The Compaction Characteristics of Clay- Glass Fiber Mixtures

Eyyüb KARAKAN

● Assoc. Professor Dr.

● Department of Civil Engineering, Kilis 7 Aralik University, Kilis, Turkey

● ORCID number: 0000-0003-2133-6796

Full contact details of corresponding author:

Assoc. Prof. Dr. Eyyüb KARAKAN

Kilis 7 Aralik University, Department of Civil Engineering

Address: Kilis 7 Aralik Universitesi Insaat Muhendisligi Bolumu 79000, Kilis, Türkiye

Abstract

The demand for new settlements is rising daily due to the expanding global population. Construction of buildings on problematic soils has become necessary as a natural consequence of the growing population. As technology advances, a wide range of soil improvement techniques are employed to prepare problematic soils for structural use. In recent years, as in every field, environmentally friendly materials have started to be used in soil improvement in geotechnical engineering. An environmentally friendly material, high compressive strength E-type fiber glass, was used in this study. This study examined the effects of glass fiber additives on bentonite, kaolin, and sepiolite clays using an experimental program. Glass fibers in powdered-6–12 mm lengths were mixed with 1%, 2%, 3%, 4%, and 5% pure clay for every length, and the samples were then prepared and compacted using standard proctor energy. As for the experiment's findings, it was found that at all sizes and ratios of the glass fiber used, the clay's optimum water content decreased and its maximum dry density increased. In a world that is changing and developing, they are thought to be a good substitute for conventional ground improvement techniques because they are more environmentally friendly.

Keywords: Glass fiber, clay, maximum dry density (MDD), Compaction behavior, optimum water content (OWC), Optimum degree of saturation (ODS).

Abbreviations and notation list

CEL	Compaction energy level
D_c	Degree of compaction (ρ_d/ρ_{dmax})
F_c	Fine content < 75 μm (%)
G_s	Specific gravity (ρ_s/ρ_w)
LL	Liquid limit (%)
PL	Plastic limit (%)
PI	Plasticity index=LL−PL (%)
MDD	Maximum dry density (g/cm^3)
ODS	Optimum degree of saturation (%)
OWC	Optimum water content (%)
ZAV	Zero air voids (%)
S_r	Degree of saturation (%)
S_{opt}	Optimum degree of saturation (%)
w	Water content (%)
w_n	Natural water content (%)
w_{opt}	Optimum water content (%)
γ_{dmax}	Maximum dry unit weight (kN/m^3)
ρ_d	Dry density (g/cm^3)
ρ_{dmax}	Maximum dry density (g/cm^3)
ρ_s	Soil grain density (g/cm^3)
ρ_w	Water density (=1.0 g/cm^3)

1. Introduction

In many geotechnical engineering applications, such as enhancing the mechanical qualities of soils, stabilizing slopes, mechanically stabilizing the base layers of flexible pavements, and increasing soil bearing capacity, the use of glass fibers has been a commonly accepted and efficient technique(Benziane et al., 2019; Lemaire et al., 2013; Çelik et al., 2017; Tajdini et al., 2018; Chen et al., 2015; Kutanaei & Choobbasti, 2015; Choobbasti, Kutanaei, et al., 2019; Wang et al., 2013).

Fiber-reinforced clay can effectively regulate the development of lateral and vertical deformation of a soil mass because it is an isotropic material. Thus, compared to unreinforced soils, it might offer some notable benefits, such as increased ductility, decreased volume changes and settlement, and higher shear strength and elastic modulus (Choobbasti, Kutanaei, et al., 2019; Consoli et al., 2010; Shen et al., 2021; Tang et al., 2012). Additionally, to stabilize and strengthen certain weak soils, fibers are occasionally combined with cement and lime (Choobbasti, Samakoosh, et al., 2019; Consoli et al., 2010; Jiang et al., 2010).

The engineering behavior of fiber-reinforced soils, including cohesive and cohesionless soils, has been the subject of numerous experimental investigations (Bell, 1996; Akbulut et al., 2007; Estabragh et al., 2012; Anagnostopoulo et al., 2014; Chen et al., 2015; Consoli et al., 2003; Gao et al., 2015; Kutanaei & Choobbasti, 2016; Karakan, 2018; Benziane et al., 2019; Dhar & Hussain, 2019). To estimate the mechanical properties of cemented sand soil reinforced with randomly distributed fibers, for instance, Kutanaei and Choobbasti (2016) conducted unconstrained compression tests and used a particle swarm optimization algorithm to construct a polynomial relationship. Bell (1996) investigated how clay soils' geotechnical characteristics were affected by lime treatment. When compared to kaolinite, the results indicated that montmorillonite had the largest decrease in plastic limits. Cement and polypropylene fiber were utilized by Tran et al., (2018) to enhance the mechanical properties of clayey soil. Their test findings demonstrate that fiber reinforcement can raise undrained shear strength and stop cracks from forming.

