

EFFECT OF GGC (*GEOFOAM GRANULE COLUMN*) ON ACCELERATION OF SETTLEMENT IN SOFT SOIL

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ABSTRACT

Soft soils has low bearing capacity and high compressibility which is potentially damage the structure laid above it. An effort is taken to use EPS beads to form GGC will accelerate of consolidation process. The purpose of study to investigate the influence of density and diameters of GGC against strength and settlement. Triaxial test are conducted to identify the shear strength parameter after consolidation test were done. The equivalence value of permeability (k_{ve}) is calculated using the Chai Method (2001) by considering smear effect. Test results showed that the settlement of soft soil in 90 degree consolidation reached in short period of time upon for smallest density and largest diameter of GCC.

Keywords : *Consolidation, equivalence of permeability, GGC, settlement, strength, smear effect, soft soil*

1. INTRODUCTION

Lately, the construction of freeway in Indonesia has been developed immediately to connect the city. One of those construction is Gempol-Pasuruan Freeway as a part of the Trans-Java Freeway. Soil characteristics of the Kedawung Wetan area can be classified as very soft soils with a depth of 11-13 m from the SPT value <1 [1]. This research will discuss soft soil structure founded at STA+32.000 from more than 10 m depth [2]. This condition will cause the consolidation process to take a long time which has an impact on construction progress. It causes great distress to freeway structures laid on soft soil and can endanger users. Then its necessary to stabilize soft soil in Gempol-Pasuruan Freeway at STA+32.000 [3].

Stabilization in this study use materials of polymer based product such as geosynthetics, and one of them called geof foam. Besides being easily obtained, geof foam is a lightweight material [4] and have been reported by few researchers as a stabilizer of soft soil [5]. Geof foam granules will be formed GGC (*Geof foam Granule Column*) by varying density and diameter. Undisturbed and stabilized soft

soil condition will be tested in laboratory such as : Falling Head Permeability test, Consolidation test, and Triaxial UU test. Those tests give parameters i.e. coefficient permeability of soil (k), compressibility index (C_c), and shear strength (c and ϕ). Analytical calculation gives results to the degree of consolidation (U) and settlement (S) for stabilized soft soil with the GGC.

Previous researchs [6] gave assumptions that GGC worked like PVD could shorten the time of consolidation for clay soil. Installation of PVD in the soil should consider the smear effect came from mandrel which can create the diameter (d_s) and coefficient permeability of smear (k_s). This assumption is used in this study as an approach to the field condition.

Chai (2001) method, is used in analytical calculations of the equivalent permeability coefficient (k_{ve}) due to the smear effect. In its use, Chai Method is also used for equivalence of numerical calculations from *Axisymmetry* modeling to *Plane Strain* [7]. In this study the method is used only for analytical calculations k_{ve} only.

2. LITERATURE

2.1 Settlement of Consolidation

Consolidation is process of reducing volume on saturated soils due to the release of pore water, causing a settlement in soil [8]. Maruto consolidation test type S-43 which has double arms is used in this study with periodic load increment: 0,2 ; 0,4 ; 0,8 ; 1,6 ; 3,2 ; 6,4 ; 12,8 kg.

The value of settlement in primary consolidation for normally consolidated clay can be calculated by the equation:

$$S = \frac{C_c \cdot H}{1 + e_0} \log \left(\frac{p_0 + \Delta p}{p_0} \right) \quad (1)$$

Whereas for over consolidated clays, the value of settlement if :

- $(p_0 + \Delta p) \leq p_c$, same with equation (1).
- $(p_0 + \Delta p) > p_c$, so :

$$S = \frac{C_s \cdot H}{1 + e_0} \log \left(\frac{p_0 + \Delta p}{p_0} \right) + \frac{C_c \cdot H}{1 + e_0} \log \left(\frac{p_0 + \Delta p}{p_0} \right) \quad (2)$$

where, H= thickness of soil sample; C_s = swelling index; C_c = compression index; $p_0 = \gamma \cdot H$ (kN/m²); γ = volume weight of soil (kN/m³); Δp = additional vertical stress (kN/m²), with e_0 is initial number of void:

$$e_0 = \frac{h_0 - h_s}{h_s} \quad (3)$$

where, h_0 = initial thickness of soil sample (mm) and h_s = equivalent thickness of soil sample (mm) = $(W_s / A \cdot G_s \cdot \gamma_w)$

