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Effect of Buoyancy, Compressive Strength, and Shear Strength of Polyurethane-Clay Composite (PU-CC) Doped with Polyurethane Filler Waste in Soft Clay Application

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ABSTRACT

The application of polyurethane waste as a filler is one of the most cost-effective strategies for enhancing the geotechnical properties in soils. The PU waste from manufacturing economies was prepared with alkaline solutions by submerging into a 0.05 M sodium hydroxide (NaOH) before sieving to 300m sizes. The PU waste as filler was prepared using two heat exposure from microwaves and drying ovens at 60°C and left for 3 hours. Then, the treated and untreated Polyurethane-Clay Composite (PU-CC) was prepared at the different ratios of PU waste filler (2.5%, 5%, 7.5%, and 10%). The physical properties of treated and untreated Polyurethane-Clay Composite (PU-CC) were examined utilizing buoyancy force, unconfined compressive strength (UCS), and direct shear strength, respectively. The result exhibited that the PU-CCTO has the highest buoyancy force at 10% of PU-$CCTO_{10}$ samples at 50%, followed by 45% of PU-$CCTM_{10}$ and 8% of PU-$CCUN_{2.5}$. The UCS and shear strength of PU-$CCTO_{10}$ are evidently the highest at 300 kPa and 50 kPa, respectively, followed by PU-$CCTM_{2.5}$ at 130 kPa and 19 kPa and PU-$CCUN_{2.5}$ at 100 kPa and 15 kPa. PU-CCTO treated by drying oven has the highest buoyancy force at 10% of PU-$CCTO_{10}$ samples at 50%, followed by 45% of PU-$CCTM_{10}$ treated by microwave, and the lowest at 2.5 wt% of PU-$CCUN_{2.5}$ untreated at 8%. In a nutshell, the prospective PU-CCTO is superior to the PU-CCUN and PU-CCTM related of the potential for overheating and burning the PU filler powder during the microwave processing procedure. In conclusion, the 10 wt% of PU filler treated by the drying oven method as a PU clay composite has the potential as an alternative material to improve the compressive strength, shear strength, and buoyancy force in soil improvement.

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1. Introduction

The interest in recycling plastics including polyurethane groups in an efficient and appropriate manner had soared within the scientific community because of the directives of the European Union concerning the current demand for recycling plastics for the year 2050 [1-4]. Polyurethane (PU) is one of the polymeric materials that offers many potential applications in numerous industries including construction and manufacturing due to its versatility such as cost benefits, energy savings, and durability with several desirable properties. However, PU generates significant amounts of waste in various forms, of which only 29.7% is recycled and 39.5% is recovered through energy recovery processes, while landfilling is, unfortunately, the first choice in many countries, accounting for 30.8% of total waste. Due to the increasing of PU amount waste, solutions have been taken to reduce the problem of polymer waste which is a cost-effective and efficient method of recycling polymer waste through mechanical recycling.

For many years, the various additives as fillers used in polyurethane composite for various purposes and as an alternative to improve mechanical and physical properties of polymer materials. However, the problems of polyurethane (PU) waste were its naturally slow rate of degradation and poor disposal methods, which posed a serious threat to the environment. Additionally, PU has multipurpose qualities such as impermeability, excellent mechanical properties, and lightweight materials [5]. The variety of properties of PU probably gives numerous possible uses in geotechnical engineering, industrial, and medical industries. It may also be used to enhance the properties of marine clay grouting [6].

In the soft soil area, expanded polystyrene (EPS) was popularly used as composite soil. This EPS has played a vital part in solving additional settling issues over soft ground in geotechnical engineering. The components of the existing EPS block in the market include EPS, soil, a binder, and water [7]. EPS is an expanded polystyrene (EPS) granule that is lightweight, environmentally friendly, and high-pressure resilient. Pre-puff EPS beads, EPS shreds, and EPS strips are among the EPS materials used in the composite soil. In soil improvement materials, fly ash is used as a binder to enhance the shear strength of materials including EPSCS [8,9]. This material offers an option for long-term EPS storage. EPSCS is particularly appealing in many geotechnical applications, including strong durability under dynamic stress and long-term monotonic loading, making it a great choice for pavement construction.

