tests was to assess variables such as the unconfined compressive strength, indirect tensile strength, indirect tensile modulus, flexural modulus, fatigue life, and deformation characteristics of the mixtures. In addition, two field trials were carried out as a complementary step to gauge the performance of the stabilised road base under real-world conditions. This method allowed for a tangible understanding of the material's effectiveness, thereby reinforcing the laboratory findings.

Ultimately, the primary objective of this study is to leverage these findings to improve road base materials in the broader context of pavement construction and rehabilitation.

2. Materials and Methodology

The concept of the proposed road base material presented in this study involves stabilising laterite aggregate with chemically modified emulsion binder incorporating biochar to produce strong interparticle material as a viable and environmentally friendly road base in pavements for road construction and rehabilitation.

2.1. Aggregate

The aggregate used in the road base material of this study was laterite, which is a common road base course material used in Western Australia. The initial assessment of the laterite aggregate included performing the particle size distribution and Atterberg limits tests to determine its suitability for chemical stabilisation. The particle size distribution was carried out following Main Road Western Australia MRWA [15] with the grading checked against the base course quality limits. The liquid limit (*LL*) was conducted following the Australian Standard AS1289.3.9.1 [16], whereas the plastic limit (*PL*) was conducted following the Australian Standard AS1289.3.2.1 [17]. The particle size distribution of the laterite aggregate used in this study is illustrated in Figure 1, and Atterberg's gradation is presented in Table 1. It is evident from Figure 1 that the sample did not meet the MRWA 501E specification in terms of particle size distribution, indicating that it needed some form of stabilisation; aggregate materials that fail to meet the specified gradation requirements must be stabilised to ensure they possess the necessary performance properties to be utilised as a pavement layer without premature failure. The Atterberg limits results presented in Table 1 categorize the fines as low plasticity silt according to the unified soil classification system.

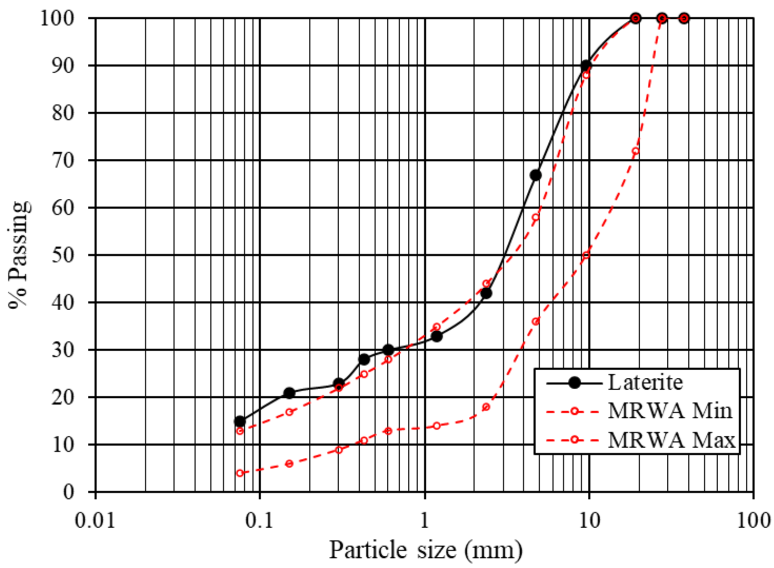

Figure 1. Particle size distribution of the laterite aggregate used.

Table 1. Atterberg limits of the laterite aggregate used.

Property	Value
Liquid Limit (*LL*)	22%
Plastic Limit (*PL*)	16%
Plasticity Index (*PI*)	6%

2.2. Emulsion

In the realm of chemical stabilisation, two primary types of bitumen emulsions are currently used, namely, cationic and anionic emulsions. However, due to the superior bonding capabilities of the positively charged particles present in cationic bitumen emulsion with acid-based minerals found in quartzite and granite, it is predominantly utilised in the stabilisation processes of road pavements. In contrast, anionic bitumen emulsion incorporates negatively charged particles containing limestone [18]. The emulsion used in the current study is called C-Twelve, which is chemically modified to allow for covalent bonding with the biochar. The specific chemical formulation employed in the utilised C-Twelve emulsion is proprietary, belonging to a private corporation, and thus, cannot be disclosed in this publication due to confidentiality agreements.

2.3. Biochar

The chemical stabilisation method under examination in this study hinges on the utilisation of biochar as a carbon source covalently binding the stabiliser (i.e., emulsion) to the base course material. The biomass products utilised in the pyrolytic process to synthesise the biochar commercially contain the following components: jarrah (Eucalyptus Marginata) = 90%, marri (Corymbia Calophylla) < 1%, karri (Eucalyptus Diversicolour) < 1%, and pine (Pinus Pinaster) = 5%. Chemically, the biochar encompasses the following constituents: carbon > 77%, crystalline silica < 3%, iron oxide = 0.5%, sulphur = 0.1%, and naphthalene < 0.1%. The gradation of the biochar employed was ascertained by employing a particle size distribution, as depicted in Figure 2.