Standard proctor tests were performed in this study on both unreinforced and reinforced materials with varying glass fiber types (powder, 6 mm, and 12 mm) and fiber contents (0%, 1%, 2%, 3%, 4%, and 5%) to assess how the fiber content affects the behavior of the compaction identifiers in the soil under test.

2. Material and Methods

In this study, clays were obtained from the ESAN manufacturer. The glass fiber specimens (powder, 6 mm and 12 mm) are presented in Figure 1. Table 1 displays the glass fibers' mechanical, chemical, and physical characteristics. The USCS classifies sepiolite as a low plasticity clay (CL) and bentonite and kaolinite as high plasticity (CH) clays. Figure 2 displays the grain size distribution curves for the clays.

The standard methodology mentioned in ASTM D698 was used. Glass fibers and clay were completely combined in a dry state. After adding the chosen amount of water, the mixture was once more well combined. A standard mold with a 943 cm^3 capacity was filled with the wet clay-glass fiber mixture in three layers. Dropped from 305 mm above the mixture, 25 blows of a rammer weighing 2.5 kg were used to compact each layer of mixture in the mold. In accordance with ASTM D698, a standard proctor test was performed on both clay soils and clay-fiber mixtures to ascertain the optimum water content (w_{opt}) and maximum dry unit weight (γ_{dmax}).

Table 1. Physical and Chemical Properties of glass fibers

Property	**Unit**	**Glass fibers**
Density	gr/cm^3	2.56
Tensile Strength	MPa	3.445
Modulus of Elastisity	GPa	76
Tensile elongation	%	2.75
Fiber diametre	µm	13
Chopped length	mm	6-12
Moisture content	%	Max 0.1

Chemical composition	% (weight)	55.0 (SiO_2) 22.0 (CaO) 14.0 (Al_2O_3) 7.0 (B_2O_3) 1.0 (MgO) 0.5 (Na_2O) 0.3 (K_2O) 0.2 (TiO_2)