As a result, a variety of fillers must be included in foam or composite samples [10]. A filler is any substance that is added to a PU composite composition to reduce the cost or improve the characteristics. The higher the degree of the filler's surface area, the greater its stiffening ability on the PU composite [11]. Several research have been conducted to get access to the field use of PU in ground improvement [12-14]. They discovered that injecting PU into the pavement subgrade enhanced strength and stiffness, decreased volume change, and increased bearing resistance. The compressibility then rises, but the void ratio decreases. Tiwari *et al.,* [10] investigated the micro-structural geotechnical properties of expanding clay combined with EPS granules. The larger expansion and EPS were not feasible as the maximum EPS increment is 1%. The addition of lightweight EPS beads improves the engineering qualities of the expanding clay soil significantly. EPS is a non-natural ultra-lightweight aggregate with closed-cell membranes and a non-absorbent that may be easily combined with sand, clay, and chemical additives [15]. The issue with EPS is that it dissolves when exposed to liquid [16]. According to Kolar and Muller [17], they investigated the possibility of polyurethane increasing subgrade soil strength. They noticed that grouting the soils with PU improved the soil significantly.

Various researchers have studied PU as a soil enhancement material. Al-Bared and Marto [11], Azahari *et al.,* [12], Yang and Hou [13], Kemona and Piotrowska [14] and Kim *et al.,* [15] conducted a study on resin injection in clay with high plasticity and discovered that pressure meter and cone penetration test results before and after injection of PU showed a significant increase in pressure limit and soil resistance for all depths studied close to the injection point. Others researched the application of PU for road flood damage reduction. This research discussed the types of soil hard soil and soft soil which are commonly utilized as soil in road construction. To achieve a safe and sustainable structure, the polyurethane waste filler was added to the clay soil without affecting the construction schedule [17,18]. The polyurethane waste filler treatment can be categorized by microwave treatment and drying oven treatment. The summary of these studies is as Leng *et al.,* [19] and Zhang *et al.,* [20] investigated the influence of microwaves on andesite samples. It showed that the temperature of an andesite specimen reached the range of 700 °C and the specimens completely melted after being exposed to 900 W of power at a frequency of 2.45 GHz for 30 min in a multi-mode cavity.

Stabilization is the technique of blending and mixing with soil to enhance certain properties of the soil to solve the problem in clay soil [21,22]. The procedure may include blending soil to obtain the required gradation or incorporating commercially available additives, such as fly ash, that may modify the gradation, texture, or plasticity or function as a binder [10]. As a result, the focus of this research has been on the characterization of polyurethane clay composite namely PU-CC with different polyurethane filler ratios at different treatment procedures as an alternative filer to apply as soil stabilizing techniques for subgrade applications.

2. Methodology

The preparation of PU waste as filler began with the preparation of PU waste by drying process via the recycling method. The PU waste fillers namely as polyurethane filler untreated (PU-FUN), polyurethane filler treated by drying oven (PU-FTO), and polyurethane filler treated by microwave (PU-FTM). This process was conducted using a crusher machine at Chemical Laboratory Universiti Tun Hussein Onn Malaysia (UTHM).

Figure 1 demonstrated the preparation of treated PUF filler with a drying oven and microwave, respectively according to standard ASTM D1140-14 [23]. The PU waste was produced by using part of the mechanical recycling approach by drying oven method. The 500g of PU waste was soaked in 0.05 M sodium hydroxide (NaOH) solution within 40 minutes and then rinsed thoroughly with distilled water. NaOH as a cleaning agent reacts to remove the dirt from the PU waste. After that, the PU waste was treated using a drying oven from Memmert brand at 60 °C for 3 hours.

This drying process was conducted to remove the liquid content in PU waste. The process was continued with converted PU waste to particle filler size by using the grinding machine Brand Fritsch Planetary Micro Mill Pulverisette 7 made in German. The grinding condition was set up at 600 rpm and 20 minutes. The grinding bowls used is 30 pieces of grinding balls during the grinding process. The powder size of PU waste filler was sieved at 300 microns under room temperature conditions. After completing the sieving process, this powder of PU waste filler is called PU waste filler treated by drying oven (PU-FTO).

