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INVESTIGATION EFFECT OF DIAMETER HOLE INFLUENCE IN COMPRESSIBILITY INJECTION OF POLYURETHANE COMPOSITE DOPED WITH RUBBER WASTE

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Abstract:

This study investigates the effect of diameter holes (10mm and 20mm) representing cracks condition and injected with polyurethane doped with rubber waste (PUCR) in the grouting method to enhance soil stability in clay soil. The PU is mixed with rubber waste using one-shot method and then injected into clay samples. Rubber waste offers an economical and sustainable solution for geotechnical and geological engineering. The research aims to evaluate the FTIR of clay soil and settlement of clay samples for normal clay condition (NC), crack 10 mm condition (CC -10), Injected PUCR0 -10mm (IP0-10), injected PUCR7.5 -10mm (IP7.5-10), crack 20 mm condition (CC -20), Injected PUCR0 -20mm (IP0-20), injected PUCR7.5 -20mm (IP7.5-20). The one-dimensional oedometer test compared clay sample compression after being treated with PUCR injection at holes of different sizes and diameters. Consolidation tests underscore the influence of the polyurethane ratio on soil compressibility and settlement behaviour. The study demonstrates the

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interrelated nature of consolidation, compaction, and plastic index tests in predicting soil response to loading and moisture, providing a comprehensive foundation for further research and development in composite materials and geotechnical engineering. The findings offer valuable insights for future applications and environmental considerations.

Keywords:

Polyurethane Composite Doped with Rubber Waste (PUCR); Ballast Track; Soil Settlement; Grouting; One-Dimensional Oedometer

Introduction

Railway track failure scenarios are the most challenging issues in Malaysia, significantly when associated with the failure of ballast track structure due high noise, and excessive uneven settlements of subgrades and jeopardize train operation safety. The previous researcher reported that the noise caused by railways is considered the second ranking of the main sources of noise after road traffic (Michali et al., 2021; Wosniacki & Zannin, 2021; Murphy & King, 2014b). According to the train accident statistic from the Department of Safety Analysis, Federal Railroad administrative (2015) reported that the highest cause of train accidents is 44.9 % due to track train failure, 28.9% human error, 13.1 % equipment failure, and 11.6 % from signal failure and others. However, due to the transfer of heavy axle loads and the train track the noise from wheel and rail interactions at the frequency range of 250Hz to 4000Hz has a significant impact on wayside noise along railway lines and may disturb the local populations (Maljaee et al., 2024; Michali et al., 2021; Kawaguchi et al., 2020; Guo et al., 2018).

In rail track systems, ballast is the dominant structure porous coarse graded granular media used mainly to transfer loads from sleepers to subgrade and also provide lateral resistance to the track system. However, due to the transfer of heavy axle loads and train track vibration effect mainly at the wheel-ballast rail interface, the ballast particles degrade and cause large vertical subgrade settlements which result in track irregularities (Liu et. al., 2022). These irregularities of the track system further led to deterioration and void pocket formation of the track structure and cause derailment that has the potential for life and economic loss. Subgrade consists of huge amounts of soil particles and understanding subgrade stresses is essential for assessing their functionality (Feng et al., 2024; Guo et al., 2022). Deformation problems such cracks and settlement pose critical problems in ballast track maintenance due to various factors contributing to this situation such as water content and suction, soil thickness, stress distribution and environmental conditions such as dry shrinkage lead to increase cracking (Ma et al., 2021; Oliveira et al., 2021; Yue et al., 2022). It has adverse effects on soil properties and compromises the structural integrity of soil-based constructions (Tang et al., 2021).

The current technology uses a ballast bed stabilizer from polyurethane (PU) is one of the available stabilization methods. Polyurethane grouting is widely applied in highways, housing construction, and underground engineering (Z. Huang et al., 2022). Bian et al. (2021) found an innovative grouting used in transportation technology is the polyurethane grouting method. By controlling the reaction and specific volume ratio, the solutions quickly create high-rigidity polyurethane foams. This polyurethane expands, solidifies rapidly and lifts the track level through expansion forces. Besides levelling and repairing structures, polyurethane materials can improve subgrade stiffness and shearing strength by filling pores and solidifying granular soil in the subgrade layers (Bian et al., 2021; Lee et al., 2017; Tannoury & Schrock, 2016).

