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A Sustainable Approach to Improving the Hydraulic Properties of Subgrade Using Marble Dust and Coconut Shell

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ABSTRACT

Subgrade materials are primarily defined by their capacity for sustained deformation under stress, which serves as an indicator of their strength or stiffness. The infiltration of rainwater into damaged pavement will have an impact on the performance of the subgrade. Submerging the subgrade in floodwater causes water to penetrate the subgrade pores, resulting in an increase in the subgrade's weight. This research aims to examine the effects of marble dust and coconut shell as additions to subgrade materials and further investigate the potential of utilising this hazardous waste to enhance the strength of the soil. This study investigates the hydraulic properties of the soil around the Universiti Pertahanan Nasional Malaysia (UPNM) campus, considering the addition of waste marble dust (MD) and crushed coconut shell (CS). The following ratio mixes of marble dust and coconut shell in this research are: MC1 (5:2.5), MC2 (10:2), MC3 (15:1.5), MC4 (20:1.0), MC5 (25:0.5), and a control sample without any additive. Laboratory experiments were conducted on the soil mixtures, which included sieve analysis, constant head pressure, and pressure plate extractor testing. The findings of the study indicate that the mixed-design MC1, consisting of 5% MD and 2.5% CS, demonstrates the most efficacy in improving the hydraulic properties of the subgrade. The primary focus of the Green Technology Master Plan Malaysia 2017–2030 is to enhance resilience to climate change and disasters by prioritising environmental sustainability. This is particularly highlighted in Chapter 6, which focuses on waste management.

1. Introduction

The most recently reported flood disaster resulted in severe devastation in Malaysia. The flood incident impacted a total of 98 federal highways and 126 state highways, according to the National Disaster Management Agency (NADMA) in December 2021. The heavy rainfall during the 2014 flood in Kelantan resulted in substantial destruction to the road infrastructure, requiring the Malaysian government to allocate 100 million Ringgit Malaysia for the restoration of the flood-damaged roadways.

Due to its insufficient drainage infrastructure and constant high intensity rainfall, Malaysia is a tropical nation that frequently encounters flooding during the monsoon season. Water seeps into the slope during and after a period of intense rainfall, contributing to surface runoff. The change in soil composition results in a reduction in matric suction, which impacts the bonding forces between soil particles [1]. [1] [2] have found that the ongoing flow of water can weaken a slope, leading to a higher chance of slope failure. This phenomenon shows similarities in scenarios where flooding events inundate the road infrastructure. [22] further noted that understanding the complex nature of slope failure caused by rainfall is crucial for comprehending the way soil behaves under various degrees of rainfall intensity and duration.

Subgrade materials' resistance to deformation under external loads is primarily determined by their strength or stiffness. Generally, a subgrade's degree of deformation resistance increases its load support until it approaches a critical deformation threshold [4].

According to the study [5], the presence of unstable and weak soil leads to the development of pavement issues, with the subgrade playing a crucial role. Rainwater seeping into the subgrade and damaged pavement has an adverse effect on the infrastructure's structural strength [6]. The presence of water significantly impacts the performance of the subgrade when the road structure becomes saturated. In pavement design, the condition of the subgrade soil is crucial because its primary function is to sustain the load from the layers above. The subgrade must possess robustness and stability to withstand significant traffic loads and adverse climate fluctuations [7]. [7] argue that the subgrade must have both durability and stability to survive heavy traffic loads and unfavourable weather conditions.

Hence, it is imperative to stabilise and repair the subgrade soil for the roads in Malaysia to optimise their performance and prolong their lifespan. When immersed in floodwater, the subgrade, which is the lowest and most prone to damage, deteriorates [8] [9]. The moisture content has a significant impact on the subgrade.