Compression index (C_c) obtained from linear slope of the plot $e - \log \sigma'$ curve or with empirical formula.

$$C_c = \frac{e_0 - e_1}{\log \frac{\sigma_1}{\sigma_0}} \quad (4)$$

The formula given for soft soil based of liquid limit test in the laboratory. Besides C_c , the characteristics of soft soil compressibility are also influenced by coefficient of change in volume (m_v).

$$m_v = \frac{1}{1 + e_0} \left(\frac{e_0 - e_1}{\sigma_1 - \sigma_0} \right) \quad (5)$$

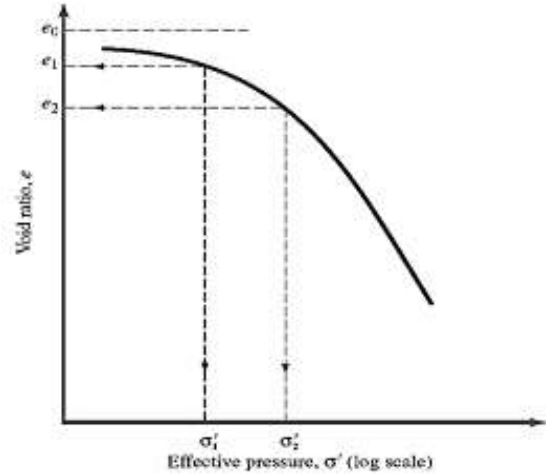


Figure 1. $e - \log \sigma'$ Curve

The settlement of consolidation occurs in 3 stages, starting from initial compressibility caused by preloading load, followed by primary consolidation where stress was transferred from water to the particles of soil, and the last is secondary consolidation with zero excess of pore water and all the stress has been received by particles of soil.

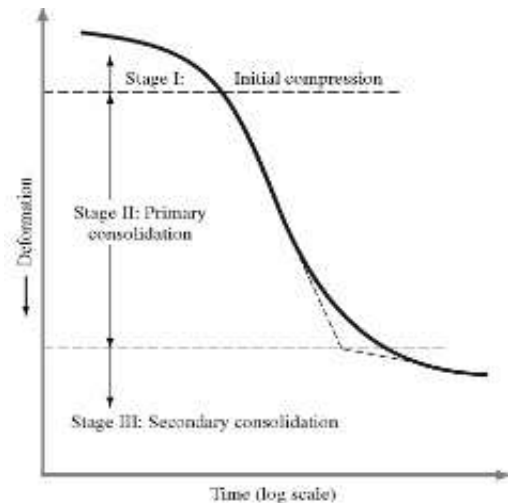


Figure 2. Time - Deformation Curve During Consolidation for An Added Load Given

Rate of consolidation settlement is affected by degree of consolidation (U), coefficient of consolidation (C_v), and time factor of vertical consolidation (T_v) [8]. k_{ve} value given from estimation of Terzaghi equation for the average of vertical consolidation degree is:

$$U_v = 1 - \exp(-C_d \cdot T_v) \quad (6)$$

with, $C_d = \text{constant}$, value as 3,2 [7] and vertical consolidation time factor is :

$$T_v = \frac{c_v - t}{H_{dr}^2} \quad (7)$$

Meanwhile, the value of horizontal consolidation degree and time factor according to Chai (2001) is :

$$U_r = 1 - \exp\left(-\frac{8}{\mu}Th\right) \quad (8)$$

$$Th = \frac{Ch - t}{De^3} \quad (9)$$

where μ described as :

$$\mu = \ln \frac{n}{s} + \frac{k_h}{k_s} \ln(s) + \left(\pi \frac{2l^2 k_h}{3.4q_w} \right) \quad (10)$$

with, $n = D_e/d_w$; $s = d_s/d_w$; $ds = 3.d_{mandrel}$; $d_w = \text{diameter of vertical drainage}$; $l = \text{length of drainage in soft soil}$; $k_h = \text{horizontal permeability coefficient}$; $k_s = \text{permeability coefficient in smear zone or } (1/5) k_h$, and $q_w = \text{vertical drainage capacity}$.