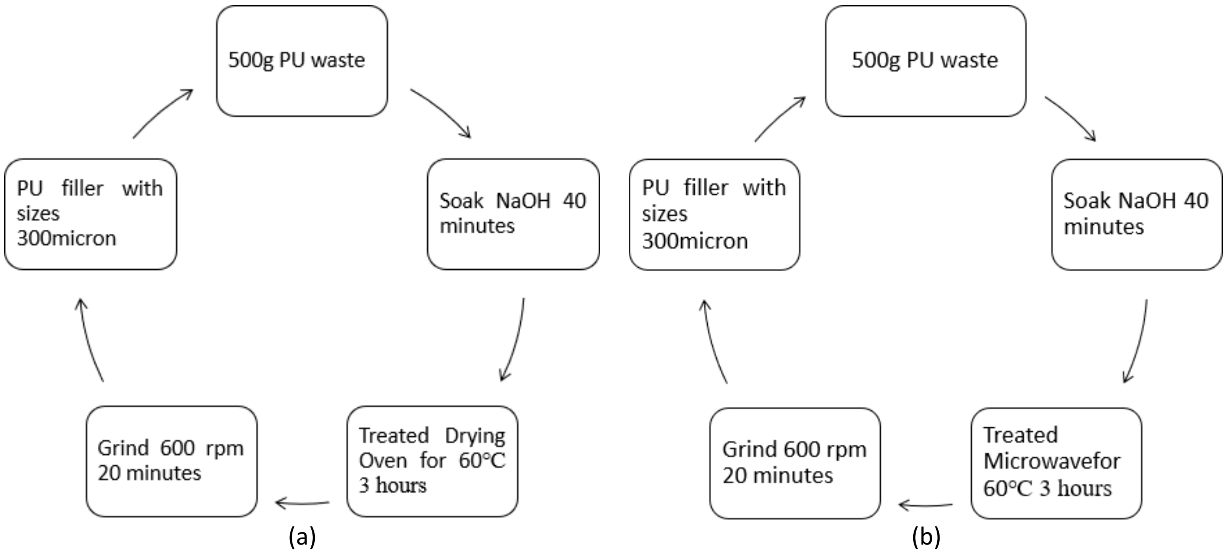

Fig. 1. Schematic diagram preparation of (a) Polyurethane waste Filler Treated Drying Oven (PU- FTO) and (b) Polyurethane Filler Treated Microwave (PU-FTM)

Figure 2 shows the fabrication process of PU-CC. The preparation of PU-CC samples was started by sieving the soft clay at 4.75 mm as follows to ASTM 4221-18 [24]. The fabrication of the PU-CC sample was initially prepared by mixing 100g soft clay and PU waste filler at different ratios of PU0%, 2.5%, 5%, 7.5% and 10% by weight of soft clay. It was categorized into four sections which is section A the soil, fly ash, and distilled water were stirred for 2 minutes with a hand mixer until obtained the homogenous conditions. While section B, isocyanate and expanded polystyrene (EPS) bead of 0.2mm were quickly stirred by magnetic stir with 1000 rpm for 2 minutes. In this stage, the colour of isocyanate was observed from yellowish colour turn to a light yellow colour. For section C, the distilled water was stirred with polyol until the mixture turn to white colour. Then, section D is prepared the PU waste filler at different ratios.

