

## Evaluation of the Effectiveness of Bitumen Emulsion for Stabilising Subgrade Sand

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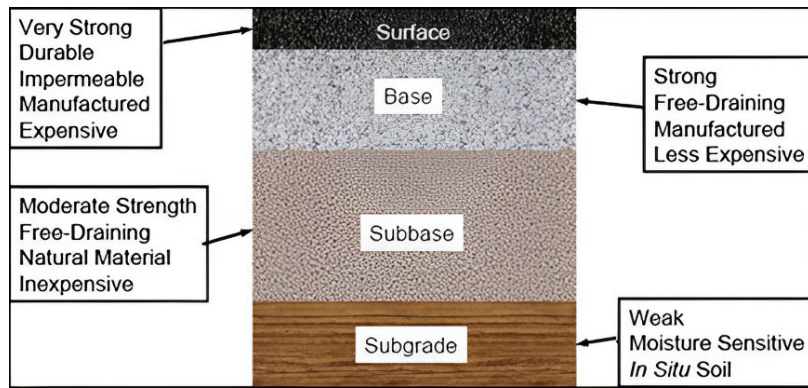
### Abstract

Sand is a type of soil that is prone to erosion and has low bearing capacity. Hence, stabilisation of a sand subgrade layer is needed. The results of a study assessing the efficiency of bitumen emulsions (2%, 3%, and 4%) for stabilising sand are presented in this paper. In this study, two different types of sand were individually mixed with bitumen emulsion: clayey sand and river sand. Soil classification, compaction test, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS) were among the laboratory tests conducted. The unsoaked and soaked CBR was measured after 4 days of curing, and the UCS of sand was measured after 7, 14, and 28 days of curing. Based on the obtained California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS), the results indicated that sand was suitable to be stabilised with bitumen emulsion. It is recommended that future research conduct long-term field studies to evaluate the performance of bitumen emulsion-stabilised sand subgrade under real-world conditions.

## 1. Introduction

A crucial element in building pavements and other structures is the subgrade, which is the layer of soil directly below the pavement surface that offers vital support. It serves as the framework for the pavement structure and is an important factor in determining the pavement system's overall longevity and performance. The load-bearing capacity, stability, and resistance to deformation of the pavement are all strongly impacted by the characteristics of the subgrade soil [1]-[3]. General geotechnical aspects of pavement layers are shown in Fig. 1.

The ability of the subgrade to support traffic loads crossing the pavement without experiencing undue deformation or settlement makes it especially important. The subgrade soil's capacity to evenly distribute applied loads and sustain the pavement structure depends on how strong and stiff it is. Premature pavement distress, such as rutting, cracking, and unevenness, can be caused by inadequate subgrade strength, endangering both driveability and safety [4]-[6].



**Fig. 1** Geotechnical aspects of pavement layers [7]

Additionally, over time, the integrity of the pavement system depends on the subgrade's stability. An excessive amount of movement or settlement can lead to structural failure and distress in the pavement layers above; however, this can be avoided with a stable subgrade. Subgrade stability is mostly dependent on variables like soil type, moisture content, and compaction. Subgrade soils that are well-drained and compacted help to create a more stable pavement structure by lowering the possibility of deformation and structural deterioration [8], [9].

In order to improve the qualities of sand and make it suitable for supporting pavements and other structures, subgrade stabilisation is an essential procedure in civil engineering. The strength, stability, and durability needed for sustainable infrastructure are often lacking in sand. The engineering properties of the soil can be enhanced, though, so that it can withstand the loads and stresses placed on it by environmental and traffic factors by using subgrade stabilization techniques [10]-[12].

There are various techniques available for subgrade soil stabilisation, such as: mechanical stabilisation, chemical stabilisation and bituminous stabilisation, and each has its own advantages and disadvantages [13], [14]. The process of bituminous stabilisation entails incorporating bitumen into the soil matrix, either in its natural state or as emulsions or foams. Bitumen coats soil particles to improve cohesion, stability, and resistance to damage caused by moisture while also offering waterproofing [15]-[17]. It involves the incorporation of bitumen, typically in the form of bitumen, cutback bitumen, or bitumen emulsions, into the soil matrix. Each type of bitumen offers unique characteristics suited for various soil conditions, construction methods, and weather conditions [18], [19].

Sand is a type of soil characterised by a wide range of grain sizes but lacks a significant amount of fine particles, such as silt and clay. This results in a less cohesive soil composition, making it prone to various challenges for pavement construction sites. One major challenge is its susceptibility to erosion, as the absence of fine particles reduces the soil's ability to resist displacement by water or wind. Additionally, sand has low bearing capacity and can experience collapse or settlement under load due to the limited cohesion between grains. These factors contribute to uneven settling of pavement surfaces, compromising their stability and integrity over time. Therefore, addressing the challenges of sand is essential through appropriate subgrade stabilization techniques to ensure durable and safe pavement construction [2], [5], [11], [20].

In Malaysia, bitumen emulsion is widely utilised for stabilising soil in a variety of construction projects, particularly for low-volume, rural, and plantation roads. Many significant benefits contribute to its popularity. In order to support the traffic load, it first greatly increases the soil's load-bearing capacity. Second, it lessens the likelihood of erosion, which is crucial in areas that frequently experience high levels of rainfall. Thirdly, bitumen emulsion increases soil resistance to moisture, preventing soil evaporation and swelling. Furthermore, it increases the stability of stabilised soil, which lowers maintenance requirements and extends the life of roads. Moreover, the ease of application of this technology expedites construction processes, thereby augmenting project efficiency. Finally, because bitumen emulsion is made of water, it has a lower environmental impact and lower emissions. In Malaysia's construction industry, bitumen emulsion is the material of choice for subgrade stabilisation due to its numerous advantages [18], [21], [22].