So, the degree of consolidation can be calculated based on Carillo theory (1942) which combine a vertical and horizontal drainage effect:

$$U_{vr} = 1 - (1 - U_v)(1 - U_r) \quad (11)$$

Then, settlement of consolidation at a certain time can be calculated as:

$$S = U_{vr} \times S_c \quad (12)$$

2.2 Permeability

Permeability is defined as the rate of water seeps through the voids of soil both horizontally or vertically [9]. Coefficient of permeability depends on the average size of the voids affected by the particles size distribution and soil structure. Falling head permeability test is applied to soil which has fine particles distribution and low permeability coefficient.

Permeability coefficient of soil in **Table 1** can be calculated using formula:

$$k = 2,303.(a.L / A.L). \log (h_1/h_2) \quad (13)$$

Table 1. Permeability Coefficient of Soil

Material	Coefficient of permeability (mm/s)
Coarse	$10^{-1} - 10^3$
Fine gravel, coarse, and medium sand	$10^{-2} - 10^{-3}$
Fine sand, loose silt	$10^{-4} - 10^{-5}$
Dense silt, clayey silt	$10^{-5} - 10^{-6}$
Silty clay, clay	$10^{-6} - 10^{-8}$

The existence of a smear effect, that create the diameter and smear coefficient, can be seen in formula (11). Smear zone in this research can be assumed like theoretical formula for PVD. So, vertical (k_v) and horizontal (k_h) permeability coefficient [10]:

$$k_h = \frac{a.L}{A(t_1 - t_0)} \ln\left(\frac{h_0}{h_1}\right) \quad (14)$$

$$k_v = \frac{a.L}{2\pi L(t_1 - t_0)} \ln\left(\frac{h_0}{h_1}\right) \ln\left(\frac{R_e}{R_i}\right) \quad (15)$$

where, $L = \text{length of drainage (cm)}$; $a = \text{inner pipe area (cm}^2\text{)}$; $A = \text{soil sample area (cm}^2\text{)}$; R_i & $R_e = \text{soil sample inner (internal) and outer (external) area (cm}^2\text{)}$.

2.3 Soil Shear Strength

In this experiment pore water pressure was not measured and during the test water was not allowed to flow, called as *Unconsolidated Undrained (UU)* condition so only undrained shear strength can be determined. The aim is to determine the parameters of soil shear strength, c and ϕ . Generally, the shear strength of fine-grained soils is caused by viscosity between granules (cohesion). In contrast to coarse grained soils, shear strength is caused by friction between the grains or friction angle. Shear strength is formulated by Mohr-Coulomb with the equation:

$$\tau = c + \sigma \tan \phi \quad (16)$$

where : $\tau = \text{Soil shear strength (kN/cm}^2\text{)}$; $\sigma = \text{Total stress (kN/m}^2\text{)}$; $\phi = \text{friction angle (}^\circ\text{)}$; $c = \text{cohesion (kN/m}^2\text{)}$.

2.4 Geofom Granule Column (GGC)

GGC material came from EPS beads (*Expanded Polystyrene*) geofom that included in geosynthetics group. Geofom granules have size (resin) ranging from 0,2 – 0,6 cm. EPS beads can behave both as a compressive material and vertical drainage. There is no

much research of EPS grains affect to the compressibility behavior of soft soils [6].



Figure 3. Expanded Polystyrene beads

Physically, geofom is materials that not easily degraded biologically and will be the source of enviromental waste. Recycling its waste as a stabilizing material will make geofom as an innovative soil stabilizer which is environmentally safe for a long time.

2.5 Smear Effect

At the installation of vertical drainage, it is assumed that the properties of the surrounding soil do not change. But in fact, the installation of vertical drainage can slightly disturb the soil, depending on the soil sensitivity [11]. This disturbed zone will have their permeability decreased so it will inhibit the rate of consolidation, known as the smear effect.

Chai (2001) assume that vertical drain effect on improving the soil bearing capacity can be analyzed in the same way as if the soil does not use vertical drain. Chai determine the value of the vertical hydraulic conductivity which represents the drainage effect both in the vertical and horizontal directions. Soft soil stabilization with GGC is early-stage research so that the permeability value approach using the Chai Method is the simplest. Besides, geofom granules are brand new material considered to behave like the vertical drain.

$$k_{ve} = 1 + \frac{2.l^2.k_h}{\mu.De^2.k_v} k_v \quad (17)$$

The equivalence of permeability coefficient value according to Chai can be calculated with the formula above. Where the other parameters are described in the previous

discussion.