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Moreover, reusing wastes is considerably helpful in preserving the environment with adding rubber to the soil can be effective in the mechanical properties of fine and coarse-grained soils (Akbarimehr et al., 2020). Using rubber in ballast layer can reduce dynamic impact loads, eliminating interlayer gaps and voids, leading to less permanent deformation and degradation (Guo et al., 2020; W. Zheng et al., 2020). An excellent example of such a material is closed-cell polyurethane foam, which has proven to be an effective stabilizer for ballast (Al-atroush et al., 2021). Hence, in this study investigates the effect of diameter injection of polyurethane foam composites doped with rubber waste at 0 % and 7.5 % ratio as a fill injection material by grouting method as a soil improvement in ballast track.

Methodology

Materials

This study used four materials which are rigid polyurethane (PU 301), rubber waste, clay soil, and distilled water. Rigid polyurethane (PU) that used in this study were purchased from Saintifik Bersatu (M) Sdn Bhd, located at Batu Pahat, Johor. The specification of this PU is Polyurethane-301 was commercialize used as material in grouting injection for soil and 180 mesh rubber waste particles was obtained from factory at Parit Sulong, Johor. Polyurethane doped with rubber waste (PUCR) were produced by mixing PU, distilled water as blowing agent and rubber waste. Then, PUCR used for grouting injection at clay soil in laboratory scale.

Fabrication Process Clay Samples

Polyurethane composite doped with rubber waste (PUCR) was prepared by mixing of rigid polyurethane PU-301, distilled water as a blowing agent, and rubber waste at a different ratio (o % and 7.5 %) by one shot open mould method. The preparation of PUCR through the one-shot open mould method followed by the previous research studied method (G. Huang et al., 2022; Kormin et al., 2018). The clay samples of prepared by compacting soil using density method (Indraratna et al., 2020). The process of adding clay and distilled water with ratio 4:1. The clay mixture are manually mix for 10 minutes until it being were homogeneous. Then it transfers into the metal mould that can fit consolidation ring with diameter 75 mm and height 20 mm. Then process of compacting using multiplex machine with 10kN load for 10 second. After the process of remoulded complete, a hole in the centre of the clay sample is prepared for PUCR injection. The PUCR composite was injected at clay samples into two sizes of diameter hole (10 mm and 20mm) and 20 mm height. Figure 1 shows the clay samples for this study.

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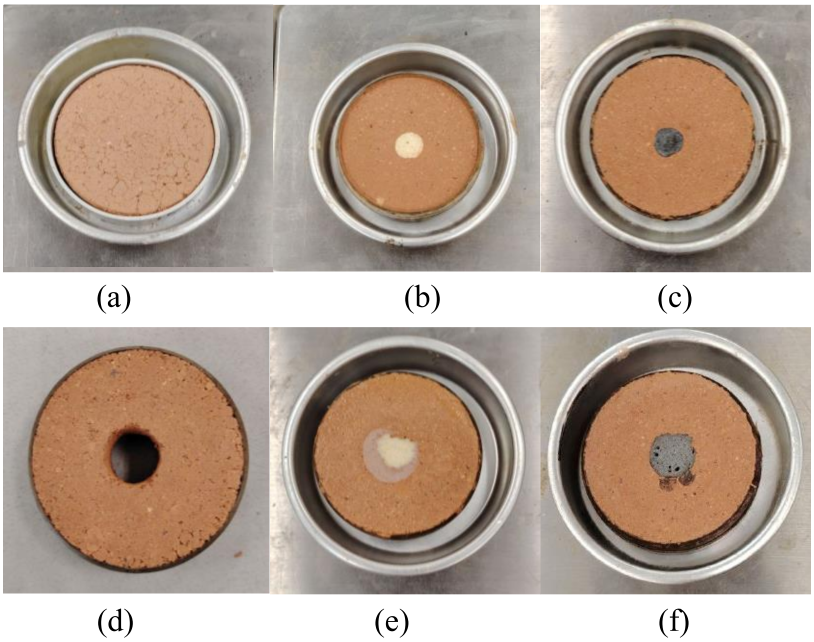

Figure 1: (a)Normal clay condition (NC-10mm), (b) Injected $PUCR_0$ – 10 mm (IP_0-10), (c) Injected $PUCR_{7.5}$ – 10 mm ($IP_{7.5}$-10), (d) Crack clay – 20 mm hole (CC-20mm), (e) Injected $PUCR_0$ – 20 mm (IP_0-20), (f) Injected $PUCR_{7.5}$ – 20 mm ($IP_{7.5}$-20)

Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform Infrared Spectroscopy (FTIR) was conducted to determine the chemical functional groups of clay soil. FTIR used instrument Agilent Technologies Cary 630 FTIR followed ASTM D6342-12: Standard Practice for Polyurethane Raw Materials: Polyurethane Reactions in Two-Component Coating Formulation. The FTIR testing was conducted in the Chemistry Analytical laboratory at Universiti Tun Hussein Onn Malaysia, Campus Pagoh, Johor as shown in Figure 3.9. The rubber waste and PUCR samples at different ratios was measured with a resolution of 4 cm-1 within the wavelength range of 4000 – 600 cm-1 following the previous study wavelength range by Sultan et al., (2021) (Sultan et al., 2021).

One-Dimensional Oedometer Test

By measuring settlement, a One-Dimensional Consolidation test was performed to determine soil compressibility (Mohamed Jais et al., 2019). The compacted specimens size is 75mm diameter with 20mm height were immersed in an oedometer cell filled with distilled water for 24H (Hao et al., 2022). Subsequently, the specimens were saturated, and it loaded with successively pressure, then consistently unloaded gradually with decreasing pressure. Every loading and unloading process takes 24 hours for completion. The load of each stage was simplified in Table 1. After that samples are oven-drying at 105ºC for 24 hours to determine the mass of solids (Murison, 2023). This test conducted using instrument UTS-0313 and following ASTM D2435: Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading, this test conducted at Geotechnical Laboratory at UTHM Pagoh, Johor. All types of samples conducted are illustrated at Figure 1.

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Table 1: Loading For All Sample Using One Dimensional Oedometer

Sample	(NC)	(CC)	(IP_0-10)	($IP_{7.5}$-10)	(IP_0-20)	($IP_{7.5}$-20)
Loading (kPa)	25	25	25	25	25	25
	50	50	50	50	50	50
	100	100	100	100	100	100
	200	200	200	200	200	200
	400	400	400	400	400	400
	800	800	800	800	800	800
Unloading	400	400	400	400	400	400
(kPa)	200	200	200	200	200	200
	100	100	100	100	100	100
	50	50	50	50	50	50
	25	25	25	25	25	25

Results

Fourier Transform Infrared Spectroscopy (FTIR) and Clay Properties

Figure 4.8 shown the spectra of clay the broadband at 3373 cm^{-1} shows the stretching for O-H groups of interlayer water molecules present in the clay. Although the samples were heated and dried before the analysis, the clear band in the area 1640–1600 cm^{-1} could be assigned to the deformation vibrations of O-H (Kuligiewicz & Derkowski,2017; Jozanikohan & Abarghooei, 2022). In addition, the band at 1647 cm^{-1} also shows the deformation vibration for H groups of the absorption by the interlayer water. While the stretching band at 1002 cm^{-1} shown the presence of Si-O (Khalil et al., 2009). While table 2 tabulated the clay sample properties used in this study.

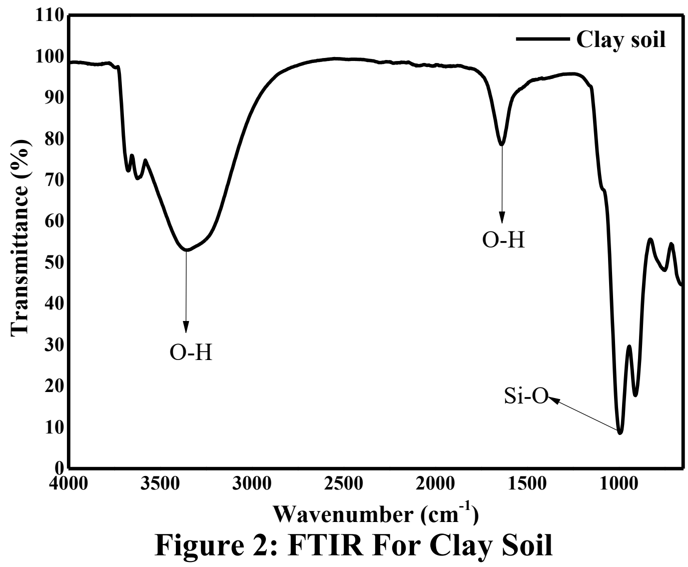

Figure 2: FTIR For Clay Soil

Table 2: Properties Of Clay Soil Sample

Parameters	Value
Optimum moisture content	24.41 %
Maximum dry density	1.42 g/cm^3
Specific gravity, Gs	2.6
Liquid limit, LL	76.44
Plastic limit, PL	28.18

