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RESEARCH ARTICLE

Strength and Compressibility of Soft Clay Reinforced with Group Crushed Polypropylene Columns

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ABSTRACT - The use of granular columns as soil reinforcement technique has proved useful in problems of foundation stability and settlement, as well as improving soft clay for foundation construction. The purpose of this study is to investigate the enhancement of shear strength of soft kaolin clay when it is reinforced with group crushed polypropylene (PP) columns. Since PP is a waste material, the cost of soil improvement can be reduced which currently was disposed totally in large quantity into landfill. In order to proceed the study, physical and mechanical properties of materials used that are kaolin (soil sample) and PP (reinforcing columns) must be identify first. Then, consolidated kaolin as soft clay was reinforced with group crushed PP columns, and subsequently tested under Unconfined Compression Test (UCT). A total of 7 batches of kaolin sample including control sample had been tested to identify the shear strength. Each batch involved of four samples to find the average value of maximum stress. The variables used for the column's installation were the column height that are 60 mm, 80 mm and 100 mm, where the column penetrating ratio are 0.6, 0.8 and 1.0 respectively. In addition, different values of columns' diameter had been used that are 6 mm and 10 mm for every different height of columns. A total of 28 unconfined compression tests had been conducted on kaolin samples. The kaolin samples had the dimensions of 50 mm in diameter and 100 mm in height. For the group PP reinforcement, shear strength increased about 2.13%, 13.51% and 12.84% for 1.44% area replacement ratio and 6.85%, 14.26% and 13.79% for 4% area replacement ratio at sample penetration ratio 0.6, 0.8, 1.0 respectively. It can be concluded that the shear strength parameters were affected by the diameter and the height of the columns and the presence of PP column greatly improve the shear strength.

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1. INTRODUCTION

Soft clays exist in most coastal plains of Peninsular Malaysia and all land including soft soil has to utilize to overcome the massive construction [1-2]. Development of activities on those sites such as road embankment, earth dams and others involve problems of stability and excessive settlement [3-4]. Structures constructed on soft soils may experience excessive settlements, large lateral flow and slope stability [5-6]. This has leads to the findings and applications of various type of ground improvement, for example granular columns. This technique is preferable because it gives the advantage of reduced settlements and accelerated consolidation settlements due to reduction in flow path lengths [7-10].

Previous studies have been proven that when the granular column is inserted into soft soil, a composite soil mass that has a greater strength and improved stiffness will be produced compared to the unreinforced soil [11-12]. The columns act as piles that transfer the structure load to greater depth. Thus, this is one of the most practical techniques to improve the mechanical properties of soft soil [8]. In detail, when the stone columns were inserted into the soft soils, a composite soil mass that has greater strength and improved stiffness will be produced compared to the unreinforced soils [13-14]. It will definitely increase the bear-ing capacity of the soils. Furthermore, stone columns also act as a vertical drain in the soils thus accelerating the dissipation of excess pore water pressure that are generated during loading [15-16]. Stone columns have also been used to improve the slope stability of the embankments on soft ground. In short, stone column can be considered as one of the most practical and versatile techniques for improving the mechanical properties of the soft soils [17].

When stone columns are installed into soft soils, they create a composite soil mass with enhanced strength and stiffness compared to unreinforced soils [18]. This results in a significant increase in the soil's bearing capacity. Additionally, stone columns function as vertical drains, facilitating the rapid dissipation of excess pore water pressure generated during loading. They are also effective in improving the slope stability of embankments constructed on soft ground [19-20]. Overall, stone columns are regarded as one of the most practical and versatile methods for enhancing the mechanical properties of soft soils.

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2. METHODOLOGY

The experimental program was designed firstly to characterize the material used which was polypropylene (obtained from Titan Petchem (M) Sdn. Bhd) and kaolin clay, followed by the shear strength tests on soft kaolin clay reinforced with a group crushed polypropylene. The summary of laboratory testing program and the standard used are as shown in Table 1.

