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A Study of the Relationship Between the Liquid Limit and the Shear Angle of Fully Softened Clay with Residual Clay in Problematic Clay Formation in Tulungagung Regency

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Keywords
Batulempung; Fully Softened Shear Strength; Residual Shear Strength; Liquid Limit.

ABSTRACT
The distribution of problematic clay rocks, also known as clay shale or stiff overconsolidated clay (overconsolidated clay), in Indonesia is not widely recognized or understood by the public or construction practitioners regarding the potential characteristics and behavior of these materials. Problematic clay stone is a type of clay rock that exhibits significant shrinkage properties, particularly when exposed to water and subjected to the loss of overburden pressure. These characteristics can lead to geotechnical problems, such as soil movement and damage to building structures founded on these materials. The objective of this study was to identify the fully softened and residual shear strength values; the researcher also examined the correlation between the liquid limit and the shear strength parameters of these soil types. Consolidated drained triaxial testing was conducted under normally consolidated conditions. The data collected by the researcher were obtained from problematic clay soils in Tulungagung Regency, which exhibited a shear stress–normal stress curve pattern similar to that of Bearpaw Shale, showing nonlinear behavior under fully softened conditions and more linear behavior under residual conditions. The results of the study indicate that the characteristics of problematic clay fall into the category of high-plasticity clay and exhibit high sensitivity to changes in moisture content. The relatively high swelling potential indicated by the Free Swell Index (FSI) test, which reached 65%, was classified as having medium to high swelling potential based on the swelling potential classification. High plasticity and swelling potential reduce shear strength ($\varphi r < \varphi fs$), indicating that progressive failure mechanisms may influence slope stability.

INTRODUCTION

The distribution of problematic clay rocks, also referred to as clay shale or stiff OC (overconsolidated clay), in Indonesia is not widely recognized or understood by the community or construction practitioners regarding the potential hazards associated with the characteristics of these rocks (Sudrajat et al., 2023; Xu et al., 2018). Problematic claystones are found in many areas of East Java Province (Erlangga et al., 2024). The distribution of problematic clay formations includes Tulungagung, Jember, Mojokerto, Tuban, and Probolinggo, among others.

Based on the distribution map of problematic clay rocks, the study area is included within the problematic clay rock zone of Tulungagung Regency, East Java Province (Sadono et al., 2017). According to the Indonesian geological map system, this area is classified as a region with problematic clay distribution. The study location is part of the Campurdarat Formation (Tmcl), which consists of crystalline limestone with intercalations of carbonate claystone.

The shear strength parameters of soil are essential for analyzing soil slope stability, including bearing capacity, slope stability, and retaining wall stability (Abdila et al., 2021; Tiwari & Ajmera, 2011). These parameters can be obtained through direct shear testing. The correlation between the liquid limit and residual shear angle of 32 natural clay soils was established by plotting the relationship between the liquid limit and the fully softened shear angle (Chu & Wana-towski, 2008; Einav, 2007). The two correlations were further developed by Stark and Hussain (2013) by incorporating additional soil types, increasing the number of data points, extending the residual strength correlation to include an effective normal stress of 50 kPa, and proposing an empirical equation to describe the correlation based on the liquid limit value and clay-size fraction (Fanni et al., 2024).

Despite these advancements, a significant research gap remains regarding the specific behavior of problematic clay in Tulungagung Regency (Fitri et al., 2023; Khusna et al., 2023). Most existing studies focus on general clay behavior without addressing the unique characteristics of local problematic clay formations, particularly the relationship between the liquid limit and both fully softened and residual shear strength parameters under local geological conditions. Furthermore, a comprehensive investigation integrating swelling potential, durability, and shear strength behavior within a single study for this region has not been adequately conducted.

Therefore, this study aims to (1) determine the fully softened and residual shear strength values of problematic clay in Tulungagung Regency through direct shear testing; (2) examine the correlation between the liquid limit and both shear strength parameters; and (3) evaluate the physical and mechanical properties, including swelling potential and durability, that influence the engineering behavior of these problematic clays. The findings of this research are expected to contribute to a better understanding of problematic clay behavior in the study area and provide empirical data for more reliable slope stability assessments and geotechnical construction practices. Additionally, the results may serve as a reference for infrastructure planning and disaster mitigation strategies in regions with similar geological conditions throughout Indonesia.