The distribution of suction during a flood primarily impacts the subgrade of unsaturated soil, thereby influencing both seepage and shear strength. The soil's shear strength values are crucial engineering properties for designing the subgrade. The shear strength of unsaturated soil is contingent upon the matric suction. When the matric suction is below the air entry value (AEV), the soil shear strength rises with an increase in matric suction. The inter-particle force resulting from negative pore water pressure causes a notable rise in the soil's shear strength at a particular level of matric suction. The relationship between shear strength and matric suction stays the same when matric suction levels are high. This is because matric suction can't reach the contact site of soil particles when water content is low. The air entry value (AEV) refers to the point at which air begins to infiltrate the soil through matric suction. The primary elements influencing AEV estimation or measurement are the maximum pore size at the soil surface and the distribution of pore sizes throughout the soil body. This is because finer particles tend to have a higher AEV. Other than that, [13] mentioned that the air-entry values of the soil samples derived from the soil-water characteristic curve (SWCC) function as an indicator of the soil's capacity to withstand soil slope failure.

To gain a deeper understanding of the intricate process of water penetration into the unsaturated soil subgrade during a flood, it is crucial to thoroughly examine the key hydraulic characteristic associated with AEV. The AEV (air entry value) and RWC (residual water content) can be estimated by graphing the Soil Water Characteristic Curve (SWCC). The SWCC (Soil-Water Characteristic Curve) plays a crucial role in analysing the hydraulic-mechanical properties of unsaturated soil. It is used to estimate many functions, including hydraulic conductivity, water storage capacity, and shear strength. SWCC plays a crucial role in the distribution of suction in the soil. The water retention curve represents the connection between the water content, θ, and the soil water potential, ψ (Figure 1).

Journal of XX
Volume XX, Issue X (2019) XX-XX

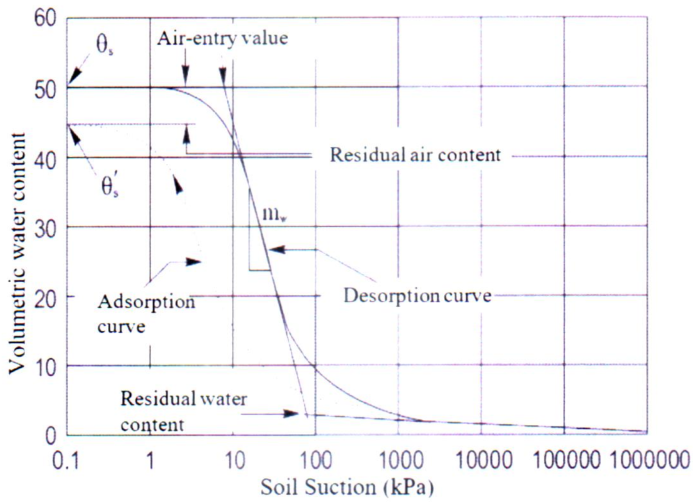

Fig. 1. Typical absorption and desorption of SWCC (18)

Agricultural activities yield the crushed coconut shell, a nano-carbon material, that is considered a byproduct. Researchers conducted a study to examine how soil water penetration affects the levels of nanocarbon content [10]. Researchers have found that adding nanocarbons to soil improves the micropores in the particles by partially filling them up. This is because nanocarbons have a very large specific surface area and are very small. The pore-size distribution change involved reducing the number of larger pores and increasing the proportion of smaller pores. Water shows enhanced fluidity when subjected to low-pressure circumstances, thereby facilitating its passage through larger pores. As the pressure increased, the macrospores expelled the water, leaving only the smaller pores intact. The smaller holes exhibited significantly higher suction forces. Consequently, the presence of nanocarbons in the soil led to a reduced rate of water drainage in comparison to the soil without nanocarbons. Therefore, the inclusion of nanocarbons has the capacity to somewhat improve the soil's water retention capability [10]. A study by [11] demonstrates that adding coconut shell charcoal boosts the soil's maximum dry density. Nevertheless, it is important to mention that surpassing the ideal proportion of coconut shell charcoal results in a decrease in the maximum dry density of the soil.