The aim of this research paper is to present the findings of a study that investigated the efficacy of bitumen emulsions in stabilising sand. The study focused on two variations of sand: clayey sand and river sand. In tropical and subtropical regions like Southeast Asia, which encompasses countries such as Indonesia, Malaysia, and Thailand, clayey sand is frequently encountered [23], [24]. It is characterized by a reddish hue and contains a high iron content. River sand, on the other hand, is a type of sand often deposited by river systems. It typically exhibits a light brown or grey coloration and possesses well-rounded grains, shaped through the natural processes of erosion and sedimentation within rivers.

Analysing particle size distribution and Atterberg limits is frequently the first step in determining the best stabilisation method for pavement materials [21], [25]. Engineers can determine the best stabilisation technique

for a given soil by measuring parameters such as the percentage of material that passes through a 75  $\mu\text{m}$  sieve and the plasticity index. A graphical representation of the relationship between these factors and the required stabilisation type is shown in Fig. 2.

Fig. 2 emphasizes that less than 25% of the material must pass through the 75  $\mu\text{m}$  sieve for bitumen stabilisation to be most successful. This suggests that because of their better drainage and binding qualities, soils with lower fines content make better candidates for bitumen stabilisation. This initial assessment contributes to improving pavement performance, streamlining construction procedures, and guaranteeing the long-term resilience of infrastructure projects.

Particle size	More than 25% passing 75 $\mu\text{m}$ sieve			Less than 25% passing 75 $\mu\text{m}$ sieve		
	Plasticity index (PI)	Plasticity index (PI)	Plasticity index (PI)	Plasticity index (PI)	Plasticity index (PI)	Plasticity index (PI)
	$PI \leq 10$	$10 < PI < 20$	$PI \geq 20$	$PI \leq 6$ & $PI \times$ $\% \text{passing}$ $75 \mu\text{m} \leq 60$	$PI \leq 10$	$PI > 10$
<b>Binder type</b>						
Cement and cementitious blends <sup>(1,3)</sup>	Usually suitable	Doubtful	Usually not suitable	Usually suitable	Usually suitable	Usually suitable
Lime	Doubtful	Usually suitable	Usually suitable	Usually not suitable	Doubtful	Usually suitable
Bitumen	Doubtful	Doubtful	Usually not suitable	Usually suitable	Usually suitable	Usually not suitable
Bitumen/lime blends	Usually suitable	Doubtful	Usually not suitable	Usually suitable	Usually suitable	Doubtful
Granular	Usually suitable	Usually not suitable	Usually not suitable	Usually suitable	Usually suitable	Doubtful
Dry powder polymers	Usually suitable	Usually suitable	Usually unsuitable	Usually suitable	Usually suitable	Usually not suitable
Other proprietary chemical products <sup>(2)</sup>	Usually not suitable	Usually suitable	Usually suitable	Usually not suitable	Doubtful	Usually suitable

Fig. 2 A guide to selecting stabiliser for different PI values and fines [26]

The study examined the impact of varying bitumen emulsion concentrations (2%, 3% and 4%) on the stabilised sand's Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR). However, the curing process of bitumen emulsions alone, which depends on water evaporation, can be slow, particularly in colder regions or with damp soil [27]. In order to promote early strength development and fasten curing, 3% cement was added to each mixture. Through heat production during hydration, water evaporation assistance, and the formation of cementitious compounds, which increase stability and strength, 3% cement speeds up the curing process [28]-[30]. In situations like road construction and pavement rehabilitation, where quick curing and attaining desired strength properties are crucial, this hybrid approach seeks to maximise stabilisation.

The California Bearing Ratio (CBR) is a critical parameter used to assess a soil's load-bearing capacity, indicating its ability to support applied loads. On the other hand, Unconfined Compressive Strength (UCS) measures a soil's resistance to compressive forces, qualifying its ability to withstand pressure without confinement. In this study, the CBR of the stabilised sand was evaluated both soaked and unsoaked after 4 days of curing to assess its load-bearing capacity under different moisture conditions. Additionally, the UCS of the stabilised sand was evaluated after 7, 14, and 28 days of curing to gauge its compressive strength over time.

The research aims to achieve three primary objectives. Firstly, it seeks to assess the effectiveness of bitumen emulsion in stabilising sand subgrade, focusing on its impact on California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS). Secondly, it aims to determine the optimal content of bitumen emulsion necessary for stabilising sand subgrade, aiming to find the balance between effectiveness and economic feasibility. Lastly, the research aims to investigate the influence of curing time on the CBR and UCS of sand subgrade stabilised with bitumen emulsion. By addressing these objectives, the study aims to provide valuable insights into the suitability and performance of bitumen emulsion for stabilising sand subgrade, informing engineering practices in infrastructure projects such as road construction and foundation engineering.

It is crucial to comprehend how bitumen emulsions stabilise various kinds of sand in order to inform engineering practices in areas where these soils are common, such as Southeast Asia. The results of this study can aid in the creation of better soil stabilisation methods that are adapted to the unique qualities and difficulties of clayey and river sand. The study intends to improve the sustainability and resilience of construction practices in tropical and subtropical regions by clarifying the effectiveness of bitumen emulsions in stabilising these soils and offering useful advice to engineers and practitioners involved in infrastructure projects in these regions.

## 2. Methodology

The methodology section of this paper outlines the approach taken to evaluate the effectiveness of bitumen emulsion for stabilising sand subgrade. Specimen preparation and testing procedures were carefully conducted, including mixing the materials to create test samples and subjecting them to specific testing methods. The primary testing methods employed were the California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) tests, which were carried out to assess the performance of the stabilised sand subgrade. This section provides a detailed overview of the procedures followed to systematically investigate the effectiveness of bitumen emulsion in stabilising sand subgrade, offering valuable insights into the suitability of this stabilisation technique for infrastructure projects.

### 2.1 Materials

The materials used in this study include clayey sand and river sand as subgrade soils, along with bitumen emulsion as stabilising agent and cement. These materials were selected to evaluate their effectiveness in stabilising sand subgrade.

#### 2.1.1 Subgrade Soil

Fig. 3 shows a sample of clayey sandy soil, while Fig. 4 shows a sample of riverine sandy soil. Table 1 shows the physical properties of clayey sand obtained from the Jalan Ledang site, Kuala Lumpur, and the corresponding properties of river sand obtained from the Sungai Pahang site, Pahang. Additionally, physical property tests, including grain size analysis and Atterberg limits tests, were conducted to further characterise the properties of both soil types.