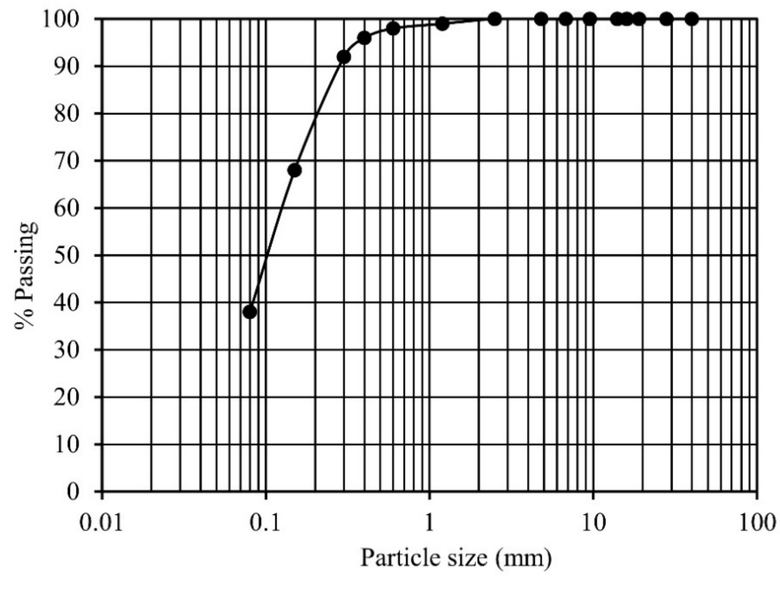

Figure 2. Particle size distribution of the biochar used.

2.4. Mixing

In this study, a diverse array of mixes was formulated, following the experimental program mentioned in Table 2. Each mix comprised a unique blend of emulsion and biochar as determined by the mass of the road base. The integration of the emulsion–biochar mixture into the dry road base material was conducted utilising a Hobart mixer. The mixing involved the gradual introduction of free water to achieve the ideal compaction parameters, namely the maximum dry density (MDD) and optimum moisture content (OMC). This procedure was carried out in compliance with the modified Proctor effort, in line with the WA 133.1 standards of the Main Roads Western Australia [19]. Preliminary testing, utilising biochar at 5% with a fixed emulsion content of 6%, indicated a minimal impact of the additives on the compaction parameters of laterite road base materials. The MDD was observed to range from 2.12 to 2.3 t/m^3, and the corresponding OMC was found to be within 10–11%. Thus, it can be concluded that the addition of the emulsion–biochar mixture in a small amount does not significantly affect the compaction parameters of laterite road base material. Based on these observations, it was determined to set the MDD and OMC at the values for untreated road base material for all specimen preparation.

Table 2. Testing matrix and design mixes.

Test	Emulsion (%) *	Biochar (%) *	Biochar: Emulsion
Unconfined compressive strength (UCS)	6	5	-
		10	-
		15	-
Indirect tensile strength (ITS)	4	3	-
		5	-
		7	-
	6	3	-
		5	-
		7	-
	8	3	-
		5	-
		7	-
Resilient modulus—indirect tensile method (ITM)	3.6	3	1:1.2
		5	1:1.4
		7	1:1.6
	4.2	3	1:1.8
		5	1:1.2
		7	1:1.4
	4.8	3	1:1.6
		5	1:1.8
		7	1:1.2
	5.4	3	1:1.4
		5	1:1.6
		7	1:1.8
Four-point beam (flexural modulus and fatigue tests)	Conducted on optimum mixture obtained from ITM testing		
Wheel tracking			

* Determined by the mass of the road base.

2.5. Sample Preparations and Lab Testing

Each set of the specially prepared mixes was subjected to a meticulous process of sample preparation and an array of comprehensive laboratory tests, as detailed in Table 2. These tests included the unconfined compressive strength (UCS), indirect tensile strength (ITS), resilient modulus using the indirect tensile method (ITM), four-point beam, and wheel tracking. To guarantee the precision of the results, a minimum of two samples were investigated for each test. All the tests performed stayed within the mandated 20% range. Consequently, the mean value was employed for the analysis of the results, thus ensuring a high level of accuracy. It should be noted that methods of sample preparation and testing followed the relevant Austroads design guides and Australian standards, but where necessary deviations might have occurred due to the unique properties of this stabilisation technique. Further details concerning the varying mixtures, samples, and testing procedures can be comprehensively explored in the subsequent text.

Unconfined Compressive Strength (UCS): This test was performed to investigate the compressive strength of road base samples, which were subjected to treatments with biochar at varying proportions of 5%, 10%, and 15% coupled with a consistent 6% emulsion dose before curing for 28 days, as per Austroads' [20] recommendation. Sample size and test aspects were carried out as per WA 143.1 of the Main Roads Western Australia standards [21]. As an initial evaluation, testing data revealed a notable increase in the UCS value of the road base material that contained 5% biochar compared to the material containing 10% and 15% biochar. Based on these findings, it was deemed necessary to concentrate subsequent tests on materials containing 3%, 5%, and 7% biochar, to further explore and validate these mixtures. The details and implications of the UCS findings will be further discussed and elucidated in the sections that follow.

Indirect Tensile Strength (ITS): This test was conducted on road base material treated with biochar percentages of 3%, 5% and 7% in conjunction with an emulsion content of 4%, 6%, and 8%. The procedural guidelines adhered to the NZTA T-19 standards [22], owing to the lack of a corresponding Australian standard for determining the indirect tensile strength (ITS). The mix design under consideration entailed the compaction of six samples, with an equal division for testing under dry and wet conditions. A curing period of 72 h was allowed for all samples in an oven maintained at 40 °C. Furthermore, the samples assigned for wet testing were subjected to a 24-h immersion in a water bath before the testing stage. Upon the completion of the curing process, the samples' strength and durability were assessed using the Marshall loading apparatus. The assessment of the indirect tensile strength (ITS) was conducted by gauging the ultimate load that led to the failure of a test specimen. The specimen underwent a steady loading rate of 1 ± 0.1 mm/min along its diametrical axis.