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Plasticity index, PI	48.26
Soil classified by USCS	CH (high plasticity clay)

One-Dimensional Oedometer Test
The one-dimensional oedometer test was conducted to determine the consolidation parameters of the remoulded clay soil samples consisting of normal clay condition (NC), crack 10 mm condition (CC -10), Injected $PUCR_0$ -10mm (IP_0-10), injected $PUCR_{7.5}$ -10mm ($IP_{7.5}$-10), crack 20 mm condition (CC -20), Injected $PUCR_0$ -20mm (IP_0-20), injected $PUCR_{7.5}$ -20mm ($IP_{7.5}$-20). Figure 3 shows the consolidation pattern of clay soil. The curve highlights the distinct stages of consolidation observed in the clay soil samples consisting of initial settlement (e_i), primary consolidation (e_p), and secondary consolidation (e_s).

The e_i, observation occurs instantaneously upon 100 kPa loading due to the elastic deformation of the clay soil. The deformation during this phase is attributed primarily to the immediate compression of water void that content in the clay soil. The e_p phase of clay samples occurs at a high rate and continues for several hours. This is due to water dissipating out from the void of clay soil particles and is significant in the determination of the stress applied and forced out the free water in the void squeezed out. This phase is significant for determining the soil consolidation properties such as coefficient of consolidation (C_v). The e_s reflects the rearrangement of the soil particles at a constant stress. Furthermore, this study only focused on the primary consolidation stage for the determination of consolidation properties.

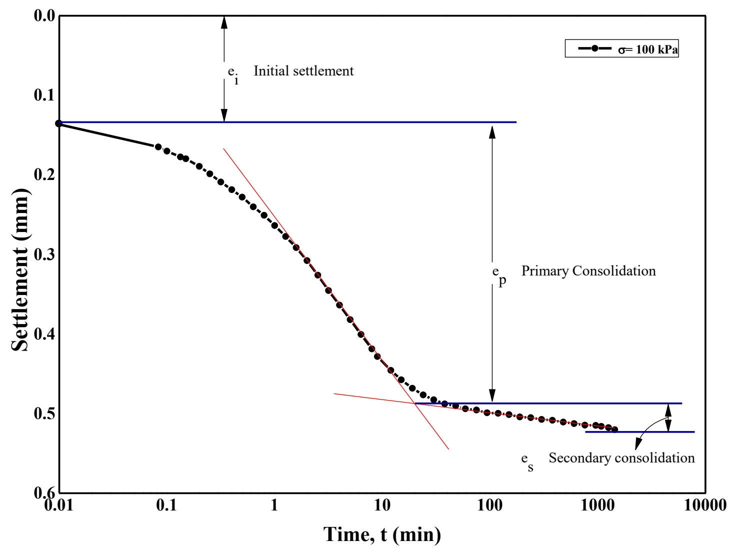

Figure 3: Consolidation Pattern for Clay Soil Sample

Settlement Based One Dimensional Oedometer Dial Gauge
Figure 4 shows the settlement values logged during the consolidation test NC sample, CC sample IP_0-10 sample, $IP_{7.5}$-10, IP_0-20 sample, and $IP_{7.5}$-20 sample. The pattern of all clay samples excludes CC and IP7.5-10 samples shows that the highest settlement occurs in the first loading, 25kPa. This pattern is due the high volume of void on the clay samples before put the load (Ibrahim *et al.*, 2012). While, second load 50 kPa were observers have lowest settlement in each clay samples except for CC and $IP_{7.5}$-20 samples. This improvement in the performance of settlement was attributed to the structural support induced by the PUCR grouting, which likely reduced the compressibility of the clay by filling voids and reinforcing the soil matrix.

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This observation aligns with the previous study finding state settlement of clay samples decreases with the increased of load since the clay samples were compacted on the previous load (Cheng *et al.*, 2020; Zaidan & Zainorabidin, 2022).