3. METHODOLOGY

Soft soil is obtained from the Gempol-Pasuruan Freeway (STA + 32.000) with EPS beads stabilizers formed in columns named GGC. Main tests of this research are falling head permeability, consolidation, and triaxial test. Property index is determined through laboratory testing according to **Table 2**.

The variabel in this research are γ_{GGC} varies into 12 kg /m³, 15 kg /m³, and 20 kg /m³, while D_{GGC} varies into 2,5 cm; 3 cm; and 3,8 cm. GGC grain weight (gr) is calculated according to the volume of ring (cm³). The number of soil samples for permeability test is 20 sample, 11 sample for consolidation test, and 33 sample for triaxial test (including undisturbed soil samples).

Table 2. Laboratory Testing Standard

Test type	Standard
Specific Gravity	ASTM D 854-58
Density	ASTM D 2937
Grain size Analysis	ASTM C 136-46
Hydrometer	ASTM D 422
Atterberg limit	LL: ASTM D 424-74 PL: ASTM D 423-66
Organic content	ASTM D 2974 - 87
Triaxial (UU)	ASTM D 2850- 70
Permeability	ASTM D 2434
Consolidation	ASTM D 2435-70

Triangle pattern is used in this study and GGC was placed centrally inside the ring test. Stabilization soft soil with GGC from each variation can be written :

- GGC with density (γ) 12 kg/m³, 15 kg/m³, and 20 kg/m³ written as **GGC 12**, **GGC 15**, and **GGC 20**.
- GGC with diameter (D) 2,5 cm; 3 cm; and 3,8 cm written as **GGC D2,5**; **GGC D3**; and **GGC D3,8**.
- GGC with density 12 kg/m³ D 2,5 cm written as **GGC12-D2,5** etc.

Laboratory test data is used to calculate 90% degree of consolidation and the duration of consolidation. Besides, k_{ve} value due to the *smear effect* by mandrel is calculated. So we get the difference in the results $k_{undisturbed}$, k_{GGC} ,

and k_{ve} . Then, dependent variables such as settlement (S), equivalent permeability coefficient (k_{ve}), soil shear strength (c and ϕ), also stress (σ) and strain (ϵ) can be determined.

4. RESULT AND DISCUSSION

Soil obtained from 1.5 m to 2 m depth and was brought to laboratory tests. Result shows that soil property index of STA +32.000 is not significantly different from the previous studies on STA + 31.500 [1].

Before stabilizing the soft soil with GGC, it is necessary to calculate the weight of GGC on each independent variable for the main laboratory test. Calculation of weight (W_{GGC}) was done based on multiplication γ_{GGC} & V_{GGC} . Example for *falling head* test with :

$$V_{ring} = \frac{1}{4} \cdot \pi \cdot d^2 \cdot t = \frac{1}{4} \cdot \pi \cdot 6,5^2 \cdot 2 = 66,4 \text{ cm}^3$$

Meanwhile, stabilization volume of GGC with a diameter varies into:

$$D_{GGC} = 2,5 \text{ cm} ; V_{2,5} = \frac{1}{4} \cdot \pi \cdot 2,5^2 \cdot 2 = 9,82 \text{ cm}^3$$

So for $\gamma_{GGC} = 12 \text{ kg/m}^3 = 0,012 \text{ gr/cm}^3$, then the weight of GGC is,

$$W_{2,5} = 0,012 \times 9,82 = 0,12 \text{ gr}$$

Those GGC weight calculation above also applied for triaxial and consolidation tests. **Table 3** presents the weight of GGC in the falling head permeability test on all independent variables.

Table 3. Weight of GGC for Permeability Falling Head Test (gram units)

γ_{GGC} (kg/m^3)	D_{GGC} (cm)		
	2,5	3	3,8
12	0,12	0,17	0,27
15	0,15	0,21	0,34
20	0,20	0,28	0,45

As the calculation for consolidation test, the weight of GGC for triaxial test is also based on thickness of soil sample, variation of γ_{GGC} , also D_{GGC} . H_{ring} and D_{ring} of the consolidated specimens are 1 cm and 6 cm, while the height and diameter of the triaxial specimens are 12 cm and 5 cm, respectively. Specifically for the triaxial height, the specimens are adjusted to settlement in consolidation calculated by comparison. For example, H_{ring} of triaxial = 12 cm and the consolidation settlement for

GGC12-D3,8 is 0,5 cm then, the height of the specimen for the triaxial test is 6 cm.