Resilient modulus—Indirect Tensile Method (ITM): The experimental procedures employed in this test relied on the UTM25 machine and UTS003—1v41b software, products of IPC Global. The tests were conducted following the guidelines set forth by the Australian standard AS2891.13.1 [23]. The test was conducted on samples treated with biochar percentages of 3%, 5%, and 7% with the emulsion varied as a ratio of biochar to emulsion of 1:1.2, 1:1.4, 1:1.6, and 1:1.8 corresponding to emulsion percentages of 3.6%, 4.2%, 4.8%, and 5.4%, respectively. Marshall drop hammer was used as the method of compaction for the ITM samples, and each sample was compacted in a 101 mm diameter mould receiving 75 Marshall blows at each end. The samples were then placed in a 40 °C oven for three days, after which testing for resilient modulus was conducted on the dry samples. The same samples were then tested for the soaked condition after being placed in a water container and a vacuum chamber at a partial vacuum of 13 kPa for 10 min. The ITM results were then used in the selection of the optimum design mix, which was then used in the following four-point beam and wheel-tracking tests.

Four-point beam tests: The four-point beam apparatus was utilised to conduct two distinct evaluations: the flexural modulus examination and the fatigue assessment. In terms of sample size, beams were cut from slabs compacted to optimum density into moulds of $400 \times 280 \times 70$ mm using a steel head hand tamper. Following a curing period of 14 days, the resultant beams, measuring $400 \times 70 \times 70$ mm, were subjected to an additional 14 days of curing. This entire curing process was executed in a 40 °C oven. The flexural modulus examination was conducted on these beam samples, which were subjected to a range of frequencies (0.1, 0.5, 1, 3, 5, 10, and 20 Hz) and temperatures (10, 20, and 30 °C). A constant sinusoidal strain value of 50 $\mu\varepsilon$ served as the peak microstrain. The modulus value was then derived after 100 loading cycles. The fatigue assessment, on the other hand, was performed under constant strain with the stress being variable, owing to the high flexibility of the pavements produced by covalent bonding. The parameters for this test were set as follows: frequency at 10 Hz and strain values at 50, 200, and 300 μ€, with the test running until 2,000,000 cycles were reached or when the modulus value experienced a drop to 50%

of the initial modulus. In instances where no significant damage occurred, the beam used in the flexural modulus examination was reused for the fatigue assessment. This methodical approach ensured the validity and reliability of the test results.

Wheel-tracking tests: In the course of this research, the resistance of the mixture to permanent deformation was examined through the implementation of the wheel-tracking test using the Cooper wheel tracker machine. Following Austroads standard [24], the test was conducted on 300 × 300 mm slab samples, which were curated from a variety of mixtures. The slab production was carried out according to the metrics outlined in the Austroads standard [25]. Subsequently, the execution of the wheel-tracking test was based on the guidelines specified in the Austroads standard [24]. A steelhead hand tamper was utilised to compact the wheel-tracking slabs to the required density. The compacted slabs were then cut into the specified dimensions as outlined in the Austroads design guides [24]. The slabs were left to cure in an oven at 40 °C for 28 days. To prevent cracking during the cutting process, the slabs were left in the mould for not less than 4 days before they could be reduced to the appropriate dimensions. Testing of the slabs was conducted using a Cooper wheel tracker machine at a controlled temperature of 25 °C. With monitoring being conducted to observe the periodic deformation values, the tests were deemed complete at either 10,000 cycles or when a deformation of 10 mm was reached.

2.6. Field Trials

In addition to lab testing, a pair of field trials was implemented to evaluate the performance of pavement that had been rehabilitated using biochar and emulsion. The laboratory tests served as a precursor to these field trials, providing a theoretical foundation upon which the practical assessments were based. The intent behind these trials was to determine the practicality and efficiency of this novel method in a real-world setting. Through these trials, the stabilisation process could be analysed and assessed, thereby providing valuable insights into its potential benefits and drawbacks. The first trial was at Watheroo, and it involved the rehabilitation of a 2500 m^2 hardstand area of clayey gravel using in situ stabilisation with 5% biochar and 7% emulsion. The second trial was at Kwinana Grain Terminal, and it incorporated a new treatment of a 30 mm layer of granite crushed rock stabilised with 3% biochar and 5% C-Twelve emulsion over the existing pavement. Laboratory tests such as stiffness determination and resilient modulus measurement were used to assess the structural adequacy of the rehabilitated pavements.

3. Results and Discussions

3.1. Unconfined Compressive Strength

The effect of the biochar–emulsion addition on the strength enhancement of treated road base, as determined by unconfined compressive strength (UCS), was investigated as shown in Figure 3. The UCS behaviour of each mixture was considered for different biochar contents (i.e., 0%, 5%, 10%, and 15%), emulsion content of 6%, and a curing period of 28 days. Generally speaking, the UCS tests indicated that the addition of the biochar–emulsion binder considerably increased the peak stress of the treated road base material, showing a high dependency on biochar content. In the absence of biochar (0%), the road base treated with emulsion demonstrated an average UCS value of 0.9 MPa. Upon the inclusion of 5% biochar into the composition, there was a notable increase in average UCS value, recorded at 1.5 MPa. This notable elevation in UCS can be ascribed to the formation of covalent bonds between the biochar and emulsion, a process that intensifies the binding among aggregate particles. It should be noted that the UCS performance of CRB treated with 5% biochar (1.5 MPa) adheres to the standard UCS range (1–2 MPa) for cemented, lightly bound base course material, as stipulated by Austroads [26].