The marble-cutting operation at quarries generates this industrial waste. Environmental contamination has occurred because of the piling of waste WMD in developing countries and the improper storage and misuse of trash. Prior studies have shown that the ideal amount of marble dust concentration might differ based on the properties of the soil. Prior studies have discovered that the ideal amount of marble dust in the soil may differ depending on alterations in the soil's qualities. [3] noted that the liquid limit and plastic limit decrease as the amount of WMD increases. The studies conducted [11] and [12] provide evidence that the liquid limit and plasticity index of the soil mixes decrease.

[3] found that micro-analyses, such as XRD and FESEM, as well as physicochemical studies, such as pH, show that there are variables that affect how strong and how much WMD-soil mixes swell. India, Pakistan, Egypt, Turkey, and other countries have conducted research to improve the subgrade's stability using waste WMD. The findings indicated that waste WMD, primarily composed of calcium, silica, and alumina, is appropriate for soil stabilisation.

It minimises swelling and flexibility, enhances the unconfined compressive strength (UCCS), and dramatically improves the California bearing ratio (CBR). Researchers in India found that adding 20% WMD to black cotton soil improves soil strength and behaviour [11]. The findings indicated that the inclusion of 15% WMD in the soil sample resulted in an increase in the CBR value compared to the untreated soil sample. [15] conducted research that showed improved soil performance when they added 5% WMD, leading to the highest UCCS value. [19] demonstrated that the inclusion of 5% WMD leads to negligible levels of swelling, shrinkage potential, and compression index, while simultaneously enhancing the unconfined compressive strength (UCCS) and flexural strength. Other experiments combined WMD with additional substances, such as fly ash and bentonite. [16] combined WMD with incinerated ash from municipal solid waste. [17] achieved enhanced soil performance by combining WMD with bentonite.

This research was conducted to overcome a lack of studies examining the impact of hydraulic properties of the treated subgrade, particularly the correlation between AEV (air entry value) and RWC (residual water content) of the soil in the context of floods. Therefore, it is currently opportune to examine and scrutinise the feasibility of utilising waste marble dust and coconut shell as a supplement for the subgrade to augment the soil's strength that has been impacted by the flood occurrence resulting from intense precipitation. Using waste in construction materials leads to cost savings and the adoption of environmental conservation practices. This research holds great importance considering the climate change phenomenon and aligns with Chapter 8 of the 12th Malaysia Plan 2021-2025, which focuses on enhancing resilience to climate change and disasters, as well as the Green Technology Master Plan Malaysia 2017-2030, namely Chapter 6 on waste management.

2. Methodology

For conducting the experiment, samples were collected from both damaged and undisturbed areas. Soil samples were collected from various locations surrounding Universiti Pertahanan Nasional Malaysia (UPNM). The soil samples will be taken to the laboratory and subjected to oven drying at a temperature of 105 ºC for a duration of 24 hours. Next, the soil sample will undergo crushing and sieving to obtain smaller grain sizes that will be used for testing purposes. The control sample, consisting of 100% soil, underwent testing for sieve analysis, the Atterberg limit, soil classification, hydraulic conductivity, and the estimation of the soil water characteristic curve (SWCC) using a plate pressure extractor.

2.1 Prepared soil with marble dust and coconut shell

A marble quarry in Simpang Pulai, Perak, Malaysia provided the waste marble stone. Construction sites produce different sizes of discarded marble pieces during the marble cutting process, which subsequently undergo crushing into a fine powder. The WMD will undergo a process of oven drying for 24 hours at a temperature of 105°C, as a soil sample shown in Figure 2(a).

The study sourced the CCSS waste from commercial suppliers, as illustrated in Figure 2(b). Before being added to the soil sample, the CCS was broken down into particles with dimensions ranging from 5 to 8 mm. Table 1 provides the mix design of soil, waste marble dust, and crushed coconut shell for this investigation.