Table 1. Laboratory Testing Program

Material	Test Name	Standard
Kaolin	Atterberg Limit	[21]
	Specific Gravity	
	Particle Size Distribution	
Polypropylene (PP)	Specific Gravity	[21]
	Particle Size Distribution	[21]
	Compaction Test	[22]
	Direct Shear Test	[23]
	Permeability Test	[24]
Soft Kaolin Clay reinforced with Group Crushed PP	Unconfined Compression Test	[25]

2.1 Installation of Bottom Ash Column

A physical models or samples were prepared in order to identify the shear strength of the kaolin clay reinforced with group crushed PP columns. For this study, a control sample was required to determine the strength of soil itself without any reinforcement, which is four samples were prepared for the control sample (Sample 25-28). Samples 1-12 were drilled using 6 mm diameter auger to produce three (3) holes to a depth of 60 mm, 80 mm and 100 mm. Meanwhile, Samples 13-24 were drilled using 10 mm diameter auger to produce three (3) holes to a depth of 60 mm, 80 mm and 100 mm. Figure 1 and Figure 2 show the detailed arrangement of columns with different area replacement ratio. Each batch of kaolin specimen contains the same penetration ratios (column height over sample height, Hc/Hs), which were 0.0 (control sample), 0.6, 0.8, and 1.0. The column diameter had two values which were 6 mm and 10 mm with area displacement ratio (column area to sample area, Ac/As) of 1.44 % and 4.0 % respectively. Sample with variables of crushed PP installation was tabulated in Table 3.2. Then, the holes of specimen were replaced by crushed PP with regular particles size range in between 1.18 mm and 3.35 mm.

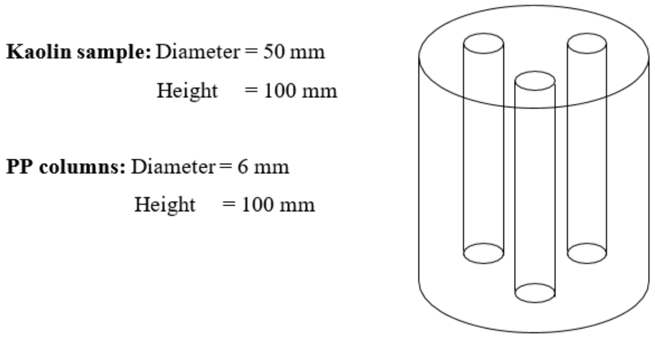

Figure 1. Column arrangement with 6 mm diameter of PP column

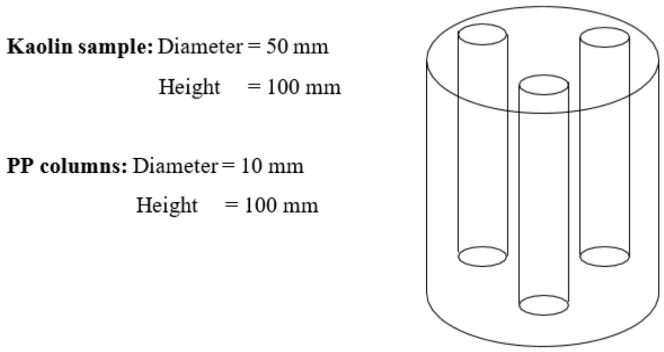

Figure 2. Column arrangement with 15 mm diameter of PP column

3. EXPERIMENTAL RESULTS

In the study, a series of laboratory testing was conducted according to the standard as mentioned in Table 1 and the shear strength of the reinforced soft clay with group crushed polypropylene column was tested. There are five (5) types of laboratory testing conducted in the study which includes Atterberg limit, particle size distribution, compaction, permeability, and unconfined compression test.

3.1 Atterberg Limit

From the experiment, the value of PL is 28 % meanwhile LL of kaolin is 38.43 % at 20 mm penetration as shown in Figure 3. Therefore, the PI for kaolin is about 10.43 %. Thus, clays of high plasticity are likely to have a lower permeability, to be more compressible and to consolidate over a longer period of time under load than clay of lower plasticity. As compared with other study that had been done by Zaini et al. [9], the value of PL and LL are 26 % and 37 % respectively, which give the value of PI about 11%. By referring this study with others, it can be concluded that the values of PI are almost similar.