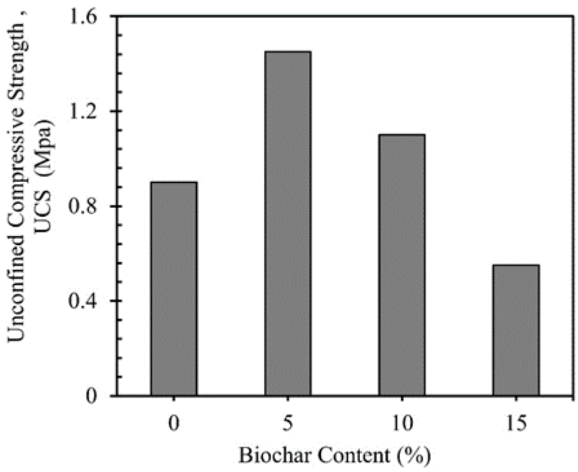

Figure 3. Effect of biochar content on peak strength of the road base treated with a typical emulsion content of 6%.

Despite the observed substantial increase in strength for the material treated with 5% biochar, there was a noteworthy decrease in strength with 10% and 15% biochar content, as depicted in Figure 3. This can be attributed to the distinct physical properties of biochar and aggregate. While aggregate is a dense composition of varying sizes of stone or rock with inherent load-bearing capabilities, biochar is a low-density, highly porous material that in its pure form does not exhibit significant strength capacity. Consequently, the composition of the blended material comprising aggregate and 10–15% biochar was disproportionately leaning towards the nonstructurally sound material, resulting in a decline in strength in terms of performance requirements when compared to the blend treated with 5% biochar.

3.2. Indirect Tensile Strength

The effect of the biochar–emulsion addition on the strength enhancement of treated road base, as determined by indirect tensile strength (ITS), was investigated at dry and wet conditions as shown in Table 3. A close examination of the results reveals a clear trend in the indirect tensile strength (ITS) values with the variation in emulsion and biochar contents. When the emulsion content was held constant at 4%, an increase in the biochar content from 3% to 5% resulted in an increase in the ITS dry from 241 to 287. However, a further increase in biochar content to 7% resulted in a decrease in ITS dry to 181. This suggests that an optimal level of biochar content may exist for this percentage of emulsion content, beyond which the road base material may not benefit from further addition of biochar. When the emulsion content was increased to 6%, the ITS dry values increased across all biochar contents as compared to the 4% emulsion content. This highlights the role of emulsion content in enhancing the stability of road base material. At the highest emulsion content of 8%, the ITS dry values were highest across all biochar contents, further cementing the role of emulsion in improving the dry strength of the road base material. Interestingly, the ITS wet values also showed an increase with the increase in emulsion content across all biochar contents, suggesting a synergistic effect of emulsion and biochar in improving the wet strength of the material. However, for a specific emulsion content, the ITS wet values showed a slight decrease with the increase in biochar content, indicating a limit to the synergistic effect observed at lower emulsion contents.

The findings of this study suggest that the inclusion of emulsion and biochar significantly contributes to the stabilisation of road base materials. This conclusion is substantiated by a noticeable enhancement in both the dry and wet strength of the materials. Nevertheless, it is imperative to accurately determine the optimal levels of emulsion and biochar to harness their full potential. According to the experimental results, the optimal dry indirect tensile strength (ITS) value was achieved with a mix design that incorporated 5% biochar and 8% emulsion. On the other hand, the peak soaked ITS value was reached with a mix that included 3% biochar and 8% emulsion. Furthermore, the data revealed that mix designs that comprised 5% biochar typically resulted in the highest dry ITS values. Conversely, mix designs that comprised 7% biochar generally yielded the lowest dry ITS values.

Table 3. Results of indirect tensile strength for the design mixes used.

Emulsion (%)	Biochar (%)	Dry ITS (kPa)	Wet ITS (kPa)	ITS Ratio (Wet/Dey)
4	3	241	228	0.95
	5	287	230	0.80
	7	181	147	0.81
6	3	286	277	0.97
	5	301	259	0.86
	7	252	239	0.95
8	3	371	391	1.05
	5	406	365	0.90
	7	340	322	0.95

The above results were further assessed against the New Zealand ITS testing standard NZTA T19 [22] shown in Table 4. It can be seen that the results of the examined base material stabilised with biochar and modified emulsion generally display comparative tensile strength to the guidance specified for foam-bitumen-stabilised base materials.

Table 4. Guidance of ITS specification for pavement materials (NZTA T/19 2020) [22].

Pavement Type	Dry ITS (kPa)	Soaked ITS (kPa)
Cement/lime modified base material	150 to 350	100 to 300
Foamed-bitumen-stabilised base material	175 to 400	150 to 350
Cement-bound subbase material	>500	>450

3.3. Resilient Modulus—Indirect Tensile Method

The results of the resilient modulus tests using the indirect tensile method (ITM), as depicted in Table 5, offer insights into the performance of samples treated with varying combinations of emulsion and biochar subsequently cured over three days under both dry and wet conditions. Notably, the addition of biochar and emulsion generally tended to increase the resilient modulus of samples cured in dry conditions, indicating an enhancement in the material's resilient modulus. Particularly, samples with a biochar-to-emulsion ratio of 1:1.6 (3% biochar and 4.8% emulsion) displayed the highest 3-day dry resilient modulus of 7007 MPa, suggesting that this combination yields optimal results. A further increase in this ratio to 1:1.8 resulted in an unexpected decrease in the modulus value for dry conditions. This pattern was consistently observed in both the 5% and 7% biochar groups, as indicated in Table 5. The explanation for this can be traced back to the unique structural characteristics of biochar, which provide a large surface area allowing it to coat the aggregate effectively, thereby strengthening the bond between aggregate particles. This bond is facilitated by the formation of covalent bonds between the biochar and emulsion, thus resulting in an increased modulus in proportion to the rising biochar percentage. On the other hand, the observed decrease in the modulus as the biochar-to-emulsion ratio increased beyond 1:1.6 to 1:1.8 could be due to the lubricating effect induced by the biochar particles. As the biochar particles increase the aggregate material's overall percentage of fines, they can disrupt the bonding process by acting as filler fines rather than bonding with the emulsion. Furthermore, the emulsion tends to encounter distribution challenges with materials having a high proportion of fines capable of passing the 75 μ sieve [26]. This provides a plausible explanation for the observed reduction in modulus at higher biochar-to-emulsion ratios.