METHOD

A method is a systematic approach used to conduct and evaluate an investigation. This study aimed to determine the relationship between fully softened and residual shear angles and the liquid limit of problematic claystones (Wang et al., 2020). The study focused on problematic claystones distributed in Tulungagung Regency, which have frequently contributed to landslides and ground movements that may cause geotechnical hazards (Hoang & Bui, 2018). The physical and mechanical properties of the soil were investigated, including fully softened and residual shear strength parameters, through slow reversal direct shear testing (Hardiyatmo, 2019; Miao & Wang, 2022). The study also included problem identification and a review of relevant literature. The research was conducted at the Soil Mechanics Laboratory, Department of Civil Engineering, Faculty of Engineering, Diponegoro University.

This laboratory-based study used soil samples collected from three locations in Tulungagung Regency, which were underlain by the Campurdarat Formation. The testing program included physical property tests (moisture content, specific gravity, Atterberg limits, grain size distribution, free swell index [FSI], and slake durability) and mechanical property tests (direct shear testing under normal loads of 5, 10, and 15 kg to determine fully softened shear angle [φ_fs] and residual shear angle [φ_r], as well as consolidation testing). The data were analyzed using descriptive statistics, regression analysis to evaluate the correlation between liquid limit and shear angles, the Mohr–Coulomb failure criterion, and comparative analysis of strength reduction behavior. The research methodology is presented in Figure 1.

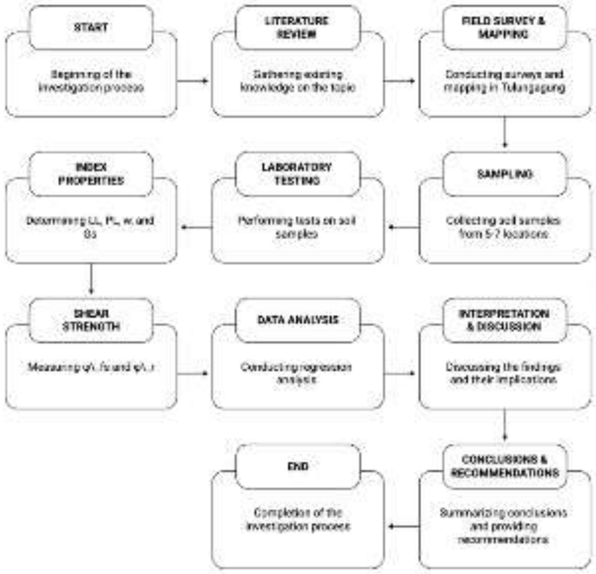

Figure 1. Detailed methodology

Source: Author's documentation, 2026

RESULT AND DISCUSSION

The process of compiling data from laboratory testing results and analysis of parameters that affect the behavior of problematic claystones in East Java Province is ongoing. The analysis focused on the relationship between liquid limit (LL) and fully softened shear angle as well as residual shear angle (Duong & Suzuki, 2022; Lian et al., 2020).

Research Data

Compilation of data from laboratory tests on soil samples from several research locations in Tulungagung Regency. The data compiled includes property index parameters, physical characteristics of the soil, as well as additional test results used to determine soil classification and its engineering behavior (Das, 2019; Raj Bhat, 2022). All data obtained are then compiled and grouped based on the region of origin of the sample to facilitate the analysis process (Wang et al., 2020; Wu et al., 2021).

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Figure 2. Existing research location

Source: Author's documentation, 2026

Technical Data

Data on the mechanical properties of problematic clay stones were obtained through direct shear slow reversal testing carried out on samples prepared by the slurry method. The test was carried out to obtain shear strength parameters in fully softened and residual conditions, which were subsequently used in slope stability analysis as well as evaluation of soil behavior against large deformations (Bardanis, 2024; Rizki Abdila et al., 2020). The main parameters obtained from the test include the fully softened shear angle (φfs) and the residual shear angle (φr). The value of the fully softened shear angle describes the condition of the soil after undergoing a softening process due to water saturation, while the residual shear angle indicates the condition of the minimum shear strength after repeated large shear deformation (Hardiyatmo, 2011; Kırım & Cebeci, 2020).

Tulungagung Regency Index Properties Testing

The data compiled included moisture content (w), specific gravity (Gs), soil volume weight, Atterberg Limits (LL, PL, PI), filter and hydrometer analysis, free swell test, and slake durability test. The test data is used to classify soil types, determine the level of plasticity, and identify potential swelling and soil resistance to weathering. To illustrate the variation in soil characteristics, testing was carried out on 3 samples from Tulungagung Regency. Here are the results of the moisture content, specific gravity and atterberg limits tests:

Table 1. Water content (w) test results

Cup Weight + Wet Ground (g)	Cup Weight + Dry Ground (g)	Cup Weight(g)	Water Content (%)
(W1)	(W2)	(W_c)	(W)
39,54	31,10	4,25	31,43

Source: Laboratory test results, 2026

In general, the test results show similar characteristics but there are some significant differences in index parameters. The value of natural moisture content was obtained at 31.43%.