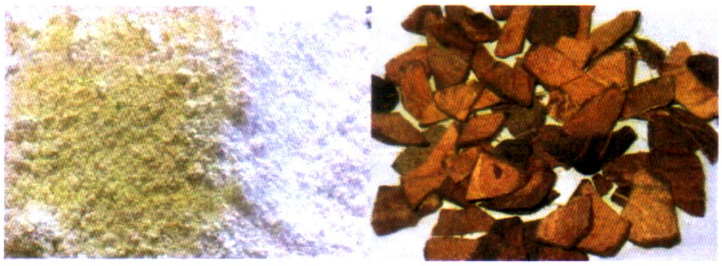
Fig. 2. (a) Raw marble dust (b) Raw crushed coconut shell

Table 1
Samples name and mixes design of soil, WMD and CCS

Sample name	Percentage of WMD (%)	Percentage of CCS (%)
Control	0	0
MC1	5	2.5
MC2	10	2.0
MC3	15	1.5
MC4	20	1.0
MC5	25	0.5

2.2 Soil water characteristic curve (SWCC)

The process of obtaining the Soil-Water Characteristic Curve (SWCC) will be carried out using a pressure plate extractor test (PPE) device in the laboratory as in Figure 3. The soil sample, along with the control sample and mixes, were remoulded into a cylindrical shape with a diameter of 50 mm and a height of 50 mm. The SWCC is calculated following the guidelines of ASTM D6836-02, which specifies the method for determining the soil water characteristic curve for a pressure extractor. The experiment employs two pressure chambers, one set at 5 bar and the other at 10 bar, along with a 20-bar air compressor and saturated ceramic plates (see Figure 2). The samples will undergo a 24-hour saturation process, followed by the application of pressure stages ranging from 0 to 15 bar, in compliance with the ASTM standards. After applying the final pressure to the samples, we dry them in an oven for 24 hours and then weigh them again.

The SWCC graph will be generated using data obtained from the plate pressure extractor. Subsequently, the curve will be adjusted employing the empirical correlation proposed by Van Genuchten (1980). The estimation of the air entry value (AEV) is derived from the soil-water characteristic curve (SWCC) generated.

Journal of XX
Volume XX, Issue X (2019) XX-XX

Fig. 3. Plate pressure extractor apparatus.

3. Results

3.1 Soil basic properties

Control soils is classified as poorly graded sand. Other results of soil basic properties and particle size distribution are as shown in Table 2 and Figure 4 respectively. Results of hydraulic conductivity for control soil samples is shown in Table 2.

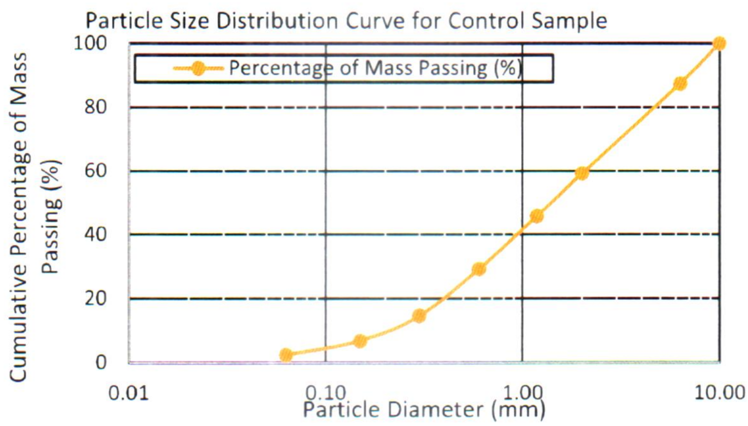

Fig.4. Particle size distribution for control soil sample

Table 2.
Basic soil properties of the control sample.

Parameter	Unit	Value
Soil Composition		
Gravel	%	5.1%
Sand	%	91.3%
Silt	%	3.0%
Clay	%	0.6%
Soil Classification		SP Poorly graded sand
Hydraulic conductivity, k_{sat}	*cm/sec*	0.0124

3.2 Soil water characteristic curve (SWCC)

SWCC for all samples are shown for control soil sample and the mixes of WMD and CCS in Figure 5 and 6respectively. As shown in Figure 5 and Table 3, control sample has the AEV of 10 kPa. Other than that, the volumetric saturated water content, θs and volumetric residual water content, θr are 0.79 2 and 0.515 respectively.