Table 5. Results of 3-day dry and soaked indirect tensile modulus for the mixes used.

Biochar (%)	Emulsion (%)	Biochar-to-Emulsion Ratio	3-Day Dry Resilient Modulus (MPa)	3-Day Wet Resilient Modulus (MPa)
3	3.6	1:1.2	5285	2062
	4.2	1:1.4	5943	5265
	4.8	1:1.6	7007	4348
	5.4	1:1.8	6261	4468
5	6	1:1.2	5124	2562
	7	1:1.4	5149	4118
	8	1:1.6	5198	4661
	9	1:1.8	4914	4351
7	8.4	1:1.2	4115	2352
	9.8	1:1.4	4609	3337
	11.2	1:1.6	4743	2821
	12.6	1:1.8	4652	2801

The outcomes of the resilient modulus testing, as presented in Table 5, displayed considerable variation across wet conditions and dry conditions. The 3-day wet resilient modulus was lower than the dry resilient modulus for all combinations, indicating that the presence of moisture reduces the material's stiffness. The variance observed can be ascribed to the distinctive environmental factors that each condition presents, which consequently impacts the comprehensive performance and outcomes of the resilient modulus evaluation. Nevertheless, the samples with a biochar-to-emulsion ratio of 1:1.4 (3% biochar and 4.2% emulsion) showed the highest wet resilient modulus of 5265 MPa, meaning that this mix is relatively more resistant to the dampening effect of moisture. Interestingly, an increase in the biochar-to-emulsion ratio beyond 1:1.6 did not appear to enhance the resilient modulus significantly in wet conditions. This could imply that there is an optimal range of biochar-to-emulsion ratio that maximizes the resilient modulus, and any further increase in this ratio might not yield additional benefits.

For average daily traffic in the first year of design (ESA) greater than 1000, Austroads [26] gives the typical minimum resilient modulus values for a base material stabilised with foam bitumen as 4000 MPa for dry samples and 2000 MPa for soaked samples. As given in Table 5 above, each of the tested mix designs showed resilient modulus values that met Austroads requirements [26].

3.4. Four-Point Beam Bending Tests

Having established the optimal biochar-to-emulsion mix ratio (1:1.6) for achieving peak resilient modulus performance, we proceeded to further evaluate its mechanical performance. This was accomplished through the implementation of flexural modulus and fatigue tests. The selected mix designs for this evaluation were derived from the 3% biochar mix designs and the 5% mix designs, respectively. A mix design incorporating 7% biochar was deliberately excluded from the investigation. The rationale behind this decision was that the emulsion percentages required when using the ratios under evaluation could potentially exceed economically viable levels. This conclusion was reached following a comparative analysis with the percentages typically employed in bitumen-based stabilising techniques such as foam bitumen and emulsion stabilisation.

3.4.1. Flexural Modulus

The flexural modulus test results, illustrated in Figure 4, provide a comprehensive understanding of the behaviour of samples prepared with an optimal biochar-to-emulsion ratio of 1:1.6 for two testing mixtures (3% biochar and 4.8% emulsion; 5% biochar and 8%

emulsion). These samples were tested under diverse temperatures (10, 20, and 30 °C) and frequencies ranging from 0.1 to 20 Hz. In general, the influence of both temperature and frequency on the rigidity of materials fortified with a viscoelastic binder was evident in the stabilisation process using the biochar–emulsion binder. Figure 4 distinctly exhibits a decline in the flexural modulus of the stabilised material as temperature increases. However, an uptick in frequency demonstrated a lesser impact. When this performance is examined from a molecular standpoint, it becomes evident that temperature influences the kinetic energy of the biochar–emulsion chain segments, thereby instigating structural modifications in the emulsion–biochar matrix. This, in turn, impacts the stiffness of the material. When subjected to lower temperatures, the restricted molecular motion results in the material mimicking the characteristics of an elastic solid, thus increasing stiffness. On the contrary, a rise in temperature infuses the material with additional thermal energy, facilitating greater molecular mobility. This subsequently leads to a decrease in resistance to deformation and a consequent reduction in stiffness. Contrarily, frequency refers to the speed at which stress or strain is applied to the material. Viscoelastic materials are known for their time-dependent behaviour, meaning their properties alter over time when subjected to constant stress or strain. At lower frequencies, polymer chains are expected to have sufficient time to reconfigure and deform, causing the material to behave more like a viscous liquid. However, at higher frequencies, the material lacks the necessary time to fully react to the applied stress, thus behaving more like an elastic solid with increased stiffness. This interpretation is specifically pertinent to the behaviour exhibited by the material that has been stabilised using the emulsion–biochar binder with a biochar content of 5% (Figure 4b). It is crucial to note, however, that this does not hold true for the binder containing 3% biochar content as indicated in Figure 4a. The latter showed a reduced susceptibility to increases in frequency.