Soil saturation was done along 24 hours for falling head permeability test and consolidation. Considering material properties of GGC (lightweight), a pore paper will be placed on the top and bottom of soil sample to keep the GGC remains in position. As for preliminary test results, only GGC beads with varying density (12, 15, and 20 kg/m^3) which can fulfill all of ring falling head volume. The result prove that GGC12 has a greater flow because it has the most tenuous voids between beads. This value is almost as same as the permeability of fine sand with a range of 0,1 to 0,001 cm/s.

Table 4. Permeability on each γ_{GGC}

γ_{GGC} (kg/m^3)	12	15	20
Permeability coefficient (cm/s)	2,62 E-03	2,58 E-03	2,56 E-03

4.1 Soil Investigation

Based on the calculation of the undisturbed condition, $U \geq 95\%$ was achieved in 7796 days (21.7 years) with settlement of 1.09 m. Compression index (C_c) 0.5046 and a coefficient of consolidation (C_v) 0.00105 $\text{cm}^2/\text{second}$. The permeability coefficient of soft soil is 0.00011 cm/second . Soil shear strength for undisturbed condition with cohesion value (c) 9,179 kN/m^2 and friction angle (Φ) $0,61^\circ$.

Table 5. Soft Soil Property Index

Properties	Soft Soil
Passing no.200	98,47%
Specific gravity (gr/cm^3)	2,6
Density γ_s (kN/m^3)	14,9053
γ_d (kN/m^3)	8,5651
Liquid limit (%)	69,84
Plastis limit (%)	40,917
Plasticity index (%)	28,89
USCS Classification	MH
AASHTO Classification	A-7-5
Organic content (%)	3,299

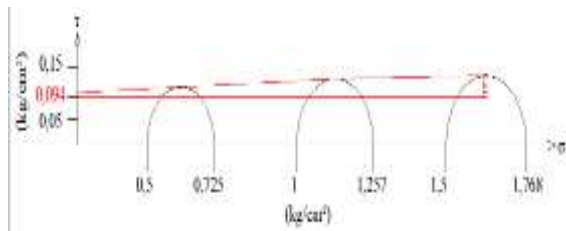


Figure 4. Mohr Diagram of Soft Soil For Undisturbed Condition

4.2 GGC Stabilization on Soft Soil

After soil property index the soil samples are ready to be tested, a consolidation test is carried out for the initial observation as a reference for making triaxial soil samples. Whereas the falling head permeability test is observed flexibly and can be done as the consolidation test goes on.

4.2.1 Settlement of Soft Soil with GGC Stabilization

Stabilization with GGC give assumption that in the presence of polymers that are not interlocked among the granules act as a drainage medium. More void is provided as a catchment areas of water to flow due to the load. The pressure around the GGC beads is lower than the surrounding of soft soil. So, if the flow of water without GGC was free in all directions, GGC stabilization will focus the water towards catchment area of GGC. This will also cause an equivalent diameter of the water absorption area due to GGC stabilization.



Figure 5. Soft Soil Specimen of Consolidation Test

Continuing pressure to all directions due to the load on the consolidation test as one of the property of water will affect consolidation time. Mineral potassium (K^+) in illite which is very easy to attract water particles (H_2O) and is reluctant to release it if it is bound to a particle of soil. This is because the area per grain for fine soils can reach until $\pm 800 \text{ m}^2 / \text{gram}$. The

internalization of water into the void in GGC as a catchment area, will be flowed through coarse grained soil or into the porous layer. This process can accelerate the rate of consolidation which causes value of settlement.

Soft soil stabilization at D_{GGC} 3,8 cm has highest settlement value because it has largest stabilization volume while γ_{GGC} 12 kg/m^3 has the lowest density between the beads so it provides maximum void space in materials of GGC, so the GGC12-D3,8 has the highest settlement and excess pore water. Higher value of excess pore water makes the void in the soil decreased and complement each other between soil particles. This results defined as secondary consolidation where plastic conditions occurs between soil grains.