Figure 1. İmages of fiber glass materials a) powder b) 6 mm c) 12 mm fiber

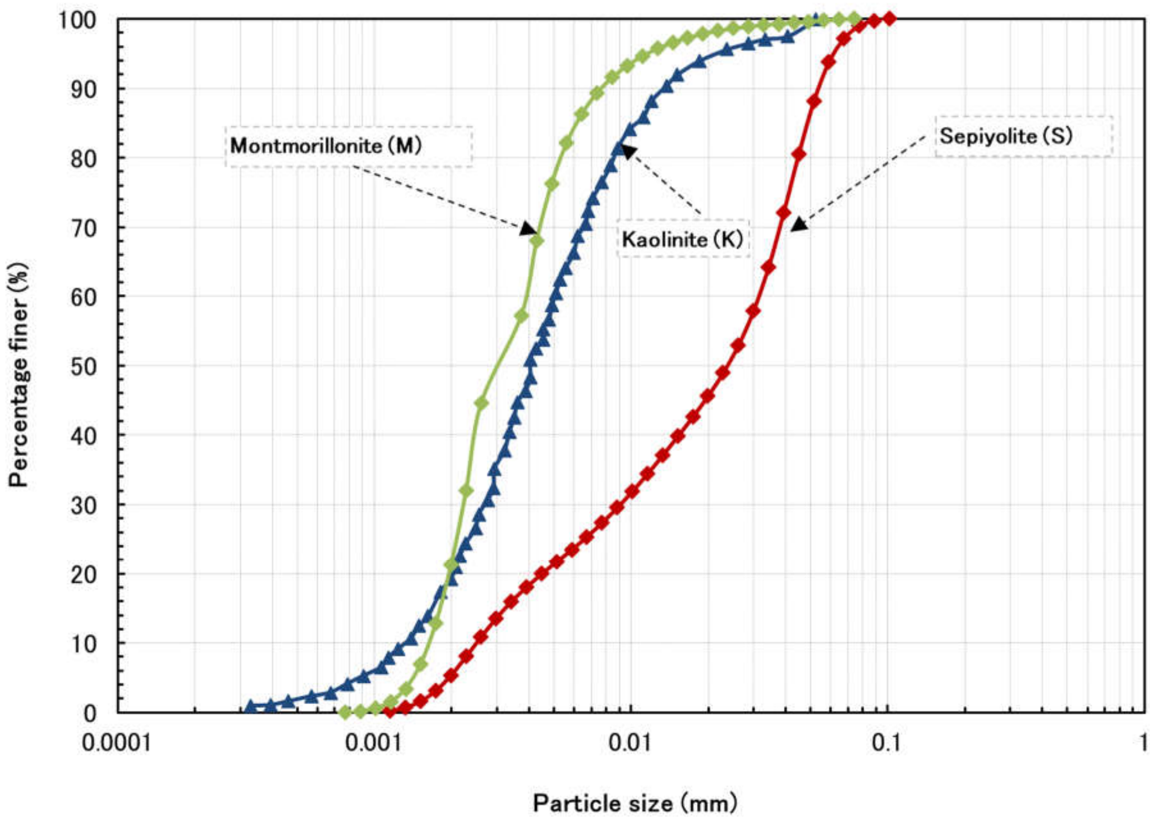

Figure 2. Particle size distribution curves of the clays

3. Results and Discussion

The optimum water content (OWC) and maximum dry density (MDD) of the reinforced specimens were determined using the standard proctor compaction test. In this study, it was investigated whether fiber lengths have any effect on MDD and OMC. Glass fibers in powder form with lengths of 6 mm and 12 mm were utilized for this purpose. In addition, for each fiber length, it was aimed to examine the influence of the fiber ratio on MDD and OWC. It is necessary to have the OWC and MDD values before field compaction. The maximum dry density at which soils have a higher bearing capacity at the optimum water content is determined by these two crucial parameters. The amount of water in soil that allows for the achievement of the highest dry density following a specific compaction effort is known as the optimum water content. The minimum amount of water needed to create a water film on the soil particle surfaces is actually just enough to allow the soil particles to slide.

3.1 Correlation between MDD and OWC

The first goal of this study is to examine and determine MDD and OWC of the target soil under specific condition. Predetermining a relationship between MDD and OWC of different soils is very effective for practical application in, for example, earthworks, considering the desirability of soil type and compaction effort. Besides, several correlations exist between maximum dry density and optimum water content of soil (Mori, 1962; Moroto, 1989; Ekwue and Stone, 1997; Uno et al. 2002; Sridharan and Nagaraj, 2005; Gurtug and Sridharan 2015).

In order to ascertain the relationship between MDD and OWC, the experimental study employed bentonite, kaolinite, and sepiolite clays. Three distinct fiber lengths—powder, 6 mm, and 12 mm—ranging from 0 percent to 5 percent with a 1 percent increment ratio were used in a total of 54 standard proctor tests conducted on these clay soils. Each experiment in the standard proctor tests was conducted in an average of 12 steps, beginning with a water content of about 2%t and gradually increasing to water contents of more than 50%. The variations in the water content with dry density of 54 standard proctor tests are displayed in Figure 3. The change in zero air content (ZAV) and degree of saturation level from 20% to 100% with a 20% increase interval is also depicted in Figure 3. Kaolin+Fibre blends achieved maximum dry density values in the range of 30% to 35% water content, whereas Sepiolite+Fibre blends achieved maximum dry density values in the range of 28% to 32% water content, as shown in Figure 3. Since bentonite clay has a different water retention capacity and chemical makeup than the other two clays, its maximum dry density values in bentonite+fibre mixtures were achieved at water content ranges of 40 to 45 percent.

Figure 3 clearly shows that the initial dry density values are extremely low because the standard compaction tests start with 2% water content. At very low water contents, reinforced mixtures have a saturation level of less than 20%. The water contents of the kaolin+fiber and sepiolite+fiber mixtures that were closest to the ZAV curve in the experiments were found to be approximately 40%. While the degree of saturation in Bentonite+Fiber mixtures stay below 20% at water contents between 2% and 22%, it does not exceed 20% in Sepiolite+Fiber and Kaolin+Fiber mixtures at very low water contents between 2% and 15%.