3.4.2. Fatigue

As previously noted, the fatigue performance of the emulsion–biochar-stabilised aggregate material was quantified via the flexural strength and the failure load cycle count (equating to 50% of the initial modulus). Samples with 3% biochar and 4.8% emulsion and those with 5% biochar and 8% emulsion were tested at a frequency of 10 Hz and different strain levels (i.e., 50 $\mu\varepsilon$, 200 $\mu\varepsilon$, and 300 $\mu\varepsilon$), all subject to a maximum of 2,000,000 load cycles. For any samples that did not fail within these cycles, trendlines were utilised to predict their respective failure points. During the fatigue testing at 50 $\mu\varepsilon$, it was observed that there was less than a 6% reduction in the modulus after 2,000,000 cycles. This indicates that the flexural modulus tends to decrease gradually with an increase in cyclic loading. Interestingly, as the loading cycles neared 2,000,000, there was a noticeable increase in the flexural modulus. The samples subjected to 200 $\mu\varepsilon$ did not reach failure within 2,000,000 load cycles. Post-testing, these samples exhibited a reduction in flexural modulus of approximately 20%. Based on trendline projections, an estimated failure point of 2,700,000 cycles was determined. In contrast, the samples tested at 300 $\mu\varepsilon$ reached failure much sooner, after just 111,510 load cycles. The behaviour observed at 50 $\mu\varepsilon$ aligns with the traditional behaviour of asphalt material tested at low strain levels. The late-stage increase in loading can be potentially attributed to the material's self-healing property, as suggested by [27]. This self-healing characteristic is explained by Liang et al. [28] to be a result of the viscoelastic binder's ability to close microcracks, thereby restoring the flexural stiffness through strong surface wetting and diffusion capabilities.

3.5. Wheel Tracking

Wheel-tracking tests were performed on samples treated with a 1:1.6 biochar-to-emulsion ratio, at two stabiliser levels: 3% biochar with 4.8% emulsion and 5% biochar with 8% emulsion. The deflection for each loading cycle was graphically represented as a function of the number of wheel load cycles, as depicted in Figure 5. The graph in Figure 5 demonstrates an initial surge in deflection, followed by a plateau phase characterised by marginal deflection fluctuations.

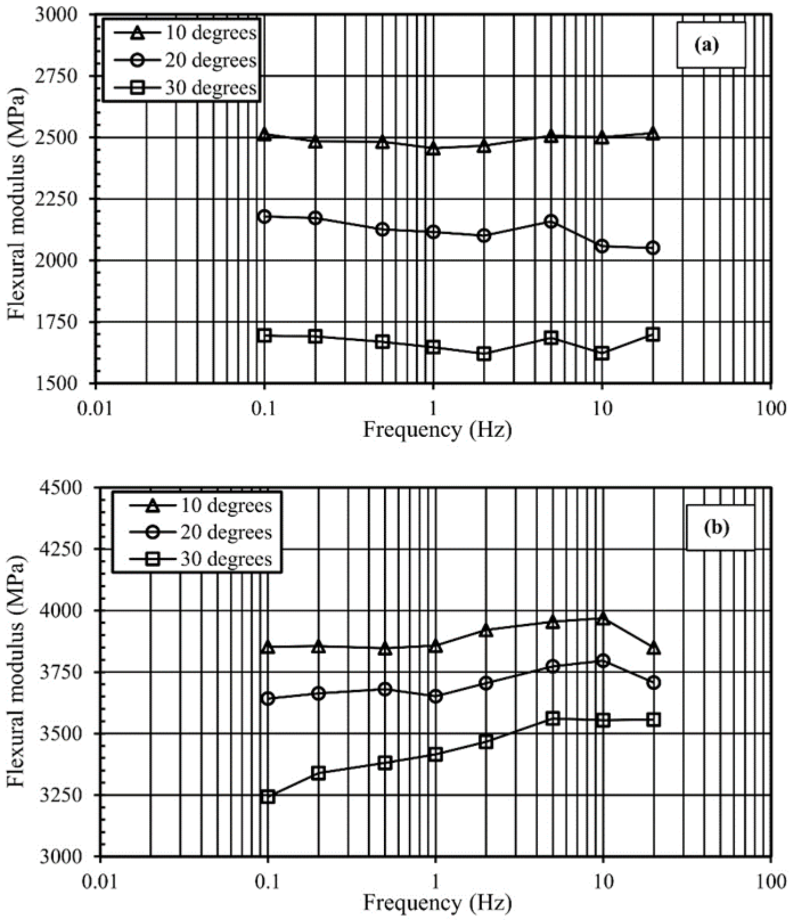

Figure 4. Flexural modulus for emulsion–biochar-treated samples tested under diverse temperatures (10, 20, and 30 °C) and frequencies ranging from 0.1 to 20 Hz: (**a**) 3% biochar and 4.8% emulsion (**b**) 5% biochar and 8% emulsion.

It is imperative to highlight that the sample, despite exhibiting a deflection plateau pattern, appeared to be in the incipient deflection phase, suggesting that the maximum deformation had yet to be reached. This observation is substantiated by the relatively stable final deflection at 10,000 cycles when juxtaposed with the deflection at the onset of cyclic loading. It was proposed that a sample's deflection per cycle is inversely proportional to the slab's modulus. Consequently, the minimal deflections presented in the results suggest that the stabilised materials exhibited relatively high moduli when subjected to wheel-tracking stresses. The deflection also serves as an indicator of the fatigue damage endured under cyclic loading. Hence, the low deflection witnessed across the 10,000 cycles suggests high fatigue resistance of the stabilised materials. As per the Austroads proposition [29], the deflection plateau stage is typically reached when an aggregate material attains a fully microcracked state. However, such a state was not achieved in the current study's testing phase. Furthermore, the absence of an inflexion point is a telling indicator that the material behaviour remained consistent throughout the cyclic loading.