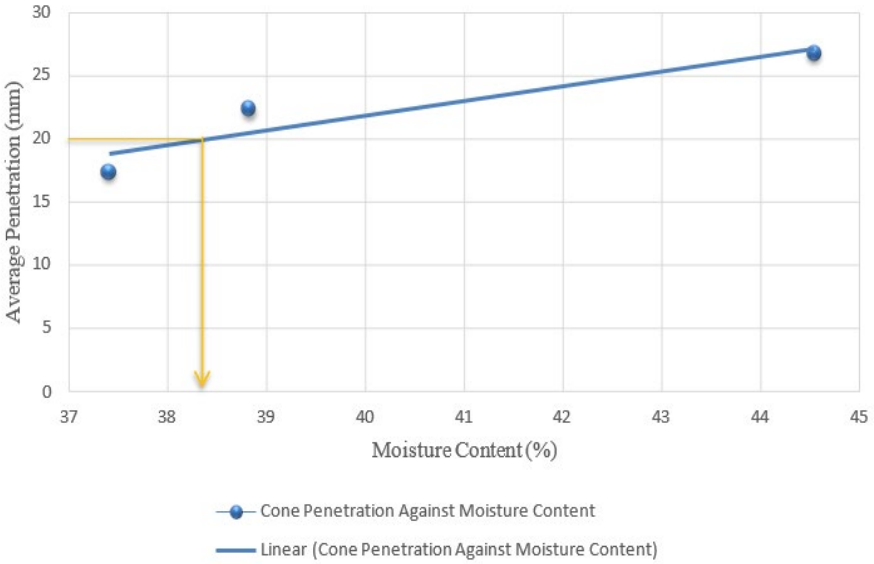

Figure 3. Graph of penetration versus moisture content for liquid limit test of kaolin clay soil

From the plasticity chart shown in Figure 4, the kaolin is stated under A-line that generally separates the more claylike materials from silty materials, and the organics from the inorganics. Therefore, kaolin can be categorized as ML. Kaolin with the LL of 38.43 % and PI of 10.43 % can be categorized as low plasticity silt, or inorganic silts of medium compressibility and organic silts. In the ML group are included very fine sands, rock flours, and silty or clayey fine sands on clayey silts with slight plasticity. Loses type soils usually fall into this group.

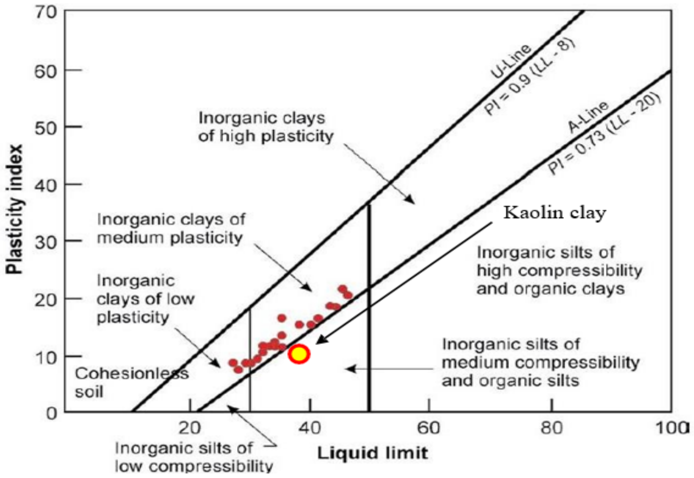

Figure 4. Plasticity chart

3.2 Particle Size Distribution

Figure 5 shows the particle size distribution of kaolin which had performed by using the combination of sieve analysis test and hydrometer test. Based on ASTM D3282 [26] Classification System the kaolin was classified as silty soils (Group A-4). The kaolin was well graded, where the sizes ranging from fine silt to fine sand. From the distribution curve plotted, we got 0.018 as a diameter in the particle-size distribution curve corresponding to 10 % finer. The effective size of a granular soil is good to estimate the hydraulic conductivity and drainage through soil. We also get 3.89 as a uniformity coefficient (Cu) and 1.27 as a coefficient of gradient (Cc). For sorting coefficient (So), we have 1.67 as a parameter of uniformity. It was also noted that 97 % of kaolin particle was passing 0.15 mm, while about 51 % passing 0.063 mm sieve size. Therefore, based on ASTM D3282 [26], the classification is Group A-6.