Final thickness of undisturbed soil sample is 0,7 cm from the initial condition (1 cm). Maximum settlement is 50% occurs at GGC12-D3,8 and has highest excess pore water with 56,4% increment from undisturbed condition.

Characteristics of soil settlement are influenced by the compressibility index. The highest C_c value results from GGC12-D3,8 soft soil. Large compression causing only a small amount of void space between the soil grains. The greater difference in void number between e_0 and e_1 , then the greater the C_c value will be.

Table 6. Height of Soil Samples With GGC Stabilization After Loading (cm units)

γ_{GGC} (kg/m^3)	D_{GGC} (cm)		
	2,5	3	3,8
12	0,6	0,55	0,5
15	0,6	0,6	0,55
20	0,6	0,65	0,55

Table 7. Excess Pore Water (cm units)

γ_{GGC} (kg/m^3)	D_{GGC} (cm)		
	2,5	3	3,8
12	10,5	13,1	14
15	9,1	9,7	13,6
20	8,3	9,2	12,5

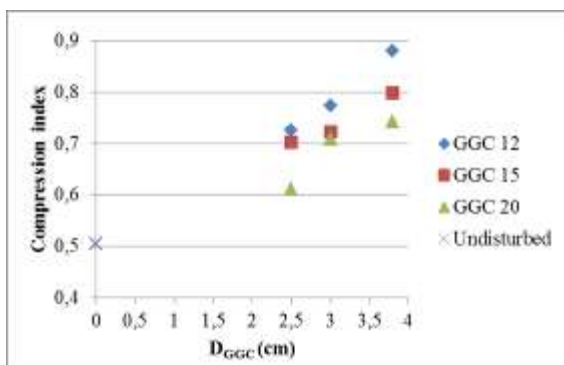


Figure 6. Cc Value of Soft Soil With GGC Stabilization

Parameters of consolidation in the laboratory are calculated with field parameters [2] to find the 90% degree of consolidation. Based on the calculation of undisturbed conditions, $U \geq 90\%$ reached within 14110 days (39,2 years) with 1,03 m of settlement.

Table 8. Duration of Soft Soil Consolidation With GGC Stabilization (day units)

γ_{GGC} (kg/m^3)	D_{GGC} (cm)		
	2,5	3	3,8
12	101	99	96
15	128	109	110
20	141	120	115

The consolidation parameters in the laboratory are calculated with field parameters [2] to find degree of consolidation (U) and the settlement time of consolidation. Maximum settlement of consolidation is stabilized by GGC12-D3,8 about 1,578 m and was achieved within 95 days (± 3 months). This indicates that the degree of consolidation ($U \geq 90\%$) was achieved at day-73 soft soil with GGC12-D3,8.

The longest time occurs in stabilization with GGC20-D2,5 for 142 days (± 5 months) with smallest settlement about 1,327 m. These values prove that the degree of consolidation ($U \geq 90\%$) was achieved at day 109 on soft soil with GGC20-D2,5.

Table 9. Settlement of Soft Soil Consolidation With GGC Stabilization (meter units)

γ_{GGC} (kg/m^3)	D_{GGC} (cm)		
	2,5	3	3,8
12	1,430	1,487	1,578
15	1,410	1,436	1,510
20	1,327	1,420	1,460

Table 10. Analytical Calculations For Degree of Soft Soil Consolidation With GGC12-D3,8 Stabilization

Waktu (t)	C_v	$H_u/2$	Faktor							U	S_p
			waktu (T_v)	U_v	$1-U_v$	C_h	T_h	U_r	$1-U_r$		
hari	$m^2/hari$	m									m
0	0,011	12,25	0	0	1	0,0128	0	0	1	0	
1	0,011	12,25	0,000	0,0002	0,9998	0,0128	0,0116	0,0307	0,9693	0,0309	0,0488
5	0,011	12,25	0,000	0,0011	0,9989	0,0128	0,0578	0,1444	0,8556	0,1454	0,2294
10	0,011	12,25	0,001	0,0023	0,9977	0,0128	0,1157	0,2680	0,7320	0,2697	0,4254
35	0,011	12,25	0,002	0,0078	0,9922	0,0128	0,4002	0,6603	0,3397	0,6629	1,0458
73,27	0,011	12,25	0,005	0,0165	0,9835	0,0128	0,8475	0,8983	0,1017	0,9	1,4198
95	0,011	12,25	0,007	0,0214	0,9786	0,0128	1,1023	0,9489	0,0511	0,95	1,4987
242	0,011	12,25	0,017	0,0533	0,9467	0,0128	2,7980	0,9995	0,0005	0,9995	1,5768
315,13	0,011	12,25	0,022	0,0689	0,9311	0,0128	3,6450	1	0	1	1,5775
400	0,011	12,25	0,028	0,0867	0,9133	0,0128	4,6267	1	0	1	1,5776