The main parameter that the wheel-tracking samples were judged against is the Austroads [29] prescribed maximum final rutting depth of 15 mm. The final rutting depth that was achieved after wheel tracking was 0.443 mm. This result shows that the samples had good deformation performance compared to Austroads' recommendation [29]. The results also showed that the change in biochar percentage has minimal impact on the initial deformation of the samples; it was observed that the samples would require significantly more loading before they reached 15 mm deformation.

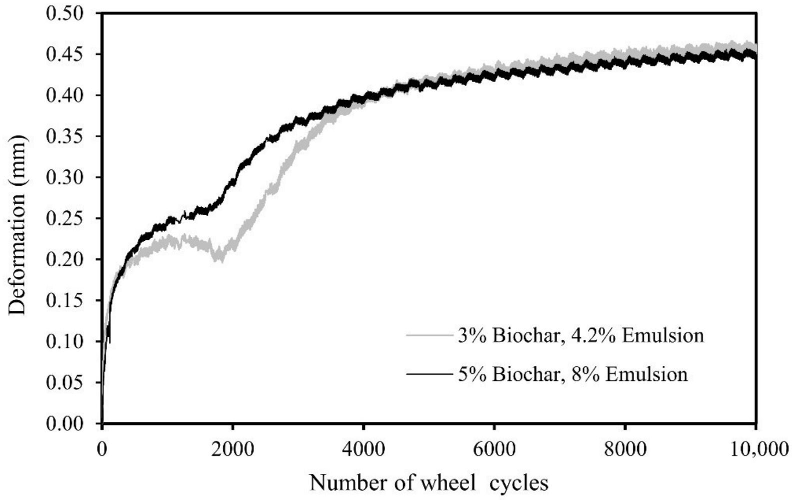

Figure 5. Response of deflection versus number of wheel cycles for samples treated with a 1:1.6 biochar-to-emulsion ratio at two stabiliser levels: 3% biochar with 4.8% emulsion and 5% biochar with 8% emulsion.

Visual inspection of the slab samples showed discontinuities at the top and edges, these discontinuities can either be attributed to the low binder content leading to low bonding in certain areas or can be attributed to the rough finish expected when a hand tamper is used for compaction. Such discontinuities can be expected to harm the deformation resistance of the slab. Due to the samples having low deformation during the 10,000 cycles, the effect of these discontinuities was deemed to be negligent during the initial deformation stage. It was observed from the visual inspection of the slab post-testing that there was no significant cracking observed after the cyclic loading. The loading did not seem to cause any dislodgement of individual aggregate particles. The tested slabs were generally observed to be minimally affected after the 10,000 cycles. Figure 6 shows the samples of the biochar stabilised slabs undergoing wheel tracking pre- and post-testing conditions.

(**a**) (**b**)

Figure 6. Visual inspection of emulsion-biochar stabilised slabs undergoing wheel tracking: (**a**) pre-testing and (**b**) post-testing.

4. Field Trials

In this section, two field trials are presented that assessed how a pavement rehabilitated with biochar and emulsion would perform in a practical sense.

4.1. Watheroo

This field trial was conducted to rehabilitate a 2500 m^2 hardstand area within the terminal, which was subjected to fully loaded, turning trucks. The treatment was a 150 mm in situ stabilisation of the existing pavement. The in situ material was stabilised with 5% biochar and 7% C-Twelve emulsion. The previous surface had severely deteriorated with evidence of delamination and rutting throughout most of the section. The assessment before the rehabilitation deemed the pavement to require reconstruction due to the significant number and depth of potholes, and it was evident that the shape of the pavement needed rectifying. The existing wearing course was a 14 mm spray seal followed by a clayey gravel base course and a gravelly clay subgrade. The in situ material was clayey gravel, with the clay content varying throughout the section. The stabilised material was to serve as the pavement base and wearing course, and thus conventional surfacing was not applied to the pavement.

The stabilised section showed some signs of minor ravelling and shrinkage cracking which formed in the initial 2 weeks poststabilisation. These surface defects are typical of a stabilised pavement that is trafficked without a wearing course. The determination of the stiffness of the pavement was measured 1 day and 15 days poststabilisation and suggested that the pavement was structurally adequate with no signs of shape loss evident. It was also evident that the stiffness of the pavement significantly increased after 15 days. Figure 7 shows the condition of the road pre- and postrehabilitation of this field trial.

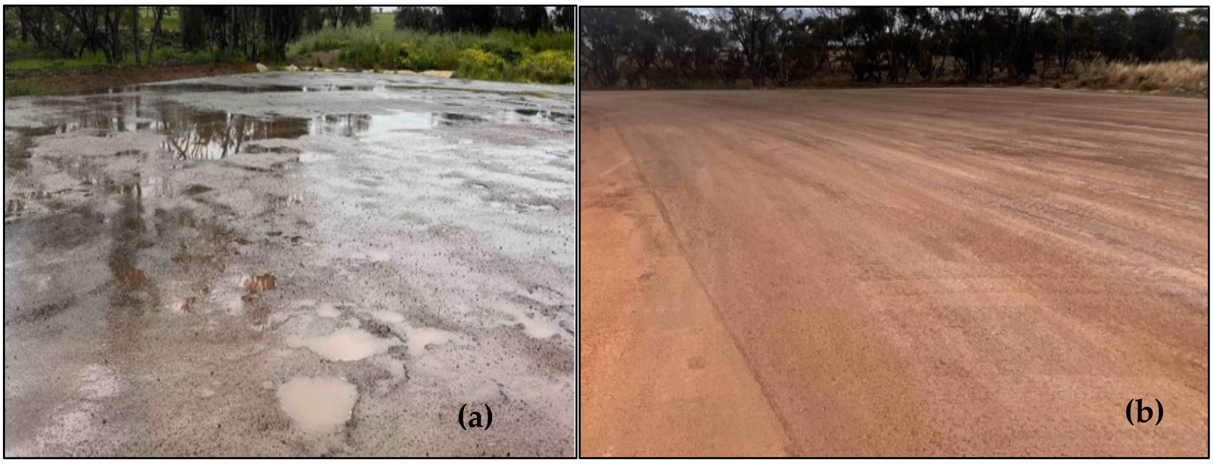

Figure 7. Watheroo field trial: (**a**) prerehabilitation and (**b**) postrehabilitation.