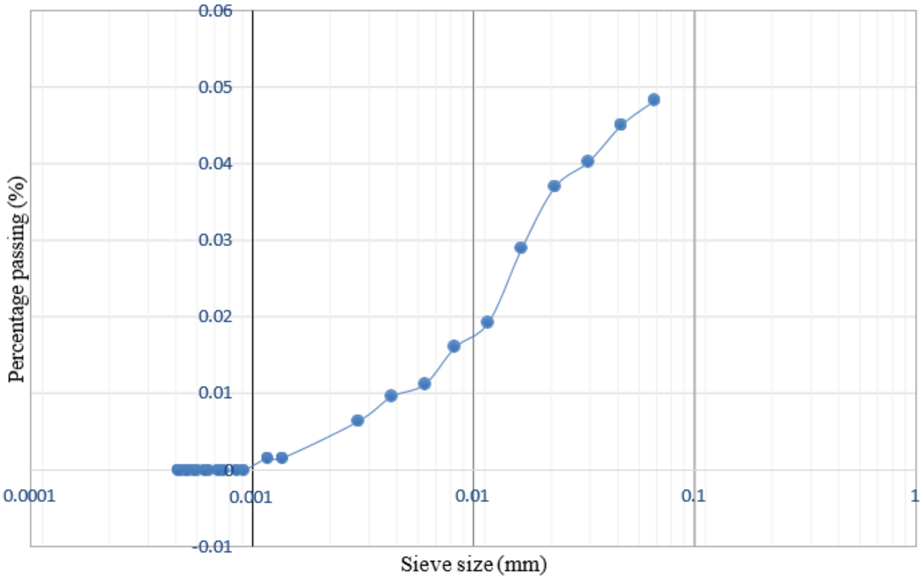

Figure 5. Particle size distribution of soft kaolin clay

In the other hand, the particle size of PP is shown in Figure 6 which had conducted using dry sieve analysis method. PP comes in several shape, size and colour. Some in pallet form, round shape, flakes shape with white, gray, black even with colourful color. So, PP used as material in this study was obtained from Titan Petchem (M) Sdn. Bhd which is in pallet form with white colour. Thus, from the test conducted, the size of PP mainly occurred in a range between 1.18 mm to 3.35 mm. As predicted, 50% of PP was retained at 3.35 mm sieve size, while 48% of PP was retained at 1.18 mm sieve size.