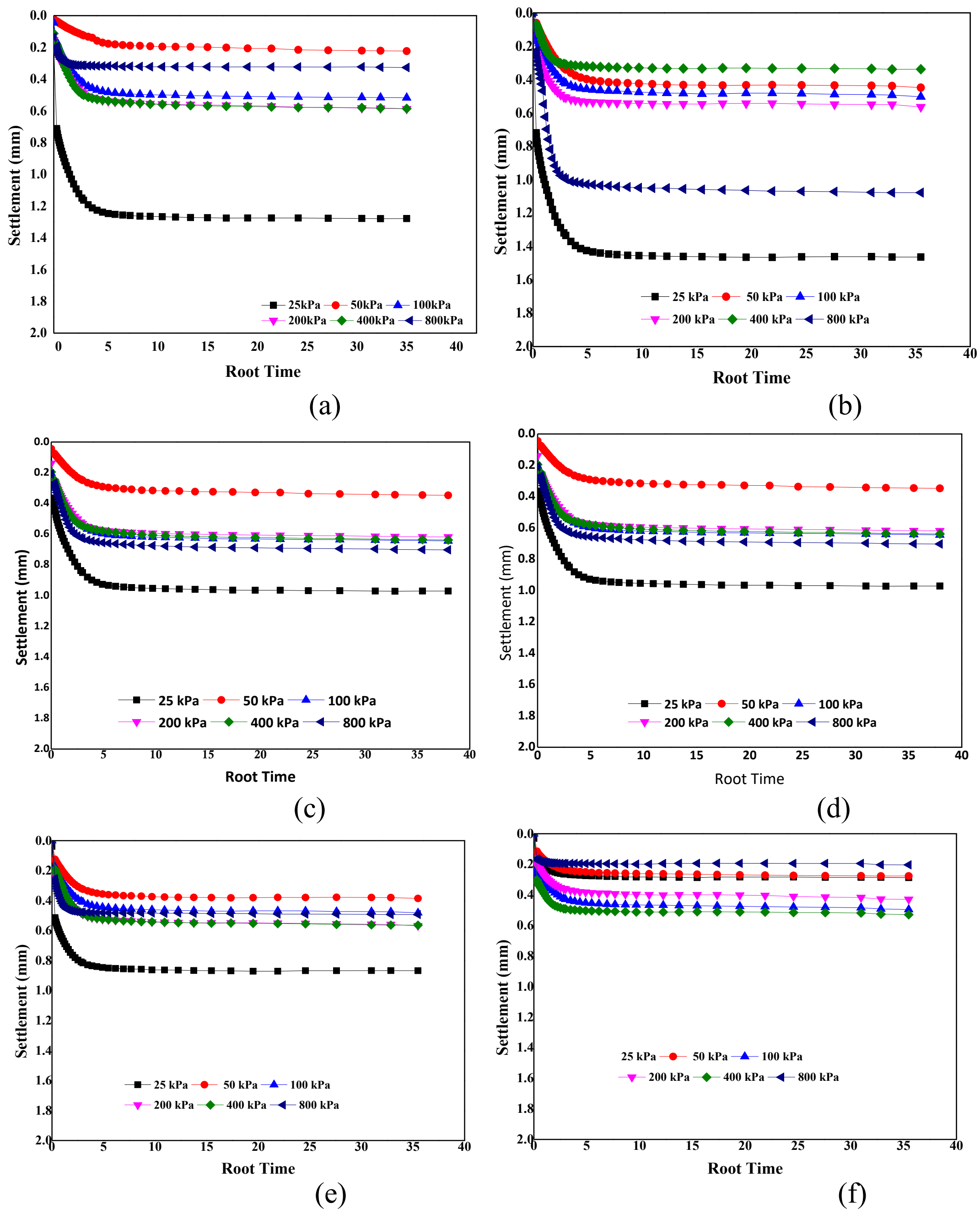

Figure 4: Settlement Trend for Each Load, (a) Normal Clay Condition (NC), (b) Crack Clay Condition (CC), (c) Injected PUCR$_0$ – 10 Mm (IP$_0$-10), (d) Injected PUCR$_{7.5}$ – 10 Mm (IP$_{7.5}$-10), (e) Injected PUCR$_0$ – 20 Mm (IP$_0$-20), And (f) Injected PUCR$_{7.5}$ – 20 Mm (IP$_{7.5}$-20)