Fig. 3 Clayey sand soil sample



Fig. 4 River sand soil sample

Table 1 Physical properties of clayey sand

Property	Value	
	Clayey Sand	River Sand
Liquid Limit (LL)	49.98	15.39
Plastic Limit (PL)	34.26	8.12
Plasticity Index (PI)	15.72	7.27
Specific Gravity	2.55	2.68
AASHTO Classification	A-2-7	A-1-a
USCS Classification	SP	SW
Optimum Moisture Content (OMC)	18.54	15.93
Maximum Dry Density (MDD)	16.35	1.75

#### 2.1.2 Bitumen Emulsion

In this study, bitumen emulsion sourced from ACP-DMT Sdn. Bhd. was utilised as a key material. The specific emulsion type employed was grave emulsion, formulated with Indulin W-5 emulsifier. This emulsion, renowned for its stability and performance, serves as a crucial component in various asphalt applications. Prior to its utilisation, the emulsion underwent a transformation process to convert it into bitumen, a fundamental ingredient in asphalt mixtures.



**Fig. 5** *Mixing and stirring bitumen emulsion before use*

The obtained bitumen was subjected to a series of tests to assess its key properties. These tests included penetration testing to evaluate its consistency and hardness, softening point determination to ascertain its thermal properties, viscosity testing to gauge its flow characteristics under specified conditions, and ductility testing to assess its long-term performance under simulated environmental conditions. These tests collectively provided valuable insights into the suitability and performance of the bitumen for use in asphalt mixtures.

**Table 2** encapsulates a comprehensive summary of the properties exhibited by the bitumen, categorised under grade 60/70 classification, along with corresponding standards and JKR requirements. Rigorously adhering to established protocols and regulatory benchmarks ensures the robustness and reliability of the findings presented herein. By illuminating the inherent characteristics of the bitumen emulsion and delineating the methodologies employed in its evaluation, this research endeavours to contribute meaningfully to the burgeoning discourse surrounding asphalt engineering and infrastructure development.

**Table 2** *Properties of bitumen emulsion of grade 60/70*

Property	Unit	Standard Procedure	JKR Standard Requirement	Result
Penetration at 25°C	mm	ASTM D5	60-70	64
Softening Point	°C	ASTM D36	49-52	49
Viscosity at 135°C	Pa.s	ASTM D4402	3.0 (Max)	1.5
Ductility at 25°C	cm	ASTM D113	100 (Min)	102

### 2.1.3 Cement

The Ordinary Portland Cement (OPC) utilised in this study was sourced from Tasek Corporation Berhad. As a widely trusted name in the industry, this OPC variant is known for its reliability and versatility in various construction applications. Acting as a vital binder, the OPC contributed to enhancing the cohesion and strength of the soil stabilization process. Detailed properties of the OPC, listed in **Table 3**, offer clear insights for future research replication and comparison.



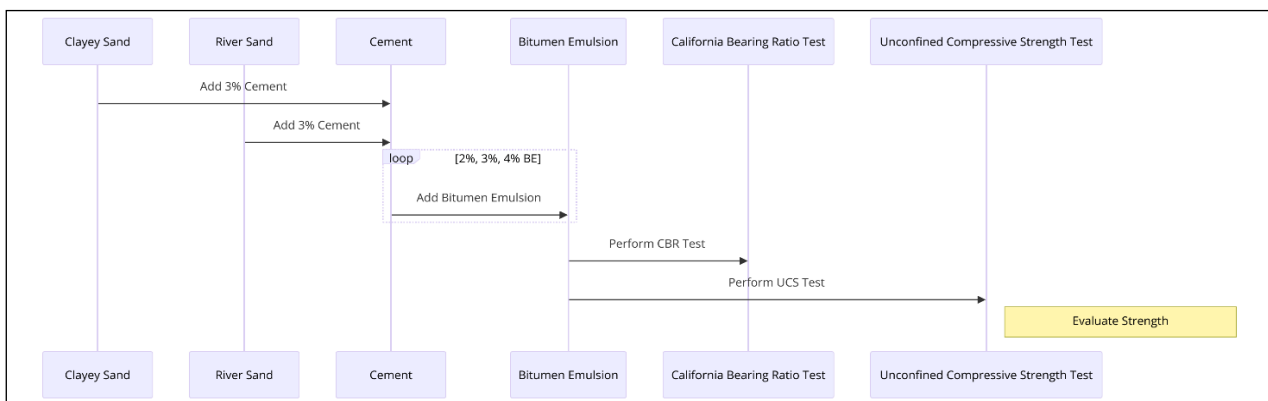
**Fig. 6** *Cement employed in the study*

**Table 3** Properties of ordinary Portland cement (Tasek Corporation Berhad)

Property	Unit	Value
Sulphuric Anhydride, SO <sub>3</sub>	%	3.5 Max
Chloride Content, Cl	%	0.10 Max
Initial Setting Time	minutes	60
Soundness (Expansion)	mm	10 Max
Compressive Strength after 2 Days	N/mm <sup>2</sup>	10 Min
Compressive Strength after 28 Days	N/mm <sup>2</sup>	42.5 – 62.5

## 2.2 Specimen Preparation and Testing Procedures

Fig. 7 displays the research’s methodological framework. The materials included in this study include river sand and clayey sand subgrade soil, in addition to necessary ingredients like water, cement, and bitumen emulsion. Oven drying was applied to the subgrade soil (river sand and clayey sand) during the material preparation stage. It was spread thinly, and oven dried for 24 hours at 105°C. Through this procedure, the soil was guaranteed to reach a stable, dry state, prepared for use in the intended application later. Subsequently, a 2 mm sieve was used to filter out any large particles or debris from the dried soil.