Table 2. Soil volume weight

Tulungagung Soil Samples	Experiment

		1
Weight of empty cups	(a)	24,74
Cup weight + wet sample	(b)	34,15
Wet sample weight (b-a)	(c)	9,41
Cup weight + mercury	(d)	97,01
Mercury weight (d-a)	(e)	72,27
Mercury specific gravity (BJ)		13,6
Mercury volume	(e/BJ)	5,31
γb wet soil	(c/vol)	1,77
γb Sample 1 Tulungagung		**1,77**

Source: Laboratory test results, 2026

The relatively moderate weight of the soil volume indicates that the material still has a considerable porosity. In soils with high plasticity, soil structures generally have a less dense particle composition due to high micropore content.

The results of the Atterberg Limits test on oven-dried conditions show:

Liquid Limit (LL) = 70,84%

Plastic Limit (PL) = 43.84%

Plasticity Index (PI) = 27,00%

Meanwhile, in the condition of no oven-dried, the following are obtained:

Liquid Limit (LL) = 106,15%

Plastic Limit (PL) = 47.52%

Plasticity Index (PI) = 58,63%

There is a significant increase in the liquid limit value in the no-oven-dried condition. This suggests that the process of drying the oven causes changes in the microstructure and bonds between clay particles. This phenomenon indicates the sensitivity of materials to changes in moisture content. A very high LL value (>50%) classifies the material into the category of high plasticity clay.

Mechanical Properties Testing

The main parameters obtained from the test include the fully softened shear angle (φfs) and the residual shear angle (φr). The value of the fully softened shear angle describes the condition of the soil after undergoing a softening process due to water saturation, while the residual shear angle indicates the condition of the minimum shear strength after repeated large shear deformation. The results of the data compilation show that the value of φfs is 26.89°, while φr is 14.52°. Lower residual values compared to fully softened indicate a decrease in shear strength due to changes in the orientation of clay particles during the deformation process.

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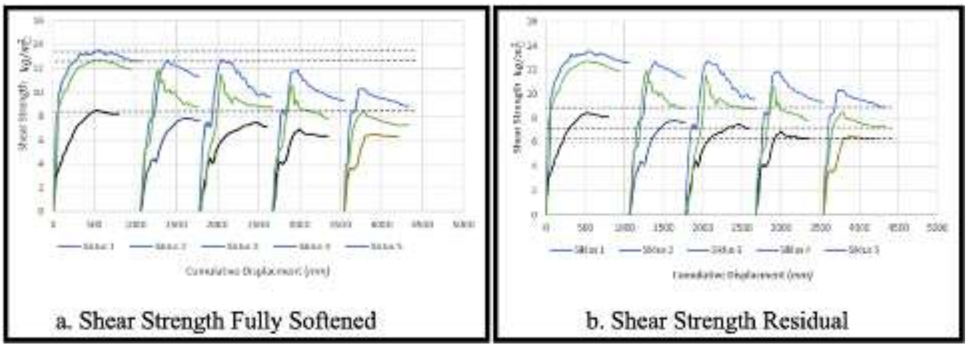

Figure 3. Shear Strength Fully Softened and Residual

Source: Laboratory test results, 2026

The results of the data compilation show that the value of φfs is 26.89°, while φr is 14.52°. Lower residual values compared to fully softened indicate a decrease in shear strength due to changes in the orientation of clay particles during the deformation process.

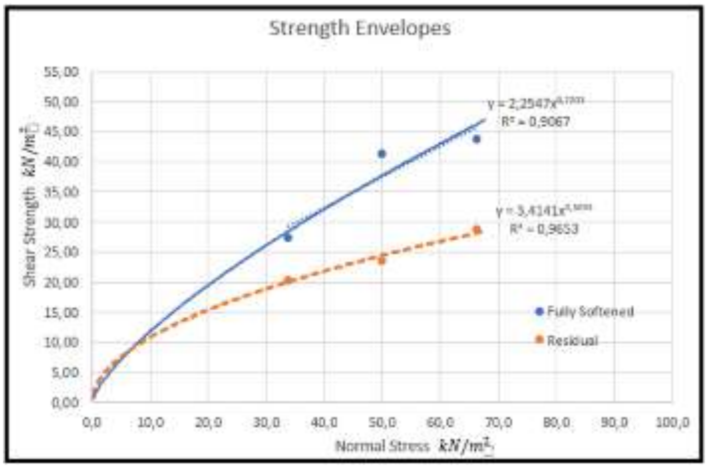

Figure 4. Strengt Envelopes Fully Softened and Residual

Source: Laboratory test results, 2026

Liquid Limit has a relationship to the shear angle of fully softened and residual. The results of the regression analysis showed that Liquid Limit had a negative relationship with the shear strength parameter.