The settlement observed in one dimensional oedometer test revealed that all injected clay soil reduce settlement value compared to NC and CC. It shows that injected clay indicates that the PUCR$_0$ and PUCR$_{7.5}$ grouting treatment improve the clay settlement. Another research that

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applied PU foam as separator between soft clay found that the buoyant effect of the PU foam is able to reduce the consolidation settlement of the soft ground due the increased load (Diana *et al.*, 2022). Notably, IP_0-20 and $IP_{7.5}$-20 exhibited low settlement compared to PUCR injected into 10 mm diameter. While samples $IP_{7.5}$-20 shows significant improvement compare to others sample. This indicates the effectiveness of PUCR grouting at 20 mm diameter compared 10 mm treatment in enhancing the settlement resistance of the clay.

Figure 5 presents overlay results of settlement in each pressure for all clay samples. The settlement result exhibited the highest value at 800 kPa is CC followed by NC, IP_0-10, IP_0-20, $IP_{7.5}$-10 and $IP_{7.5}$-20 corresponding settlement values are 5.1 mm, 4.0 mm, 3.9 mm, 3.4 mm, 3.0mm and 2.2 mm respectively. The settlement of sample CC represents the crack condition is higher than other samples due to soil particle move to filled the empty hole in load applied. In a comparison, injection $PUCR_{7.5}$ improve clay stability better than injection $PUCR_0$, shows the significance of rubber waste added to the PUCR matrix. However, $PUCR_{7.5}$ injected into 20 mm, observed 27 % more effective compared to 10 mm. While $IP_{7.5}$-20 improve 66.6 % when compared with worst situation (crack), CC sample. The PUCR as a filled material exhibited an ability to repair cracks in the soil with remain and improve the soil settlement conditions.

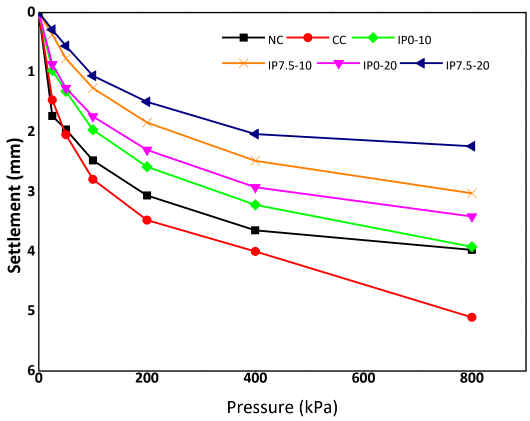

Figure 5: Final Settlement for Each Load Of All Samples

Void Ratio

Figure 6 presents the graph pattern of void ratio,e with log pressure for all clay samples. The initial void ratio for NC sample, CC sample IP_0-10 sample, $IP_{7.5}$-10, IP_0-20 sample, and $IP_{7.5}$-20 sample are 14.89, 15.42, 15.54, 16.04, 15.62 and 16.11 respectively. From the observation, NC shows the lowest void ratio and the highest is $IP_{7.5}$-20. This is due the NC sample was most compacted while $PUCR_{7.5}$ foam pore contribute the void of sample. At 800 kPa, the void ratio was decreased to 13.00 (NC), 13.11 (CC), 13.05 (IP_0-10), 13.80 ($IP_{7.5}$-20), 13.48 (IP_0-20), and 13.83 ($IC_{7.5}$-20), respectively. As the pressure increases, the void ratio gradually decreases with the clay soil sample. This finding also similar pattern with Cheng *et al.*, (2020) in which the result of void ratio of clay soil mix nano-bentonite gradually decreases when the pressure increases with the void ratio.