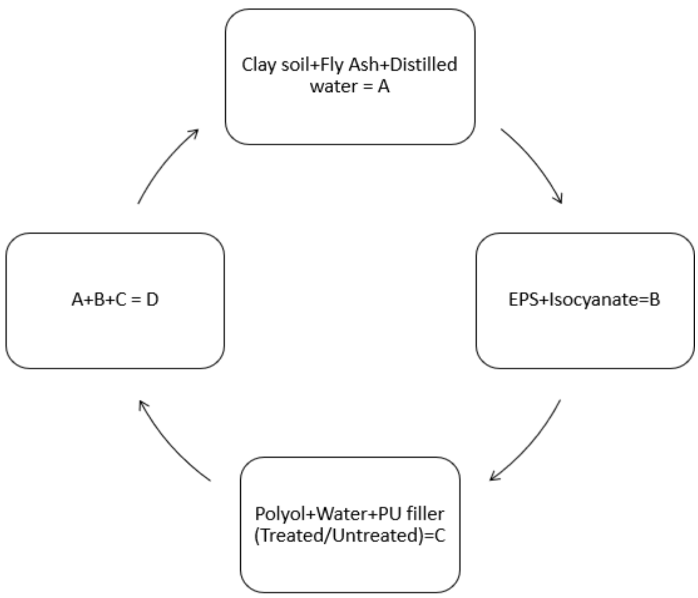

Fig. 2. Fabrication of Polyurethane Clay Composite (PU-CC) Samples

Next, all sections (A-B-C-D) were mixed in the container within 2 minutes, and the mixture was called PU-CC mixture. The PU-CC mixture was poured into containers at room temperature condition. During the process of pouring, the containers were lightly tapped on the orbital shaker at 300 rpm within 2 hours to blend all material homogeneously and removed the bubble trap during the polymerization stages. Next, the PU-CC was immediately after 2 hours, the samples were covered with a lid to avoid moisture loss. The preparation of PU-CC samples was repeated at different ratios of PU waste filler treatment such as untreated filler PU-CCUN, treated drying oven (PU-CCTO), and treated microwave (PU-CCTM), respectively.

3. Results

3.1 Buoyancy Force

Figure 3 shows the buoyancy performance of Polyurethane-Clay Composite (PU-CC) doped with treated and untreated Polyurethane Filler (PUF) at different ratios were 0%, 2.5%, 5%, 7.5%, and 10%, respectively. The different ratio of filler loading was observed gives a significant effect on the buoyancy rate of the samples. The buoyancy force of the samples shows an increase with increasing PUF filler loading. Meanwhile, as compared to different treatments, the PUCCTO gives the high buoyancy force at 10% of PU-CCTO$_{10}$ samples at 50% followed by 45% of PU-CCTM$_{10}$, and the lowest at 2.5% of PU-CCUN2.5 at 8%. This evidently shows that the treatment process of filler loading was given contribution to increasing the buoyancy force in the subgrade soil layer. According to previous researchers, the buoyant force was determined by Archimedes' Principle, and the higher of the specimen was recorded at the ranges of 25% to 40% floating on the surface in a soil application [22-24].

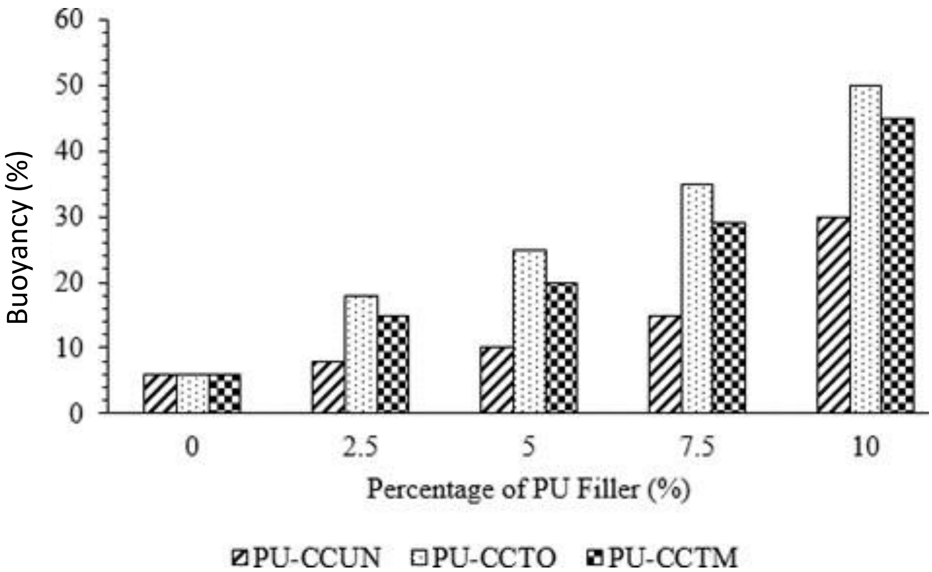

Fig. 3. Buoyancy of PU-CC at different untreated PUF filler ratios of 0%, 2.5%, 5%, 7.5%, and 10% of PU-CCUN, PU-CCTO and PU-CCTM

Therefore, the property of water was effectively incompressible in soil applications. At deeper depths, water was acts as higher absorption water in the soil and slightly affects the buoyancy of the submersible. Hence, the balance of water absorbance is dependent upon the system design and the amount of air-filled space within the submersible. The effect of buoyancy can clearly be seen as the water absorption of PU-CCUN10 is the maximum percentage of water absorption at 20% as compared to PU-CCTO10 and PU-CCTM10.