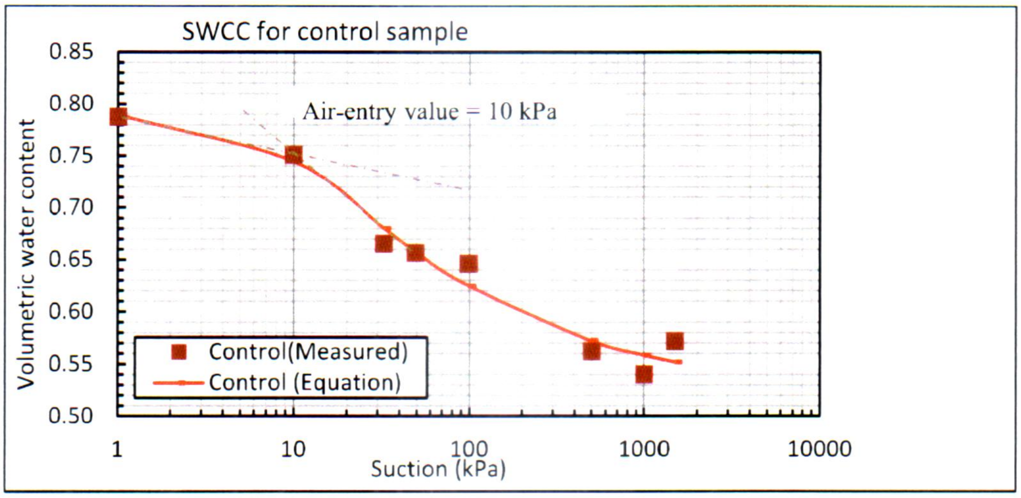

Fig. 5. SWCC graph for control soil sample

Table 3. Parameter of control samples

Parameter	**Value**
Volumetric saturated water content, θ_s	0.792
Volumetric residual water content, θ_r	0.515
Inverse to air entry suction, α	0.093
Pore-size distribution, n	1.413
R^2	0.972
Air-entry value	10

The characteristic and air-entry values of soil samples were initially obtained and used as control samples. Table 4 displays the variation in air-entry value based on varying proportions of waste marble dust and crushed coconut shell combined in soil. By incorporating 5% marble dust and 2.5% fractured coconut shell into the soil, the air-entry value rose from 10 kPa to 23 kPa. The air-entry value of the mix samples decreased gradually from 25 kPa to 18 kPa when a 5% increase in WMD and a 0.5% decrease in CCS were introduced. The air-entry value decreases to 14 kPa and increases to 19 kPa when the WMD is increased and the CCS content in the soil is reduced.

This demonstrates that CCS improves at retaining water in the soil and can release water content in an optimal amount compared to the control sample. On the other hand, WMD decreases the

Journal of XX
Volume XX, Issue X (2019) XX-XX

volumetric water content when submerged, as it has the potential to reduce the pores of the soil samples.