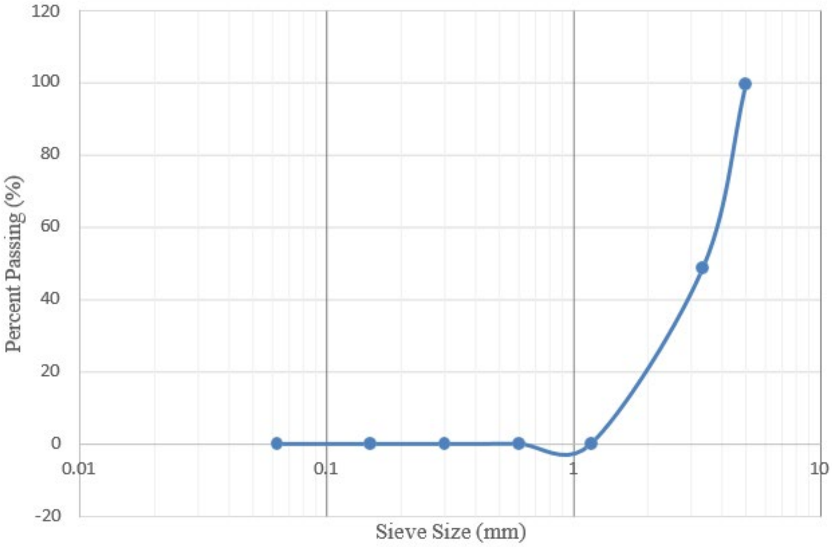

Figure 6. Particle size distribution of polypropylene

3.3 Compaction Behaviour

Figure 7 shows the result of relationship between dry unit weight versus average moisture content of kaolin. From the graph, the maximum dry density, $\rho_{d(max)}$ was 1.53 g/cm^3 (15.35 kN/m^3) with the optimum moisture content is about 19.50 %. The optimum water content is the water content that results in the greatest density for a specified compactive effort. Compared with Zaini et al. [9], the values of maximum dry density and optimum moisture content for kaolin are quantitatively similar, which are 1.60 Mg/m^3 and 20 % respectively. Basically, the variations of compaction characteristics are mainly due to the low specific gravity and high void content. Compacting at water contents higher than (wet of) the optimum water content results in a relatively dispersed soil structure (parallel particle orientations) that is weaker, more ductile, less pervious, softer, more susceptible to shrinking, and less susceptible to swelling than soil compacted dry of optimum to the same density. The soil compacted lower than (dry of) the optimum water content typically results in a flocculated soil structure (random particle orientations) that has the opposite characteristics of the soil compacted wet of the optimum water content to the same density.

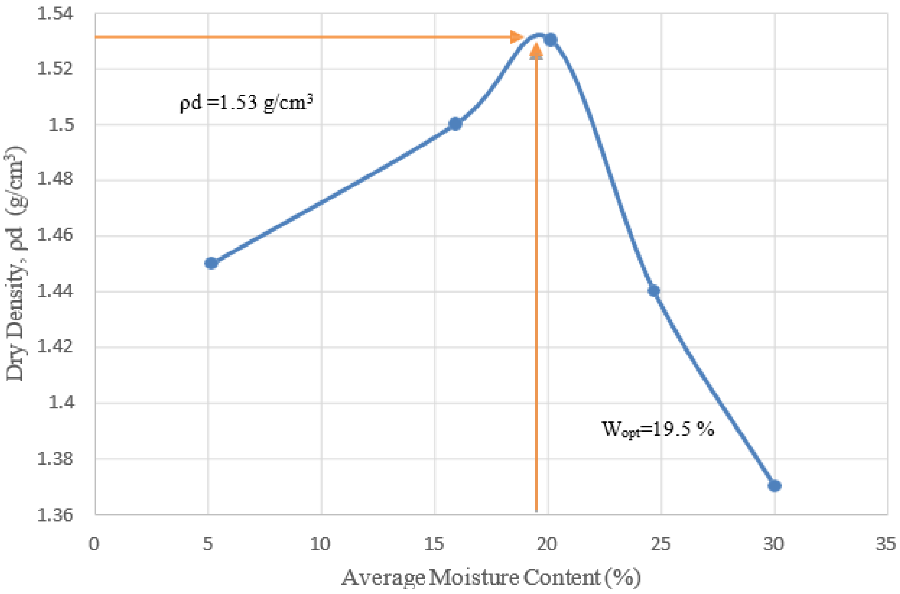

Figure 7. Compaction curve of kaolin

3.4 Permeability

Falling head permeability test is used for measuring the permeability of soils of intermediate and low permeability (less than 0.0001 m/s). The falling head method of determining permeability is used for soil with low discharge, whereas the constant head permeability test is used for coarse-grained soils with a reasonable discharge in a given time. For very fine-grained soil, capillarity permeability test is recommended. From the experimental results, we obtained the coefficient of permeability for manometer tube 1, 2 and 3 (T1, T2 and T3) as 8.282×10^{-12} m/s, 2.748×10^{-12} m/s and 3.387×10^{-12} m/s respectively. According to Head [6] and Zaini et al. [9], the value obtained for kaolin shows the impermeable behavior of kaolin and indirectly indicates its poor drainage characteristics, which generally corresponds to clay. By referring study that had been done by Zaini and Hasan [1], the value of permeability coefficient of kaolin obtained from the falling head permeability test was 2.58×10^{-10} m/s at maximum dry density 1.60 Mg/m³. According to Zaini et al. [9], the value obtained for kaolin shows the impermeable behavior of kaolin and indirectly indicates its poor drainage characteristic, which generally corresponds to clay. Basically, the water is able to pass through the soil is because the voids between the solid particles in soil are interconnected. There are various factors that affect the soil void. They are particle, particle size, particle shape and texture, size distribution, void ratio and mineralogical composition. Typically, when the particles are smaller, the voids between them are smaller too. Hence, the resistance to flow of water increases which will result in the decreases of permeability. Furthermore, Zaini et al. [9] stated that void ratio has a significant influence on the permeability because it may change considerably depending on how soil is place or compacted.