Analysis of Liquid Limit Characteristics

Analysis of liquid limit characteristics was carried out to determine the level of soil plasticity and identify potential shrinkage behavior in problematic clay stones. The test results showed that the liquid limit value of the Tulungagung Regency sample was 80.37%. Based on the plasticity classification, most samples fall into the category of high plasticity. A high liquid limit value indicates the ability of the material to absorb large amounts of water so that it has the potential to experience significant volume changes. The distribution of liquid limit values is shown in the following Figure:

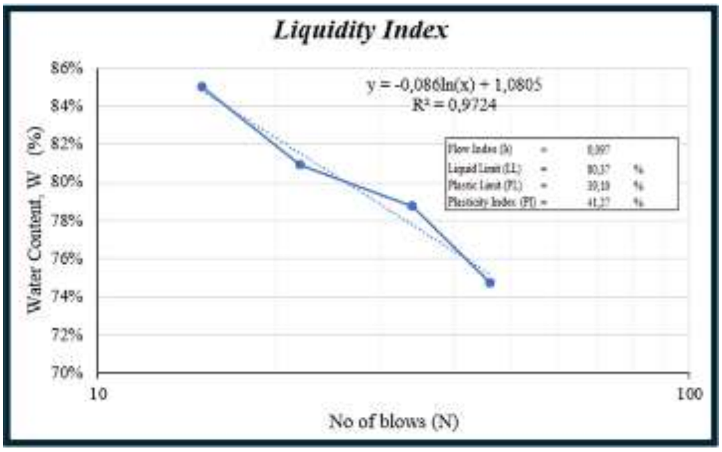

Figure 5. Liquid Limit Value Distribution

Source: Laboratory test results, 2026

In general, it can be seen that the increase in the LL value is directly proportional to the increase in swelling potential. This is in accordance with the theory of expansive soil behavior which states that soils with high plasticity tend to deform due to changes in moisture content.

Shear Angle Analysis

The fully softened sliding angle is obtained from the peak condition after the sample has been softened due to saturation. The results of the Tulungagung Sample 2 test showed a value of φfs = 26.89°. This value indicates variations between samples that are influenced by:

1. Plasticity level
2. Mineral content of clay
3. Soil microstructure
4. Until air

The relationship between the liquid limit value and the fully softened sliding angle is shown in Figure 8.

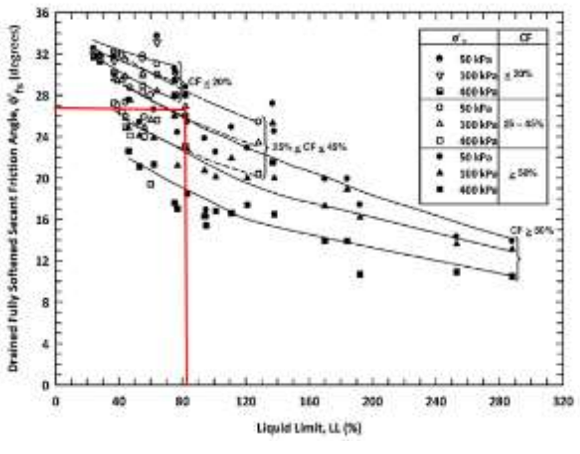

Figure 6. Relationship of LL to φfs

Source: Laboratory test results, 2026

The residual shear angle is obtained after the sample undergoes repeated large shear deformation. The test results showed a residual shear angle value of 14.52°. This decrease in shear strength indicates a change in the orientation of the clay particles towards conditions

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parallel to the direction of shear. A comparison of residual and fully softened values showed that the conditions reflected a progressive failure mechanism common in plastic clay soils.