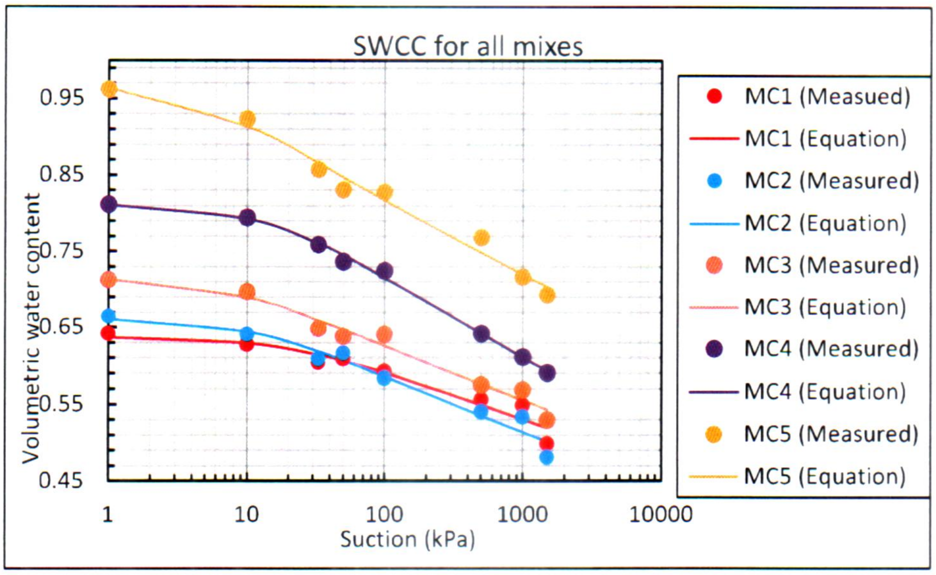

Fig. 6. SWCC graph for the soil, WMD and CCS mixes samples

Table Error! No text of specified style in document.. Parameters of soil mixed with WMD and CCS

Parameter	5% WMD 2.5% CCS MC1	10% WMD 2.0% CCS MC2	15% WMD 1.5% CCS MC3	20% WMD 1.0%CCS MC4	25% WMD 0.5% CCS MC5
Sample label	0520	1020	1515	2010	2505
Volumetric saturated water content, ϑs	0.637	0.663	0.744	0.813	0.973
Volumetric residual water content, ϑr	1.01E-19	1.00E-10	1.62E-09	1.00E-10	1.00E-10
Inverse to air entry suction, α	0.033	0.071	0.139	0.048	0.231
Pore-size distribution, n	1.052	1.0596	1.0488	1.0735	1.0555
R^2	0.937	0.960	0.990	0.996	0.982
Air-entry value	23	18	14	19	13

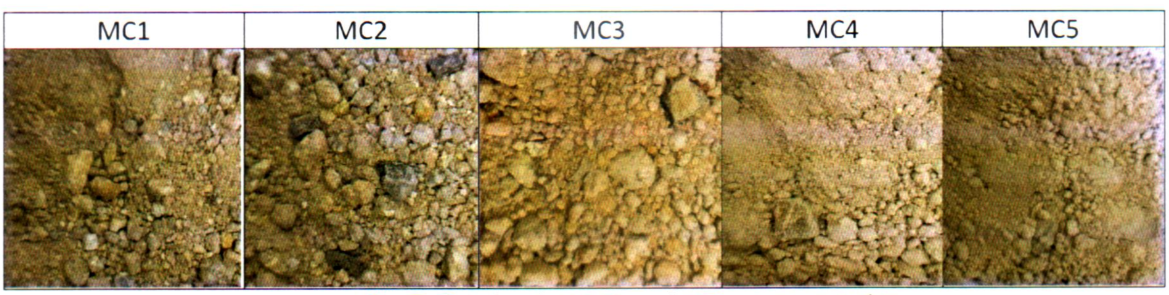

Fig. 7. Dried soil, WMD and CCS mixes samples

The decrease in absorption resulting from WMD on the subgrade will prevent the infiltration of water into the subgrade, leading to surface runoff. Nevertheless, WMD enhances the subgrade's cohesion. We noted the presence of marble dust when we took soil samples from the core ring. The samples maintain their cylindrical shape as the WMD content increases. On the other hand, CCS exhibits excellent water absorption properties, facilitating the infiltration of surface runoff into the subgrade. However, the increased CCS resulted in the samples becoming brittle during the experiment.

As shown in Figure 7, during the experiment to obtain the soil-water characteristic curve (SWCC), we visually examined the samples to observe the specific characteristic of the soil, particularly when mixed with WMD and CCS additives. There are two primary visual distinctions among the control samples: the sample modified with WMD, the sample modified with CCS, and the sample modified with both WMD and CCS. These differences relate to the colour of the design sample and the refined shape after removal from the core ring.