**Fig. 7** Study sequence diagram

The mixing process began after the necessary volume of dry soil (river sand or clayey sand) was added to the mixing pan. To enhance the strength and facilitate a quicker curing process, 3% percent cement is added to each mixture and thoroughly mixed to ensure a uniform distribution [31], [32]. But for cement to undergo hydration—a chemical reaction that turns cement into a powerful binding agent—it needs enough water. Water was thus added little by little while mixing. Furthermore, the addition of water following the cementation process guarantees even dispersion and full hydration, which promotes the best binding strength possible in the stabilised soil [33], [34].

The mixture was thoroughly mixed and bitumen emulsion (2%, 3%, and 4%) was added gradually in tiny increments until it was evenly coated with a uniform dark brown colour. Overmixing was carefully avoided to prevent bitumen stripping. In addition to binding soil particles together, bitumen emulsion serves as a waterproofing agent. Bitumen emulsion interaction with the cement hydration process is minimised when bitumen emulsion is added last, allowing for a better coating of the soil’s particles, and optimising bitumen emulsion binding and waterproofing properties [16], [35], [36]. After achieving a uniform dark brown colour through the gradual addition of bitumen emulsion in varying concentrations (2%, 3%, and 4%), the mixture underwent rigorous testing to evaluate its engineering properties: California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) test.

## 2.3 Testing Method and Mix Design

The soils targeted for stabilisation encompassed clayey sand and river sand, representative of common subgrade materials encountered in infrastructure projects. The design mix, delineating the proportions of cement and bitumen emulsion for each soil type, is presented in Table 4.

### 2.3.1 California Bearing Ratio

In the context of California Bearing Ratio (CBR) sample preparation, the procedure entails a systematic approach according to BS 1377-9:1990. The CBR mould is first filled with a carefully mixed mixture that is split into three

layers. With the rammer, each layer is compacted according to the prescribed number of blows—typically 25 blows per layer. Next, to ensure consistency, the top surface is leveled and any excess material is carefully trimmed off.

**Table 4** *Mix design*

Mix Design
Soil
Soil + 3% Cement
Soil + 3% Cement + 2% Bitumen Emulsion
Soil + 3% Cement + 3% Bitumen Emulsion
Soil + 3% Cement + 4% Bitumen Emulsion

This study included both soaked and unsoaked California Bearing Ratio (CBR) tests, with a standard curing period of 4 days. This allowed for a consistent assessment of the bitumen emulsion's effect on the subgrade soil under different moisture conditions. In order to determine the CBR strength of the subgrade soil in the worst-case scenario of a pavement being submerged under water during floods for a minimum of 4 days, the soaked CBR value of the subgrade is typically preferred when designing flexible pavements [37]-[39].

### 2.3.2 Unconfined Compressive Strength

In the preparation of Unconfined Compressive Strength (UCS) samples, a systematic procedure according to BS EN ISO 17892-7:2018 is followed to ensure the accuracy and reliability of subsequent testing. The pre-prepared mixture is poured into the UCS mould, and compaction is accomplished by using the rammer in accordance with the recommended protocol. To guarantee accuracy and consistency in the UCS sample, care is taken to level the top surface and carefully trim off any excess material after compaction. A crucial stage in the procedure entails letting the sample cure at room temperature and humidity for a specified 24 hours. The development of the sample's strength characteristics depends on this curing time. The UCS is then tested following designated curing intervals of 7, 14, and 28 days.

The 7, 14, and 28-day curing times chosen in the study are in line with accepted practices in several concrete and cement-based material protocols, including BS EN 196-1 and ASTM C39. These time frames are significant because they represent important turning points in the hydration process. By measuring the initial hydration and strength development, the 7-day period enables the assessment of early strength gain. An intermediate strength estimate can be obtained at day 14, which offers important information for specific applications. Since there has been significant hydration progress by then, 28 days are typically considered the design strength for concrete. Stabilised soils containing cement experience a similar hydration-based strength development process, though they are not directly comparable to concrete [38], [40], [41].



**Fig. 8** *Performing California Bearing Ratio (CBR) test on soil sample*



**Fig. 9** *Conducting the Unconfined Compressive Strength (UCS) test on clayey sand stabilized with 3% cement and 2% bitumen emulsion after a curing period of 7 days*

### 3. Results and Discussion

The objective of the laboratory tests was to evaluate the subgrade soil's suitability for bitumen emulsion stabilisation and establish the ideal bitumen emulsion dosage needed for stabilisation. To fully evaluate the subgrade soil's characteristics, several significant laboratory tests were performed, such as soil classification test, modified Proctor compaction test, California Bearing Ratio (CBR) test, and Unconfined Compressive Strength (UCS) test.

The soil classification provided insights into the inherent properties of the subgrade soil, aiding in understanding its composition and behaviour. Subsequent compaction tests were performed to gauge the soil's density and compaction characteristics, offering crucial information about its engineering properties. To evaluate the subgrade soil's strength and load-bearing capacity under various moisture conditions, tests of the California Bearing Ratio (CBR) were carried out both soaked and unsoaked. The results of these tests gave important information about the soil's behaviour in both dry and saturated states after bitumen emulsion stabilisation, demonstrating the soil's adaptability to shifting environmental conditions. Furthermore, Unconfined Compressive Strength (UCS) tests were utilised to assess the overall compressive strength of the subgrade soil, providing insights into its ability to support loads and maintain structural integrity under vertical stress.

The discussion that follows is based on the collective outcomes of these lab tests, which enable a thorough examination of the subgrade soil's response to bitumen emulsion stabilisation. The results aid in a more sophisticated comprehension of the behaviour of the soil under various circumstances, which helps to form well-informed conclusions and suggestions for real-world implementations in pavement design and geotechnical engineering.

#### 3.1 Sieve Analysis

Table 5 to Table 8 display the results of the sieve analyses conducted on specimens of clayey sand and laterite, respectively.