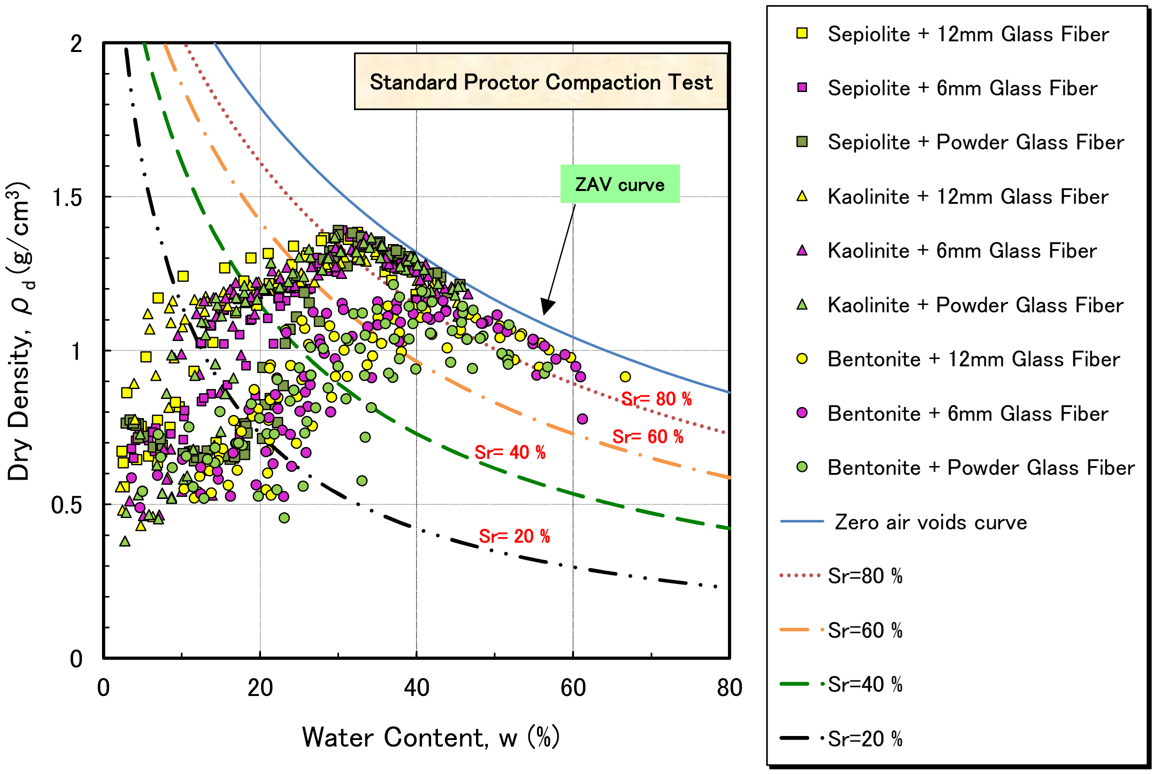

Figure 3. Dry density water content relationship of the clay+fiber mixtures

The MDD-OWC relationship for each clay+fiber mixture is displayed in Figure 4 for a total of 54 experimental results, including 6 experiments with a 1% increase rate from 0% to 5%. The mixtures of sepiolite+fiber was found to have the highest MDD and lowest OWC values. In contrast to the other two clays, Bentonite+Fiber mixtures have lower MDD and higher OWC values, while Sepiolite+Fiber and Kaolin+Fiber mixtures have similar MDD and OWC values, as shown in Figure 4. The experimental study's standard proctor results showed that the mixture of Sepiolite+12 mm glass fiber had the lowest OWC value (26.98%), while the mixture of Bentonite+powder glass fiber had the highest OWC value (52.50%). Bentonite+12 mm glass fiber mixture had the lowest MDD value at 1.05 g/cm^3, while Sepiolite+Powder glass fiber mixture had the highest MDD value at 1.41 g/cm^3.