4.2. Kwinana Grain Terminal

The Kwinana terminal road was partially renovated in May 2022, with a 30 mm thick overlay being placed over the wearing course as the treatment. The surface resurfacing material was a cold emulsion that forms covalent bonds with carbon. The section rehabilitated was a two-lane intersecting road with a total area of 320 m^2. The previous surface had severely deteriorated with evidence of cracking, rutting, and delamination throughout most of the section. The pavement consisted of a thin layer of 14 mm thick asphalt which overlayed a base course consisting of blast furnace slag. The typical trafficking of the pavement was predominantly trucks with weights of either 22 or 45 tonnes. The assessment of the pavement showed that it was structurally inadequate and in need of treatment.

The new treatment consisted of a 30 mm layer of granite crushed rock stabilised with 3% biochar and 5% C-Twelve emulsion over the existing pavement. A light spray of water onto the existing surface was applied to act as the "tack coat". The bonding mechanism of the material was such that no bituminous tack coat was required for adhesion to the base course. The section was visually inspected on the day of construction and in the initial following days, as well as after 8 weeks' postconstruction. On the day after construction, the surface of the majority of the section remained moist, with early signs of curing suggesting that the stabilised material was structurally adequate. The section remained closed to traffic, as a conservative approach was taken for the curing duration due to overcast weather conditions. Four days after construction, the stabilised material had sufficiently cured with little evidence of excess water remaining in the material. The section was then opened up for trafficking at this stage. Eight weeks after construction, the surface remained structurally sound with some evidence of light ravelling, which occurred because the individual aggregate particles dislodged from the surface causing a rough surface texture. This is typically a result of inadequate production practices and/or poor construction procedures.

Laboratory testing was conducted on cores extracted from the pavement after eight weeks' postconstruction. The resilient modulus of the extracted cores was determined through ITM laboratory testing, and the results showed an average resilient modulus of 3210–3800 MPa. The Austroads (2017) design guide [20] outlines an acceptable modulus range of 2000–6000 MPa, with a typical value of 3500 MPa, confirming that the structural performance of the pavement was adequate. Figure 8 shows the condition of the road pre- and postrehabilitation of this field trial.

Figure 8. Kwinana Grain Terminal field trial: (**a**) prerehabilitation and (**b**) postrehabilitation.

5. Conclusions

This research focused on a detailed analysis of the laboratory performance characteristics of a laterite-based coarse aggregate fortified with biochar and emulsion. An extensive evaluation of the properties indicated that the introduction of biochar in the stabilisation procedure for a laterite base course using emulsion is a feasible approach. The implications of this approach included the display of tensile strength, resilient modulus, flexural modulus, fatigue life, and deformation resistance properties that meet industry standards and conventional stabilisation methods.

The explicit conclusions derived from the study include the following:

1. The unconfined compressive strength (UCS) tests demonstrated that the biochar–emulsion binder significantly augmented the strength of road base materials, with the optimal content being 5% biochar. However, an increase beyond this percentage led to a decrease in strength, attributable to the physical properties of biochar.

2. The indirect tensile strength (ITS) results suggested that both emulsion and biochar content significantly affect the strength of road base materials. The optimal dry ITS value was achieved with a mixture composed of 5% biochar and 8% emulsion, while the maximum soaked ITS value was reached with a mixture comprising 3% biochar and 8% emulsion.
3. A review of the resilient modulus outcomes revealed that a biochar-to-emulsion ratio of 1:1.6 yields the highest resilient modulus for the material in dry conditions. Conversely, in wet conditions, a biochar-to-emulsion ratio of 1:1.4 demonstrated the highest resilient modulus.
4. The flexural modulus tests indicated that material stiffness decreases as temperature rises, while an increase in frequency has less of an impact. Furthermore, fatigue testing suggested that the flexural modulus decreases gradually with an increase in cyclic loading.
5. Wheel-tracking tests showed that emulsion–biochar-treated samples have good deformation performance and high fatigue resistance, with the final rutting depth being significantly lower than the recommended maximum.
6. Field trials carried out in Watheroo and Kwinana Grain Terminal exemplify the practical effectiveness of using biochar and emulsion in pavement rehabilitation. The treated pavements exhibited enhanced stiffness and structural adequacy, with minor surface defects observed.

The study conclusively affirms the potential of biochar–emulsion binder as an effective and efficient stabiliser for road base materials. However, the results underscore the need to ascertain the optimal levels of biochar and emulsion to maximise their stabilising potential. Future research could focus on refining these parameters and investigating the long-term performance of road base material treated with biochar–emulsion binder under different environmental and traffic conditions. The primary conclusion drawn from this study is that the use of biochar and emulsion in pavements for road construction is a feasible technique. This could facilitate carbon sequestration, aiding in the mitigation of climate change while maintaining superior pavement performance.

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