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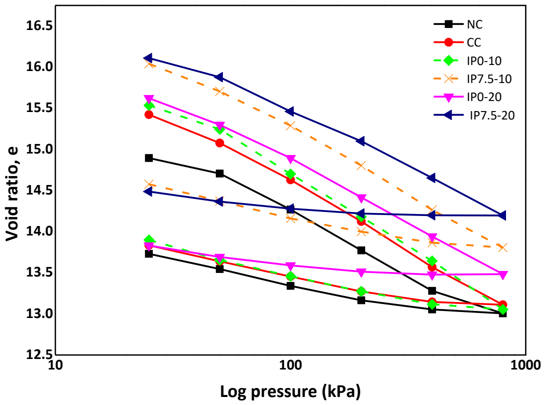

Figure 6: Void Ratio Versus Log Pressure Graphs of Samples

Compression Index, Cc and Swelling Index, Cs

Figure 7 presents the trend of compression index (Cc) and swelling index (Cs) for samples NC, CC. IP_0-10, $IP_{7.5}$-10, IP_0-20, and $IP_{7.5}$-20 sample. In this study, the recorded compression index Cc for all clay soil samples ranged from 1.6 to 1.9. Samples CC and IP_0-20 show the highest Cc index value (1.9). After injection of $PUCR_{7.5}$, the value of Cc improves by 10.53 % ($IP_{7.5}$-10) and 15.8 % ($IP_{7.5}$-20) compared to CC and IP_0-20. It shows that sample $IP_{7.5}$-20 through grouting into the clay soil resembles the OC sample performance (1.6). Previous studies that used the same injection method on peat soil found a 95% improvement in compressibility when injecting PU compared to un-injected peat. This confirms the ability of PUCR into as injection material in 20 mm clay (Mohamed Jais *et al.*, 2019).

The reduction of Cc signified that the soil becomes less compressible (Saleh *et al.*, 2019). These results show the $IP_{7.5}$-20 effective to be applied in clay soil since it reduces the Cc value compared to IP_0-10. While the swelling index, Cs, analysed for all clay samples was in the range of 0.63 to 0.24. The Cs of $IC_{7.5}$ exhibited lower compared to the swelling index of OC soil, NIC soil, and IC_0, which is 0.24. It revealed that the added rubber waste in the PU significantly decreased the swelling properties of clay soil samples. The lower swelling index on the clay soil samples represents that the clay soil was exposed to heavy load, occurred compressed condition and contributed the settlement of clay soil remains permanent due to less rebound.

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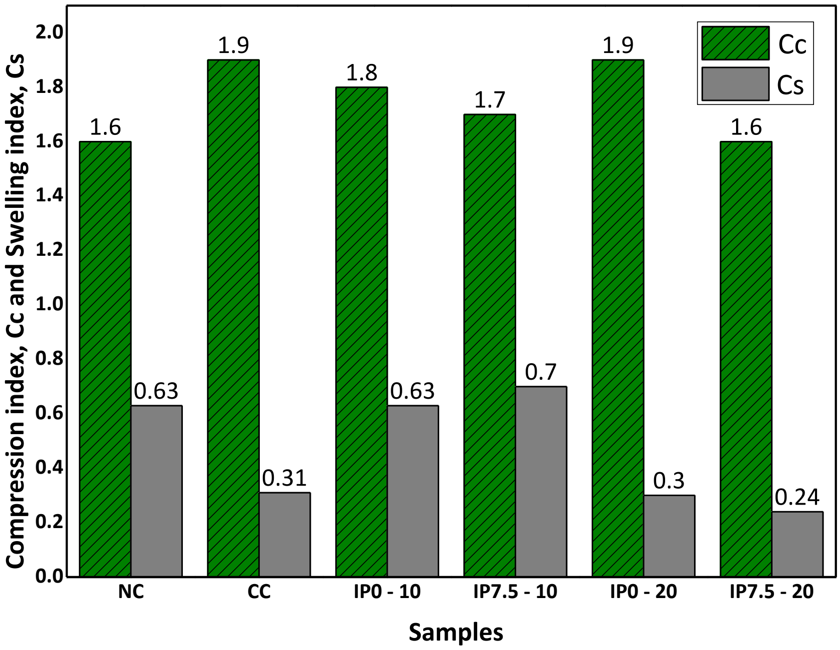

Figure 7: Trend Of The Compression Index (Cc) And Swelling Index (Cs) Of Clay Soil Samples

Coefficient of Compressibility, m_v and Coefficient of Consolidation, c_v

The relationship between m_v and c_v was analysed under incremental loading as presented in Table 3. Both m_v and coefficient of consolidation, c_v decreased with increasing load. The c_v values representing the primary consolidation were determined using two curves fitting methods.