3.2 Unconfined Compressive Strength (UCS)

The maximum compressive strength of Polyurethane-Clay Composite untreated (PU- CCUN), Polyurethane-Clay Composite treated by drying oven (PU-CCTO) and Polyurethane-Clay Composite treated by microwave (PU-CCTM) with different percentages of PUF fillers (2.5%, 5%, 7.5%, and 10%) result shown in Figure 4. The results present clear changes in ratio for a better understanding of untreated compressive strength and percentage PUF treated. The results show that the minimum compressive strength of 2.5% of filler loading, PU-CCTO2.5 was 180kPa and the maximum compressive strength was 300kPa at 10% filler loading, PUF-UN10.

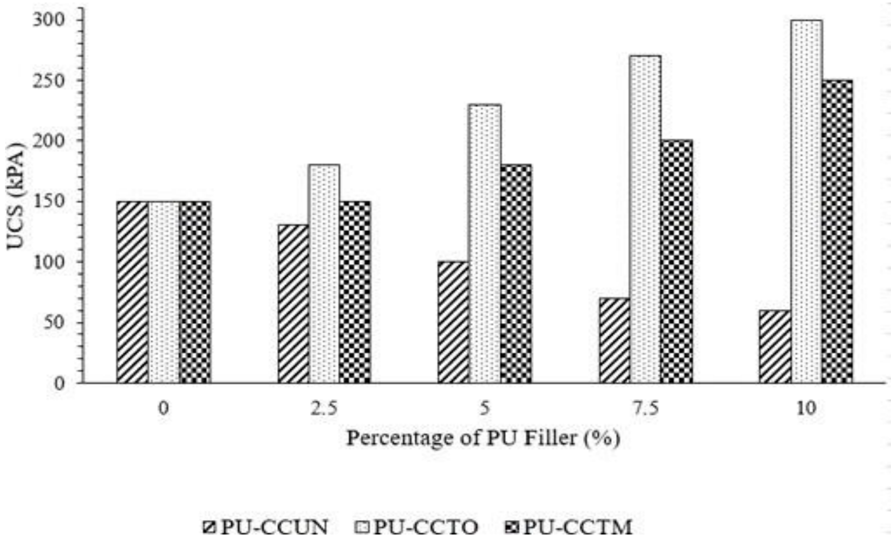

Fig. 4. Unconfined Compressive strength (UCS) of PU-CC at different untreated PUF filler ratios of 0%, 2.5%, 5%, 7.5%, and 10% of PU-CCUN, PU-CCTO and PU-CCTM

The results exhibited that the compressive strength was increased with an increase of the percentages of PUF filler for PU-CCTM and PU-CCTO, respectively. The compressive strength was recorded at the minimum ratio of 2.5% PU-CCTM at 150kPa and the maximum compressive strength at 250kPa for 10% of PU-CCTM. The maximum compressive strength is a gradual decrease of the PU-CCUN2.5 is 130 kPa followed by 60 kPa for a PU-CCUN10. This depicts that the compressive strength decreases PU- CCUN because, in 10% PU- FUN, the PU-FUN is in very low structure particles which creates a void in the soil [25-27]. These voids, when filled with water and the soil particles create a bond with the PUF treated and untreated. The reduction can be due to PU-FUN adding the clay soil and consequently a reduction in the structure area of PU-CCUN. In contrast, in the PU-CCUN specimen, the ductility of the soil behavior changes from being ductile to becoming brittle, where abrupt strength reduction occurred.

3.3 Direct Shear Strength

Figure 5 shows the maximum expansion percentage of treated and untreated PUCC composite samples. From the results, the maximum shear strength was recorded at 50kPa for PU- CCTO10. It can be noted that the increasing percentage of PU-FTO filler gives the higher shear strength as proved by the graph is directly proportional to the ratio of treated PUF. This result was followed by PU-CCTM and exhibited similarly with PU-CCTO samples recorded the maximum shear strength of 43kPa. The shear strength for maximum PU-CCUN$_{2.5}$ is 15kPa and the minimum PU- CCUN10 is 6kPa. This is because of the effect of the specimen of PU-CCUN fabrication process by using NaOH as a cleaning agent to remove dirt and impact the structure of PU-CCUN. With the lower concentration of PUF-treated content, the powder gets evenly distributed in the soft clay mix homogenously and reduces the specific surface area of hydrophilic clay minerals.