3.5 Unconfined Compressive Test

The shear strength of the reinforced soft kaolin clay with group crushed polypropylene was measured by using the UCT test. This test is limited to determine the shear strength of the cohesive soils only because since there is no lateral support. Table 2 shows the summary of analysis done on the results of unconfined compressive test. For the controlled sample which is the sample without reinforcement, the average shear strength is 22.38 kPa. Besides, for samples reinforced with 6 mm diameter of PP column with 0.6 column penetration ratio, the average shear strength is 22.84 kPa, which the increment is about 2.13 %. As for 0.8 column penetration ratio for 6 mm diameter column, the average shear strength is 25.39 kPa which indicates an increase of 13.51 %. For 1.0 column penetration ratio (fully penetrating), the average shear strength is about 25.24 kPa and gives the improvement to 12.84 %. Basically, there are only a small improvement of shear strength obtained which is less than 20%. From the observation, high improvement might happen with the high scale of the test sample. So that soft clay can behave naturally and PP columns can act like solid mass of column just like in actual field work. In the other hand, for samples reinforced with 10 mm diameter of PP column with 0.6 column penetration ratio, the average shear strength is 23.90 kPa, which the increment is about 6.85 %. As for 0.8 column penetration ratio for 10 mm diameter column, the average shear strength is 25.56 kPa which indicates an increase of 14.26 %. For 1.0 column penetration ratio (fully penetrating), the average shear strength is about 25.45 kPa and gives the improvement to 13.79 %. Both result for 6 mm and 10 mm diameter of column show a consistent increment of shear strength.

Table 2. Summary of analysis on unconfined compressive test

Sample	Number of Columns	Column Diameter (mm)	Area Ratio, A_c/A_s (%)	Column Height (mm)	Average max. deviator stress, q (kPa)	Average Shear Strength (kPa)	Improvement of shear strength (%)
C	0	0	0	0	44.73	22.37	-
6-60	3	6	1.44	60	45.69	22.85	2.13
6-80				80	50.78	25.39	13.51
6-100				100	50.48	25.24	12.84
10-60		10	4.00	60	47.80	23.90	6.85
10-80				80	51.12	25.56	14.26
10-100				100	50.90	25.45	13.79

However, 10 mm diameter give higher increment of shear strength compared to 6 mm diameter column. To conclude, area of columns gives a big influenced to modify the strength of soft soil. From the graph, the shear strength of the specimens increases after being reinforced with group PP columns and similar behavior was obtained in 1.44 % and 4 % area replacement ratio with different penetration ratio 0.6, 0.8 and 1.0. The pattern of shear strength increases was shown in Table 4.12. In both cases of group columns, the pattern of increment of shear strength are almost similar which it increased from 60 mm height of columns until it reached 80 mm height. But, when the columns reinforced was 100 mm in height, the shear stress immediately decreases slightly. The results are in a good agreement with an investigation conducted by Zaini nd Hasan [1].

4. CONCLUSION

The purpose of this study is to investigate the enhancement of shear strength in the soft kaolin clay when it is reinforced with the bottom ash. Kaolin was classified as low plasticity silt (ML) with a specific gravity of 2.62, maximum dry density of 1.53 g/cm³, and optimum moisture content of 19.50%. The PP columns, with diameters ranging from 1.18 mm to 3.35 mm, were found to have a low specific gravity of 0.9 g/cm³, offering good bulk and cover. The installation of PP columns significantly increased the shear strength of the soft clay, with improvements influenced by the area replacement ratio and column penetration ratio. The greatest shear strength increase was observed with a 10 mm diameter column at a 0.8 penetration ratio, showing a 14.26% improvement. The study also confirmed the concept of a 'critical column length,' beyond which no further shear strength increase was observed, indicating a higher risk of column failure.

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AUTHOR CONTRIBUTIONS

Muhammad Syamsul Imran Zaini: Original draft preparation, Conceptualization, Methodology, Software
Muzamir Hasan: Supervision
Nuraini Yusuf: Laboratory works

DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included within the article.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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