**Table 5** Sieve analysis of clayey sand sample

Sieve Number	Sieve Opening (mm)	Mass of Soil Retained (g)	Accumulative Mass of Soil Retained (g)	Percentage of Soil Retained (%)	Percentage of Soil Passing (%)
#4	4.75	0	0	0	100
#10	2.00	19.15	19.15	3.83	96.17
#16	1.18	96.30	115.45	19.26	76.91
#30	0.60	112.25	227.70	22.45	54.46
#40	0.43	94.5	322.2	18.90	35.56
#50	0.30	108.74	430.94	21.75	13.81
#100	0.15	33.30	464.24	6.66	7.15
#200	0.075	22.64	486.88	4.53	2.62
Pan	-	13.09	499.97	2.62	-

**Table 6** Results of sieve analysis of clayey sand sample

Parameter	Unit	Value
Percentage of Gravel	%	0
Percentage of Sand	%	97.38
Percentage of Fines	%	2.62
D <sub>60</sub>	mm	0.74
D <sub>30</sub>	mm	0.39
D <sub>10</sub>	mm	0.21
Coefficient of Uniformity, C <sub>u</sub>	-	3.47
Coefficient of Curvature, C <sub>c</sub>	-	0.97

As shown in Table 5 and Table 6, the sieve analysis revealed a poorly graded particle size distribution for the clayey sand, with a high percentage of sand (97.38%). This is further supported by the coefficient of uniformity (C<sub>u</sub>) of 3.47, indicating a wide range of particle sizes. However, the coefficient of curvature (C<sub>c</sub>) of 0.97 suggests the soil is not well-sorted, meaning the particle sizes are not evenly distributed across the different sieve fractions.

Compared to typical poorly graded sands ( $C_c > 1$ ), this clayey sand exhibits a slightly lower  $C_c$  value, which could be attributed to the presence of a small amount of fines (clay and silt) within the sand matrix. Potential concerns associated with the presence of fines in sand encompass several critical factors that warrant consideration in engineering and construction practices.

Firstly, the introduction of fines can lead to a reduction in permeability, impacting the soil's ability to facilitate water flow. This occurs as the fines can accumulate and clog the pores between sand grains, impeding the movement of water through the soil matrix. Moreover, fines, particularly in the form of clay particles, may exacerbate the soil's susceptibility to liquefaction under specific conditions. The presence of fines can contribute to a loss of strength and stiffness in the soil, increasing the risk of liquefaction during seismic events or other dynamic loading scenarios. Furthermore, fines possess cementation potential, particularly with certain clay minerals acting as binders within the soil matrix. This cementation can influence the overall strength and behaviour of the soil, impacting its response to various loading conditions and environmental factors.

**Table 7** Sieve analysis of river sand sample

Sieve Number	Sieve Opening (mm)	Mass of Soil Retained (g)	Accumulative Mass of Soil Retained (g)	Percentage of Soil Retained (%)	Percentage of Soil Passing (%)
#4	4.75	0	0	0	100
#10	2.00	23.60	23.6	4.72	95.28
#16	1.18	65.00	88.60	13.00	82.28
#30	0.60	126.00	214.60	25.20	57.08
#40	0.43	167.74	382.34	33.55	23.53
#50	0.30	31.10	413.44	6.22	17.31
#100	0.15	72.89	486.33	14.58	2.73
#200	0.075	8.35	494.68	1.67	1.06
Pan	-	5.30	499.98	1.06	-

**Table 8** Results of sieve analysis of river sand sample

Parameter	Unit	Value
Percentage of Gravel	%	0
Percentage of Sand	%	98.94
Percentage of Fines	%	1.06
$D_{60}$	mm	0.67
$D_{30}$	mm	0.46
$D_{10}$	mm	0.22
Coefficient of Uniformity, $C_u$	-	2.97
Coefficient of Curvature, $C_c$	-	1.40

As shown in [Table 8](#) and [Table 9](#), the sieve analysis revealed a well-graded particle size distribution for the river sand, dominated by sand particles (98.94%). This is supported by the coefficient of uniformity ( $C_u$ ) of 2.97, indicating a moderate range of particle sizes. Additionally, the coefficient of curvature ( $C_c$ ) of 1.40 suggests the soil is well-sorted, meaning the particle sizes are relatively evenly distributed across different sieve fractions.

Compared to the previously discussed clayey sand, the river sand exhibits significantly higher  $C_c$  and lower  $C_u$  values. This indicates a wider range of particle sizes with a more even distribution, characteristic of well-graded materials. The distinct depositional environments of these two sands significantly influenced their particle size distribution and resulting engineering properties.

River sand, continuously transported and sorted by water flow, exhibits a well-graded nature with a moderate range of particle sizes and even distribution (as indicated by  $C_u$  and  $C_c$  values). This translates to favourable engineering characteristics, including good permeability due to well-distributed pore spaces, reduced liquefaction risk due to the absence of fines and even particle distribution, and minimal cementation potential due to the lack of significant fines.

In contrast, clayey sand, likely influenced by terrestrial weathering processes, displays a wider range of particle sizes with some fines present. While well-graded overall, the presence of fines introduces subtle nuances to its engineering behaviour. Permeability might be slightly impeded due to partial pore space clogging, and

liquefaction risk could be marginally increased depending on the specific fines characteristics and loading conditions. However, the overall well-graded nature suggests generally positive engineering properties. This comparison clearly demonstrates how depositional environments shape the physical characteristics of sand, ultimately influencing their suitability for different engineering applications.

### 3.2 California Bearing Ratio (CBR)

Fig. 12 illustrates the CBR values for the treated clayey sand mixture, while Fig. 13 represents those for the treated river sandy mixture. In comparison, Fig. 10 and Fig. 11 display the CBR values for the untreated control group. For clayey sand mixtures, the addition of cement alone led to a moderate increase in CBR values compared to the untreated clayey sand. However, incorporating clayey sand with 3% cement alongside the emulsion resulted in a significant improvement, with CBR values as shown in Fig. 12, indicative of a substantial gain in strength and stability. Similar trends were observed with river sand mixtures as shown in Fig. 13.