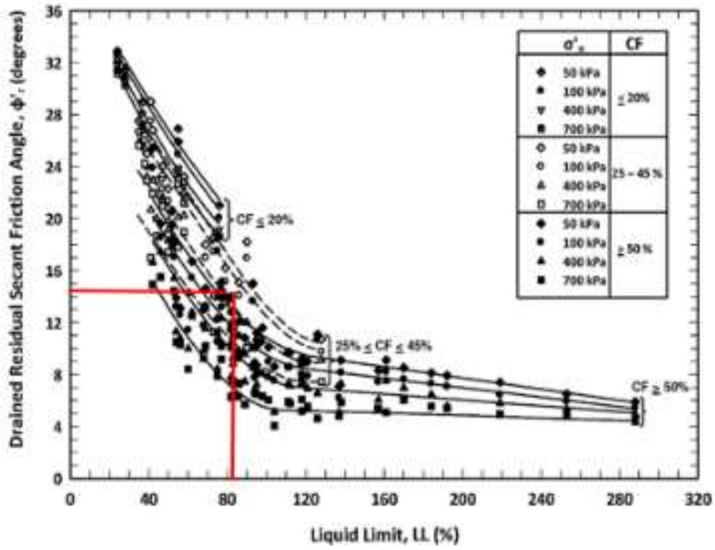

Figure 7. The relationship of LL to φr

Source: Laboratory test results, 2026

Variable Analysis

Variable analysis was carried out to identify the relationships between the parameters used in the study and determine the degree of influence of each variable on the geotechnical behavior of problematic claystones. The research variables are arranged based on the research objectives, problem formulation, and theoretical approaches used in the development of an empirical model of the relationship between Liquid Limit (LL) and the shear strength parameters. In this study, variables are differentiated into independent variables, dependent variables, and supporting variables.

The independent variable or independent variable used in this study is Liquid Limit (LL). The Liquid Limit was chosen because it is one of the most commonly used index parameters to describe the plasticity characteristics of clay soils. The LL value indicates the limit moisture content when the material changes from a plastic state to a liquid state. The results of laboratory tests showed that the Liquid Limit value of Tulungagung 2 clay stone was 80.37%. This value indicates that the material has high plasticity and is very sensitive to changes in moisture content. A high LL value indicates that the material has the ability to absorb large amounts of water so it has the potential to experience volume changes and a decrease in strength.

The dependent variables or bound variables in this study consist of, fully softened shear angle (φfs) and residual shear angle (φr). Both parameters were chosen because they play an important role in the analysis of slope stability, especially in clay materials that undergo large deformations. A fully softened shear angle describes the strong shear condition after the material has been softened due to saturation, but has not undergone a large shear deformation. While residual shear angle describes the shear strength condition after the internal structure of the material has been damaged and the orientation of the particles tends to be parallel to the shear plane. In this study, parameters were obtained through Direct Shear Test testing with normal load variations of 5 kg, 10 kg, and 15 kg. Analysis based on Mohr–Coulomb collapse criteria yielded Φfs = 26.89° and φr = 14.52°. The difference in values shows a decrease in shear resistance due to large deformation. This phenomenon indicates the occurrence of softening strains that are commonly found in plastic clay stones.

CONCLUSION

Based on the results of laboratory testing, data processing, statistical analysis, and discussion of the relationship between the liquid limit (LL), fully softened shear angle (φ_fs), and residual shear angle (φ_r) of problematic clay in East Java Province, the following conclusions were obtained:

1. The characteristics of problematic clay in East Java Province indicate that the material is classified as high-plasticity clay and exhibits high sensitivity to changes in moisture content. These characteristics indicate a relatively high water absorption capacity, which may lead to significant volume changes and a reduction in shear strength.
2. Problematic claystones exhibit relatively high swelling potential. The Free Swell Index (FSI) test results showed a value of 65%, which is classified as having medium to high swelling potential. This high swelling value indicates that the material tends to increase in volume when exposed to water. Such conditions may cause geotechnical problems, including pavement cracking, slope deformation, and reduced structural stability.
3. The durability of the problematic claystone was classified as very low. The Slake Durability Index (Id_2) test results showed a value of 7.56%. Based on the Franklin and Chandra classification, this value falls within the Very Low Durability category. A very low durability value indicates that the material is highly susceptible to disintegration under repeated wetting and drying cycles.
4. The direct shear test results demonstrated strain-softening behavior. Based on direct shear testing under normal loads of 5 kg, 10 kg, and 15 kg, the obtained shear strength parameters were:

Fully softened shear angle (φ_fs) = 32°

Residual shear angle (φ_r) = 28°

The relationship φ_fs > φ_r indicates a reduction in shear resistance due to large deformation. This reduction is associated with the reorientation of clay particles into a more parallel arrangement along the shear plane, resulting in decreased interlocking between particles. This behavior represents a progressive failure mechanism commonly observed in highly plastic claystones.

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