4.2.2 Soft Soil Permeability with GGC Stabilization

Grain size test results indicate that the STA + 32.000 of Gempol-Pasuruan Freeway is classified as a silt with a little organic content. Generally, soft soil such as silt and clay has very small void due to the high density and cohesion between grains. This is proved by the permeability value of undisturbed soils including silt soils according to **Table 2**.



Figure 7. Soft Soil Specimen After Falling Head Permeability Test

Soft soil stabilization with GGC 12 has more void space than GGC 15 and 20 which can help water around the soil flow to the drainage faster. GGC grains will immediately drain the water after being accommodated between void space. This happens because water flows from high pressure to low pressure. It occurred due to the GGC material that made of light polymers which can release water without bind to it like clay. So, the GGC stabilization will help the water flow faster by utilizing void between GGC grains.

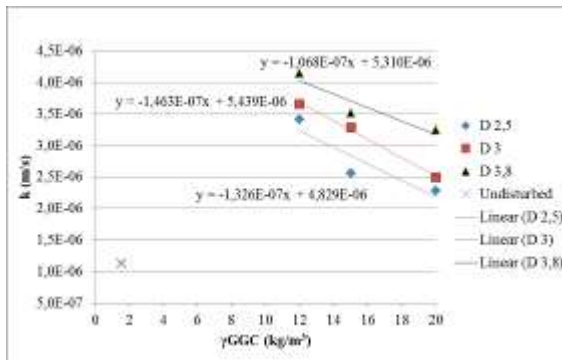


Figure 8. GGC Value of Permeability Coefficient of Soft Soil With GGC Stabilization

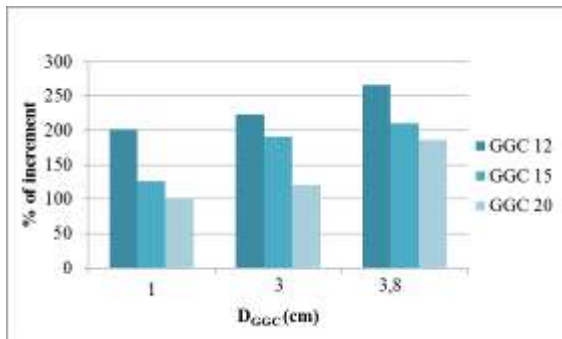


Figure 9. Increment of Soft Soil Permeability Coefficient With GGC Stabilization

It proved that GGC inclusion has given void to accommodate lateral flow from water and the biggest permeability coefficient is GGC12-D3,8 with an increase of 266,6%. So, the bigger D_{GGC} will make the permeability coefficient value greater. Furthermore, the smaller γ_{GGC} , the greater the permeability coefficient value will be.

4.2.3 Shear Strength of Soft Soil with GGC Stabilization

For triaxial tests, the height of the soil sample must be adjusted to the value of the settlement that occurs in the consolidation test.

However, the weight of GGC remains same as **Table 6**. Remake of test specimen for triaxial must be done because of the limitations of the laboratory apparatus. Consolidation should be carried out on a large scale using CBR molds. The goal is the sample specimens have the same height and density at each stabilization. That way the triaxial specimen sample can automatically be taken directly from the CBR mold effectively.

In addition, GGC inclusion against soft soil for triaxial test must be suppressed with an extruder to achieve the stabilization volume and match with GGC weight calculations. Referring to **Table 6**, 9 cm height of triaxial specimen is used in GGC12-D3; GGC12-D3,8; GGC15-D3,8; and GGC20-D3,8, while the 10 cm height is used in GGC12-D2,5; GGC15-D2,5; GGC15-D3; GGC20-D2,5; and GGC20-D3.