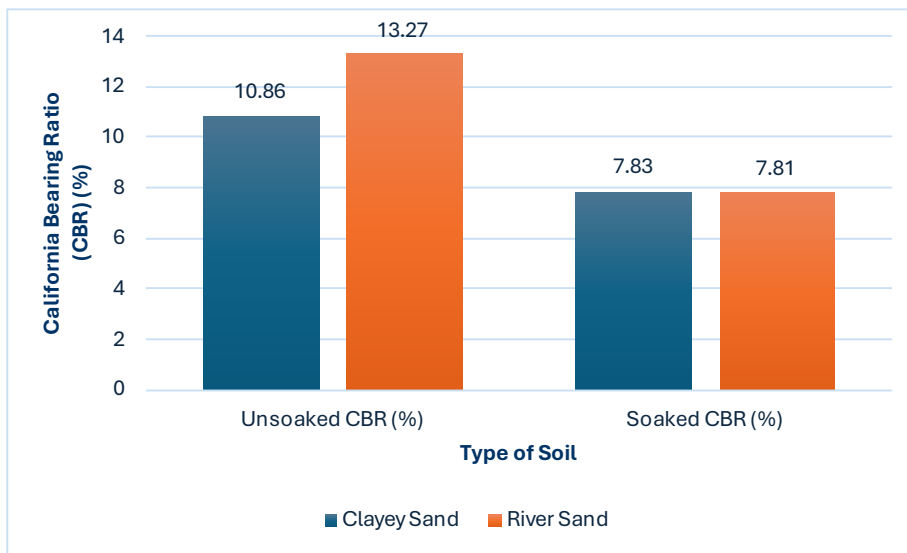


Fig. 10 California Bearing Ratio (CBR) of untreated clayey sand and river sand

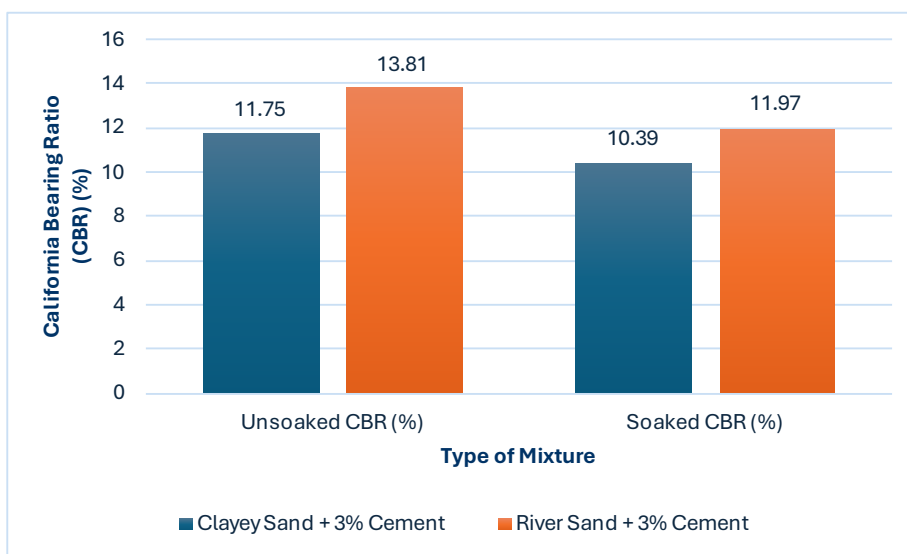


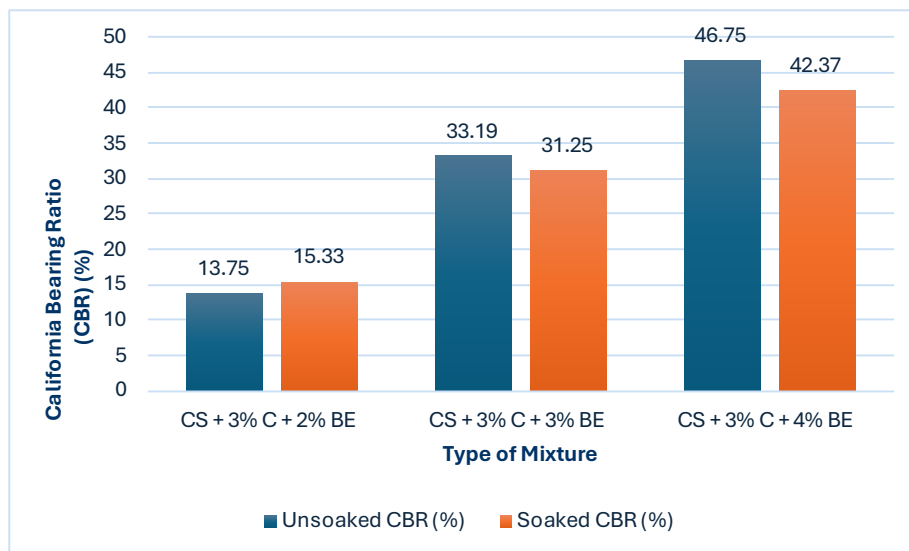
Fig. 11 California Bearing Ratio (CBR) of clayey sand and river sand mixed with 3% cement

The minimum California Bearing Ratio (CBR) value for a suitable subgrade according to the Standard Specification for Road Works from the Public Works Department Malaysia (JKR) is more than 20%. While bitumen emulsion alone offered some improvement, the combined inclusion of 3% cement yielded the most significant CBR enhancement. This synergy suggests that when bitumen emulsion and cement are used together, they work in tandem to enhance the stability and durability of the subgrade soil.