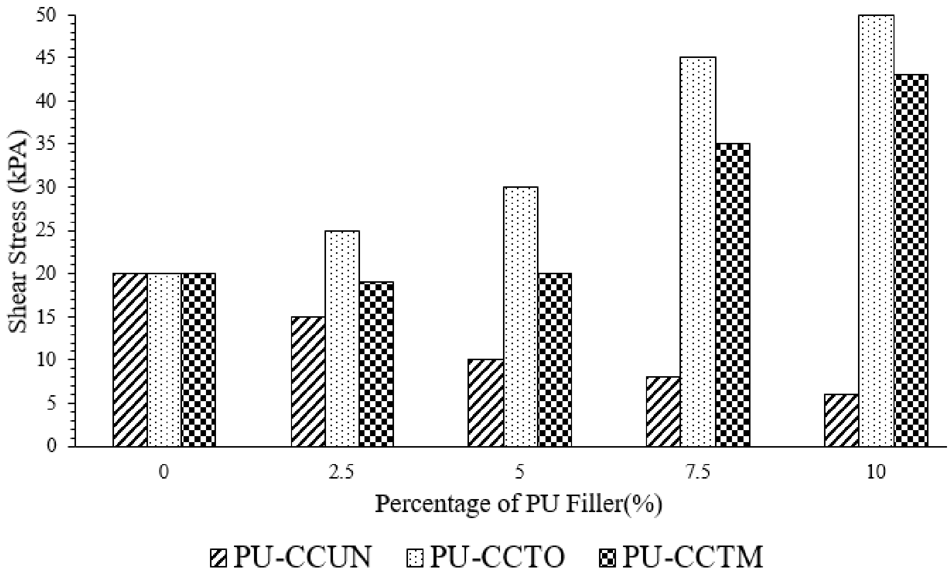

Fig. 5. Direct shear strength of PU-CC at different untreated PUF filler ratios of 0%, 2.5%, 5%, 7.5%, and 10% of PU-CCUN, PU-CCTO and PU-CCTM

Due to a reduction in the specific surface area, the nature of the reinforced soil specimens is controlled. At higher concentrations, the cluster formation due to PUF filler and clay interaction is increasing a permeable path, thereby increasing the water infiltration rate. The statement was agreed upon by Kolar and Muller [17] and Jiao *et al.,* [28] The maximum shear stress in clay soil was measured approximately at the ranges of 20kPa to 40 kPa as referred to the previous research findings. Therefore, as compared to PU-CCTO10 and other researchers, the PU-CCTO10 is successfully improved by increasing the filler of PU-FTO with a treatment drying oven at 60°C within 3 hours was proved according to the graph.

4. Conclusions

This experimental study had been conducted to characterize the potential of polyurethane clay composite (PU-CC) with different ratios of polyurethane filler at different treatment methods as an alternative to soil stabilization techniques for subgrade applications. In this study, increasing the percentage of PU-CCUN and PU-CCTO may increase the possible changes to absorb the water. While PU-CCTM changes to absorb the water are lowest due to the overheating effect and burning of PU filler. The PU-CCTO has the highest buoyancy force at 10% of PU-$CCTO_{10}$ samples at 50%, followed by 45% of PU-$CCTM_{10}$ and 8% of PU-$CCUN_{2.5}$. The UCS and shear strength of PU-$CCTO_{10}$ are evidently the highest at 300 kPa and 50 kPa, respectively, followed by PU-$CCTM_{2.5}$ at 130 kPa and 19 kPa and PU-$CCUN_{2.5}$ at 100 kPa and 15 kPa. PU-CCTO treated by drying oven has the highest buoyancy force at 10% of PU-$CCTO_{10}$ samples at 50%, followed by 45% of PU-$CCTM_{10}$ treated by microwave, and the lowest at 2.5 wt% of PU-$CCUN_{2.5}$ untreated at 8%. The use of PU filler shows significant improvement in the engineering properties of the clay soil. The modified reconstituted soils of different percentages of PU can be used for controlling the nature of the clay soil subgrade.

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