Table 11. Shear Strength Parameters of Soft Soil With GGC Stabilization

D (cm)	2,5		3		3,8	
	c	ϕ	c	ϕ	c	ϕ
12	12,52	18	12,45	18,3	11,96	19,2
15	14,55	16,5	13,68	18	12,19	18,7
20	17,3	14,6	14,6	17	13,45	17,4

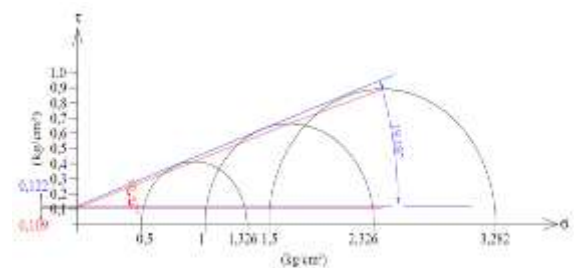


Figure 10. Mohr Diagram of Stabilization Soft Soil With GGC12-D3,8

The highest shear strength results was obtained on the stabilization with GGC12-D3,8. The cohesion and saturation of soft soil are greatly reduced so that the density between the soil grains is getting more solid and the friction between the grains is high. Shear strength of soft soils increased by 2702.25% from the undisturbed condition by the stabilization using GGC12-D3,8.

4.2.4 Smear Effect

After *falling head* test, the coefficient of

permeability of k_h and k_v are obtained. As a result, the equivalence of the k_{ve} permeability coefficient (formula 17) raises the μ value due to the inclusion of the mandrel which results a smear effect.

The unit is changed to m/sec, adjusted from laboratory to the field conditions. Diameter mandrel in field has difference 0.2 mm from each GGC stabilization diameter under laboratory conditions. The greater diameter of the stabilization will bring greater effect of disturbance around the soft soil. As a result, the equivalence of the permeability coefficient due to the effects of the smear disturbance occurs at GGC D3,8.

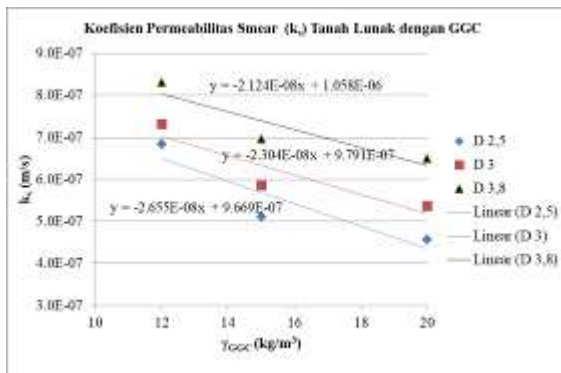


Figure 11. Permeability Coefficient of Smear (k_s) (m/sec. units)

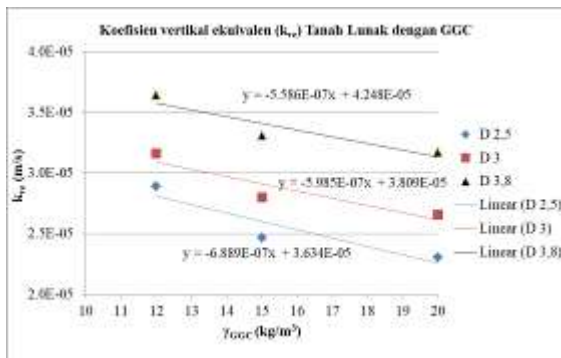


Figure 12. Equivalency of Permeability Coefficient (k_{ve}) (m/sec. units)

5. CONCLUSIONS

1. Consolidation with GGC12-D3,8 gives a settlement of 1,516 m in soft soil within 91 days ($U \geq 90\%$) from undisturbed condition.
2. The greater stabilization of D_{GGC} , the greater compression in soft soil will be. Inversely for γ_{GGC} , greatest compression occurs at lowest γ_{GGC} .
3. GGC12-D3,8 provides greatest number of

pore space to drain water that flow due to the load, so the permeability coefficient increases up to 266,6% higher than undisturbed condition.

4. Disturbances around soft soil due to the greatest diameter of the mandrel (D3,8) cause the value of k_s to be even smaller.
5. The value of k_{ve} is proportional to k_s , so the smaller smear area, the lower k_{ve} will be.
6. GGC behaves like PVD as a water-transferring medium to stabilize soft soil so it has better physical and mechanical properties than the initial conditions.

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