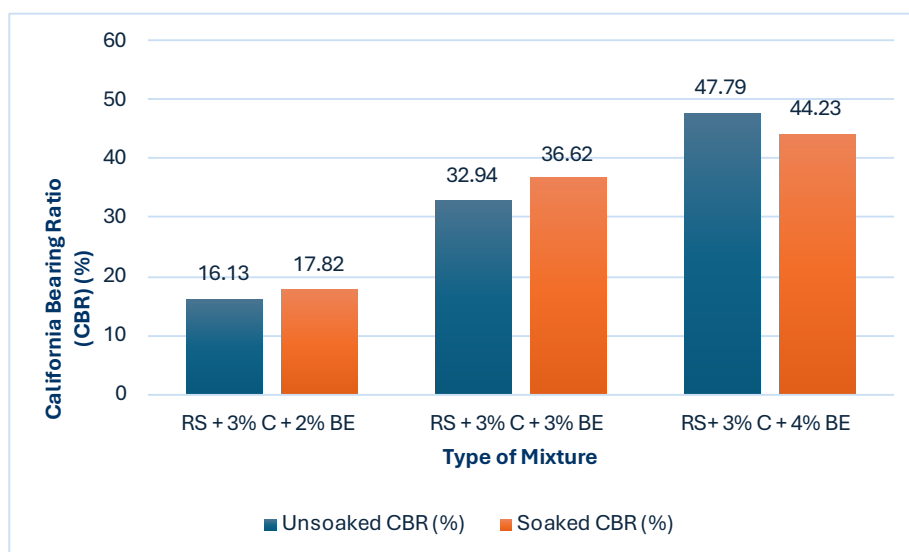
The cementation effect refers to the binding of soil particles, resulting in increased cohesion and strength, while the waterproofing properties help to minimise moisture infiltration, thereby further improving soil stability. This combined effect highlights the potential for leveraging both bitumen emulsion and cement as complementary stabilisation agents, offering enhanced performance in subgrade stabilisation applications [42].

Further analysis is needed to determine the optimal bitumen emulsion dosage for each soil type, balancing cost-effectiveness with desired strength improvement. Furthermore, investigating the specific mechanisms contributing to the observed synergy between bitumen emulsion and cement would provide valuable insights for future optimisation.

Based on these findings, utilising bitumen emulsion in conjunction with 3% cement presents a promising approach for stabilising poorly graded sand subgrades. This method offers the potential to enhance subgrade strength, improve pavement performance, and potentially reduce construction time due to the accelerated curing facilitated by cement. However, further field-based studies and cost-benefit analyses are recommended before widespread implementation.



**Fig. 12** California Bearing Ratio (CBR) of clayey sand stabilised with 3% cement and bitumen emulsion



**Fig. 13** California Bearing Ratio (CBR) of river sand stabilised with 3% cement and bitumen emulsion

### 3.3 Unconfined Compressive Strength (UCS)

The addition of both bitumen emulsion and 3% cement, as demonstrated in Fig. 16, for clayey sand resulted in a significantly higher UCS than mixtures containing only cement and the untreated clayey sand at all curing periods, as indicated in Fig. 14 and Fig. 15 respectively. This remarkable improvement suggests a synergistic effect between the cement and bitumen emulsion as stabiliser. Cement likely contributes by promoting hydration and

bonding between soil particles, further enhancing the cohesion and strength gains achieved by the bitumen emulsion.

Similar trends were observed with river sand, where the combined use of bitumen emulsion and 3% cement yielded the highest UCS values as shown in Fig. 17. This finding highlights the potential of this method to effectively address the inherent lack of cohesion in river sand. The observed synergy between the bitumen emulsion and cement warrants further investigation to understand the underlying mechanisms and optimise dosages for different soil types.

PWD Malaysia requires a minimum Unconfined Compressive Strength (UCS) of 800 kPa for stabilised subgrade [43]. This criterion serves as a crucial measure to ensure the structural integrity and stability of road subgrade. Notably, the 3% emulsion content exceeds the minimum design requirement for subgrade strength, which are 1108.29 kPa and 1064.74 kPa., for clayey sand and river sand after 28 days of curing, respectively.

As with UCS results for bitumen emulsion alone, the observed gradual increase in UCS with curing time emphasises the importance of considering long-term strength development. The combined use of bitumen emulsion and cement further accelerates this process, potentially allowing for reduced construction lead times compared to relying solely on cement-based stabilisation.

Similar to the UCS discussion for bitumen emulsion alone, additional tests focusing on other mechanical properties like tensile strength and shear strength would provide a more comprehensive understanding of the stabilised soil's behaviour. Additionally, investigating the long-term durability and moisture susceptibility of the combined stabilisation method under various environmental conditions is crucial for ensuring long-term performance.

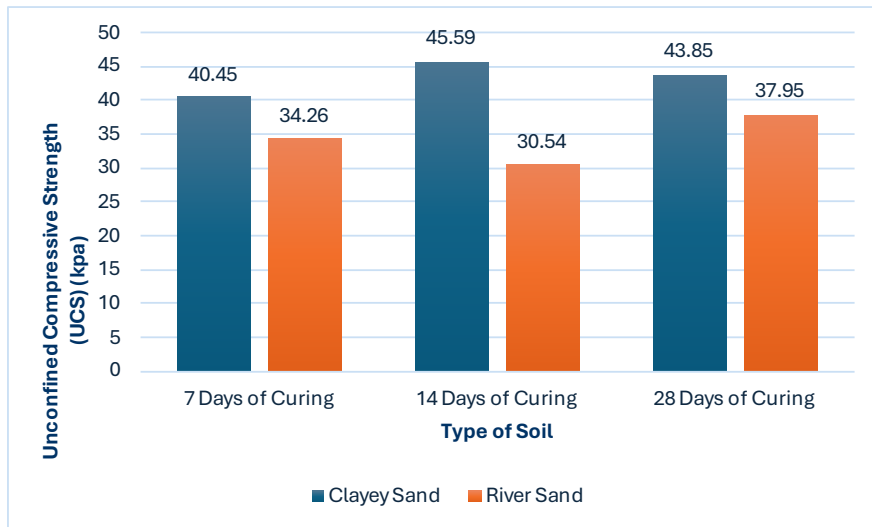


Fig. 14 Unconfined Compressive Strength (UCS) of untreated clayey sand and river sand