According to [20], the variation in air-entry value may be observed by altering the percentage of crushed coconut shell added to the soil. The addition of 0.5% crushed coconut shell to the soil resulted in an increase in the air entry value from 10 kPa to 25 kPa. The air-entry value of the mix samples decreased gradually from 25 kPa to 20 kPa when 0.5% crushed coconut shell was added. When we supplement the mix samples with 1.5%, 2.0%, and 2.5% of crushed coconut shell, the air-entry value stays constant at 13 kPa. Adding a small percentage of crushed coconut shell to the mixture will result in a notable change in the air-entry value.

However,[21] claimed that varying percentages of waste marble dust mixed with soil can result in obvious differences in the air-entry value. The inclusion of 5% waste marble dust in the soil resulted in an increase in the air entry value from 10 kPa to 23 kPa. The air-entry value of the mix samples decreased gradually from 23 kPa to 20 kPa when 5% waste marble dust was added. The air-entry value subsequently decreases to 16 kPa upon the addition of 15% waste marble dust to the mixed samples. The air-entry value initially reaches 15 kPa and subsequently increases to 12 kPa when 20% and 25% of waste marble dust are added, respectively.

In this study, Table 4 displays the variation in air-entry value based on varying proportions of waste marble dust and crushed coconut shell combined in soil. By incorporating 5% marble dust and 2.5% fractured coconut shell into the soil, the air-entry value rose from 10 kPa to 23 kPa. The air-entry value of the mix samples decreased gradually from 25 kPa to 18 kPa when a 5% increase in WMD and a 0.5% decrease in CCS were introduced. The air-entry value decreases to 14 kPa and increases to 19 kPa when the WMD is increased and the CCS content in the soil is reduced.

This demonstrates that CCS is better at retaining water in the soil and can release water content in an optimal amount compared to the control sample. On the other hand, WMD decreases the volumetric water content when submerged, as it has the potential to reduce the pores of the soil samples.

The decrease in absorption resulting from WMD on the subgrade will prevent the infiltration of water into the subgrade, leading to surface runoff. Nevertheless, WMD enhances the subgrade's cohesion. We noted the presence of marble dust when we took soil samples from the core ring. The samples maintain their cylindrical shape as the WMD content increases. On the other hand, CCS exhibits excellent water absorption properties, facilitating the infiltration of surface runoff into the subgrade. However, the increased CCS resulted in the samples becoming brittle during the experiment.

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4. Conclusions

The AEV for the control sample is 10 kPa. The average effect value (AEV) for the mixed WMD is twice that of the control sample. On the other side, the mix design sample and CCS mixed rise by 40% and 30%, respectively. A higher AEV indicates that the sample requires increased pressure to facilitate the entry of air into the pores and the removal of water from the sample. Due to the varied distribution of WMD, a higher pressure is required for air to enter the voids. In contrast, the CCS mixture requires a lower pressure for air to enter the sample due to an increase in pore distribution. Nevertheless, elevated pore levels and a high CCS content make the sample susceptible to immediate breakage. But WMD can be modified and improved in appearance.

Essentially, the subgrade must possess great strength to withstand the strain, and it should not be prone to fracture. Additionally, it should have the ability to allow surface runoff or flood water to pass through, minimising any potential risks. In this study, we examined the soil mixture to ascertain the impact of WMD and CCS. The results indicate that WMD helps to improve the sample's form, while CCS is effective in retaining and releasing water under applied pressure, reducing the sample's AEV. As WMD and CCS content increases, the overall pattern of the AEV decreases as the content of WMD and CCS increases. At a certain rate, the AEV value stayed constant. To determine the maximum AEV, the WMD and CCS range percentages must be below 5% and 2.5%, respectively.

Future experiment recommendations include minimizing the WMD and CCS materials in the soil. Next, analyse the durability and strength of the subgrade by examining the efficacy and mechanical attributes of marble dust and coconut shell. Triaxial and shear box tests are crucial for assessing the load-bearing capacity of subgrades. In addition, the field emission scanning electron microscope can be used to examine the soil's bonding.

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