The compressibility of clay soil refered to the reduction of clay soil volume when subjected to mechanical load. The result shows the coefficient of volume compressibility (m_v) value fluctuated at early stage of consolidation, 25kPa. After the consolidation pressure of 50kPa, the m_v for all samples became reduced. The reduction of m_v indicates that the injection facilitated more effective dissipation of excess pore water pressure under load. Such structural changes the clay, make it less compressible and lowering m_v value. As expected, all clay samples exhibited a similar relationship pattern of m_v and pressure. This result shows that $IP_{7.5}$-20 can be reduced the overload pressure on soil compared to others sample. Previous study that underlying soil with PU found that PU is lightweight material then future settlement can be minimise to a tolerable settlement value (Mohamed Jais *et al.*, 2019).

The findings align with the principles of consolidation, confirming c_v decrease as the applied load increases. The higher c_v all clay sample recorded at 25 kPa to 200 kPa. These findings are consistent with other studies reported the highest c_v values were recorded at early loading stage which primarily caused by the stress acceleration and settlement (Azam *et al.*, 2024). The high c_v indicates faster consolidation. This can be attributed to the high void ratios observe in CC, $IP_{7.5}$ -20, $IP_{7.5}$-10 and IP_0-20 as tabulated in Table 3. The empty hole and pores in PUCR composite facilitated to higher permeability and further contributed to the higher c_v values.

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Table 3: c_v and m_v Values on Every Consolidation Pressures of Clay Soil Samples

Clay soil sample	Pressure (kPa)	Void Ratio	c_v (m^2/yr)	m_v (m^2/kN)
Normal clay condition (NC)	25	14.89	15.7142	0.7534
	50	14.71	10.9442	0.8307
	100	14.27	6.40561	0.5293
	200	13.77	6.83581	0.3172
	400	13.28	9.95765	0.1828
	800	13.01	21.1801	0.0800
Crack clay condition (CC)	25	15.42	24.0777	3.1724
	50	15.08	17.6080	0.9954
	100	14.63	16.7015	0.5745
	200	14.12	14.2519	0.3331
	400	13.57	13.5149	0.1017
	800	13.11	15.6533	0.0846
Injected $PUCR_0$ – 10mm (IP_0-10)	25	16.35	7.88426	2.0400
	50	15.53	11.5012	0.7436
	100	15.24	9.80279	0.7145
	200	14.70	6.93360	0.3549
	400	14.18	10.7628	0.1901
	800	13.64	11.8244	0.1091
Injected $PUCR_{7.5}$ – 10mm ($IP_{7.5}$-10)	25	16.35	8.83186	2.0980
	50	16.04	8.77593	0.9876
	100	15.70	7.05782	0.6028
	200	15.28	6.24073	0.3337
	400	14.80	8.02191	0.1853
	800	14.26	7.00658	0.1092
Injected $PUCR_0$ – 20mm (IP_0-20)	25	15.62	14.0358	1.8165
	50	15.30	12.1190	0.8240
	100	14.89	11.5696	0.5281
	200	14.42	10.0978	0.3214
	400	13.94	9.47107	0.1649
	800	13.48	10.6681	0.0821
Injected $PUCR_{7.5}$ – 20mm ($IP_{7.5}$-20)	25	16.11	20.8317	0.5838
	50	15.88	18.3614	0.5702
	100	15.46	16.0754	0.5243
	200	15.10	15.3083	0.2324
	400	14.6	14.5329	0.1475
	800	14.20	14.4661	0.0781

Conclusions

In this paper, the consolidation characteristics of clay samples were investigated through one dimensional oedometer test. The influence of the $PUCR_0$ and $PUCR_{7.5}$ injected into 10 mm and 20 mm diameter on the settlement, void ratio, compression index, swelling index, coefficient of compressibility, and coefficient of consolidation was observed. As the result, the ratio of rubber waste doped with PUCR and diameter hole for injection had impact on every clay consolidation parameter. When increasing the pressure on the clay sample, the value of settlement of the clay reduced. Injected PUCR with 7.5 % rubber waste into clay soil in both hole size (10 mm and 20 mm) was observe improved the consolidation characteristics. The settlement result revealed that cooperated PUCR with 7.5 % rubber waste reduce the settlement. Aside from that, the injection on different diameter hole impact the settlement, while $IP_{7.5}$-20 shows the most significant improvement in term of settlement, reduce 66 %. As conclusion the $PUCR_{7.5}$ injected into 20 mm diameter hole shows the greater improvement compared to others clay sample condition.

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