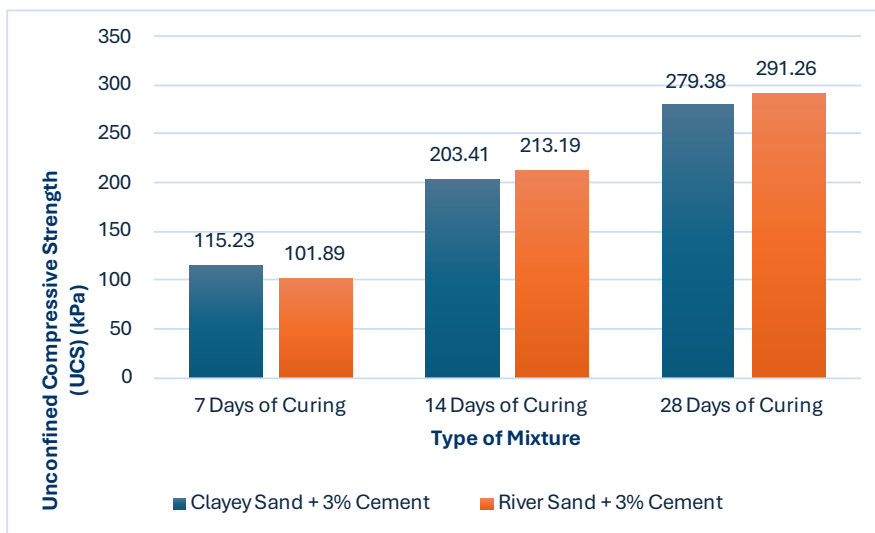
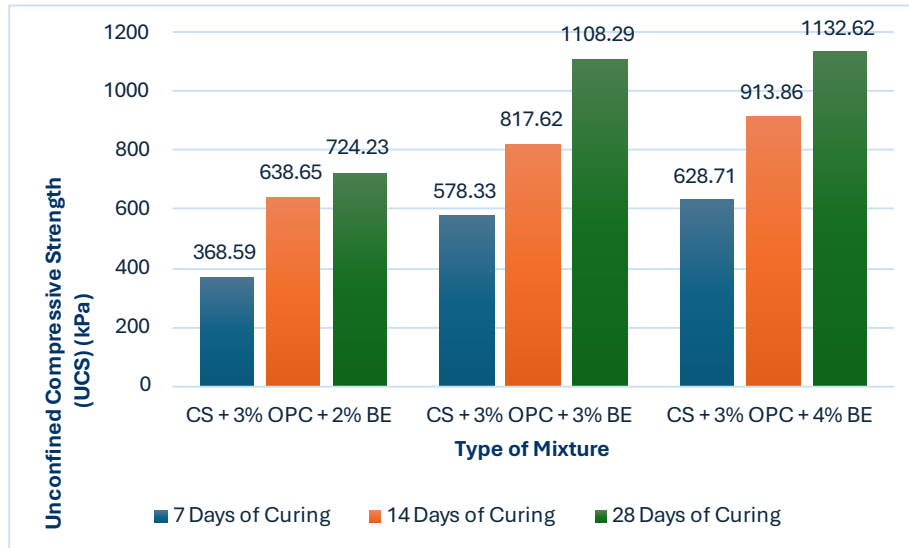
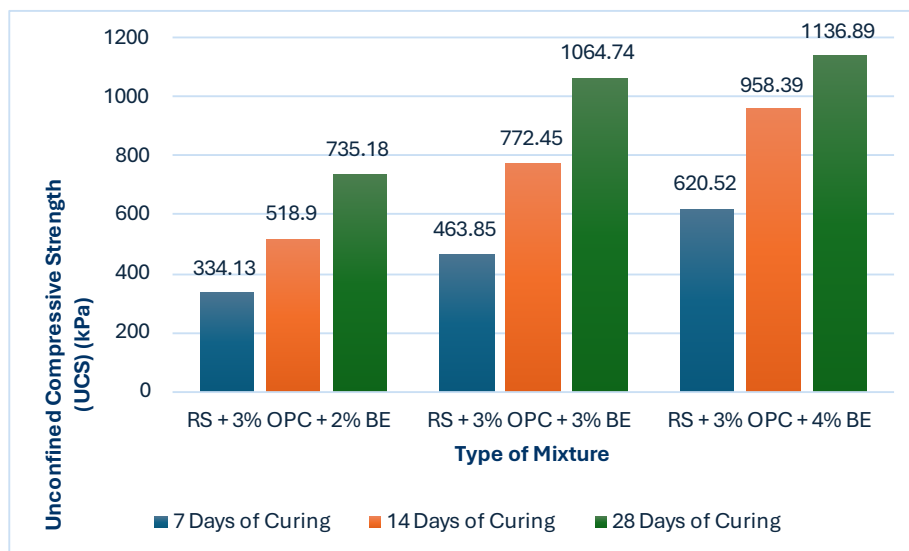


Fig. 15 Unconfined Compressive Strength (UCS) of clayey sand and river sand mixed with 3% cement



**Fig. 16** Unconfined Compressive Strength (UCS) of clayey sand stabilized with 3% cement and bitumen emulsion



**Fig. 17** Unconfined Compressive Strength (UCS) of river sand stabilized with 3% cement and bitumen emulsion

#### 4. Conclusion

In accordance with the study's outcomes, the following conclusions can be ascertained: (i) The soil's cohesiveness and shear strength are improved by the coating and binding of the sand particles by bitumen emulsion, (ii) Bitumen emulsion increases the rigidity of the soil and makes it more resistant to deformation under load, (iii) Bitumen emulsion is an effective stabilisation method for sand subgrade, (iv) The optimum bitumen emulsion content for stabilising sand subgrade is 3% by weight of the dry soil, (v) Curing time has a significant influence on CBR and UCS of bitumen emulsion-stabilised sand subgrade, with CBR and UCS increasing with increasing curing time, and (vi) The design and construction of roads and other pavements on sand subgrade can be improved by using the study's findings.

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#### Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

## Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Jacqueline Michella Nathen, Ahmad Kamil Arshad; **data collection:** Jacqueline Michella Nathen, Nuryantizpura Mohamad Rais, Ekarizan Shaffie; **analysis and interpretation of results:** Fauzilah Ismail, Noor Azreena Kamaluddin, Ahmad Zakilfikri Abdul Malek; **draft manuscript preparation:** Jacqueline Michella Nathen, Ahmad Kamil Arshad. All authors reviewed the results and approved the final version of the manuscript.

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