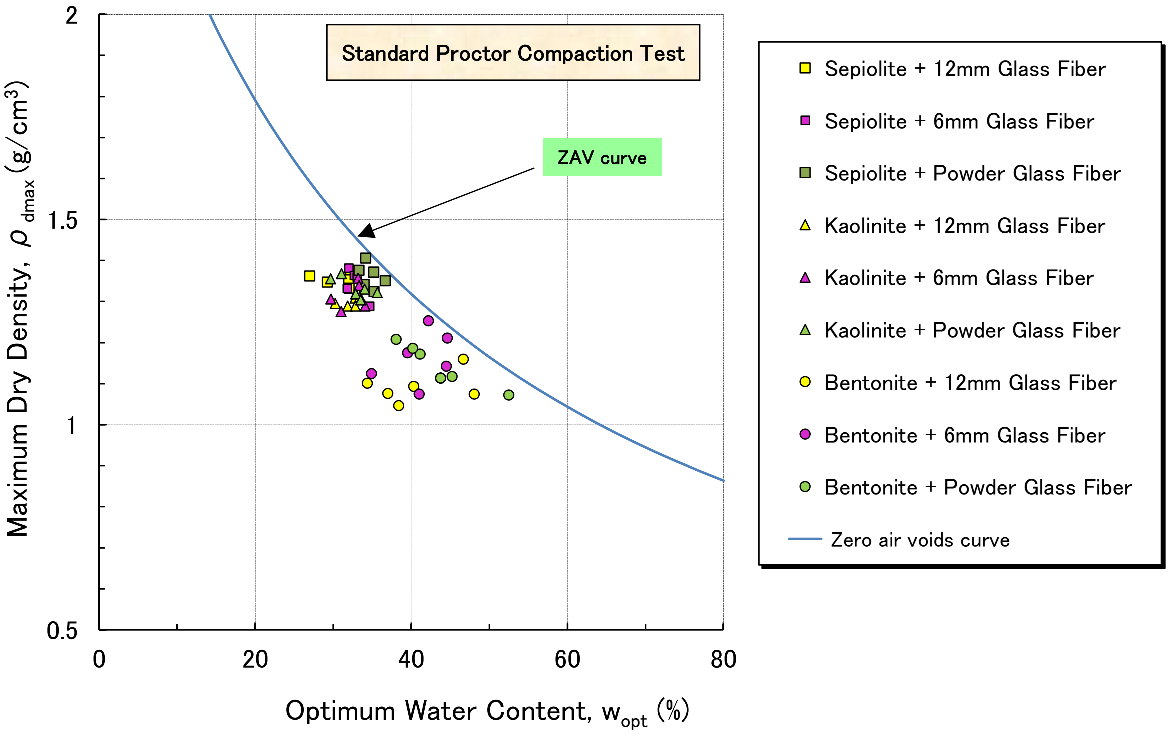

Figure 4. Maximum dry density optimum water content relationship of the clay+fiber mixtures

Shimobe (2012) proposed the equation represented in Equation 1 and defined the optimum degree of saturation (Sopt) as the saturation of soils at optimal compaction.

$$S_{opt} = \frac{w_{opt}\rho_{dmax}\rho_s}{(\rho_s - \rho_{dmax})\rho_w} \qquad (1)$$

In Equation 1, w_{opt} is the optimum water content of soils, ρ_{dmax} is the maximum dry density of soils, ρ_s, is the density of soils and ρ_w is the density of water. On the other hand, Shimobe (2012)'s equi-MDD lines are plotted for values of ρ_{dmax} between 1.0 g/cm^3 and 1.5 g/cm^3 with an increase of 0.1 g/cm^3 using Equation 1, which is shown in Figure 6. All of the experimental data fell below the fixed line at $\rho_{dmax} = 1.5\frac{g}{cm^3}$. Bentonite+12 mm glass fiber had the lowest optimum degree of saturation level (S_{opt}=64.75%), while Sepiolite+6 mm glass fiber had the highest (S_{opt}=108.48%). At first glance, the data appears to be quite dispersed, but upon closer inspection, it turns out that Bentonite+fiber mixtures have the lowest optimum degree of saturation, while Sepiolite +fiber mixtures have the highest (Figure 5). For the Bentonite+fibre, Kaolinite+fiber, and Sepiolite+fiber mixtures, 18 experiments were conducted in the experimental study. Sepiolite+fiber, kaolinite+fiber, and bentonite+fiber had maximum optimum degrees of saturation 102.36, 92.29, and 108.48, respectively, while the lowest values were 75.63, 72.71, and 64.75 (Figure 5). Sepiolite+fiber, kaolinite+fiber, and bentonite+fiber were found to have average optimum degrees of saturation 91.27, 83.09, and 80.25, respectively. It was found that the average S_{opt} for each clay+fiber mixture was 85.78.

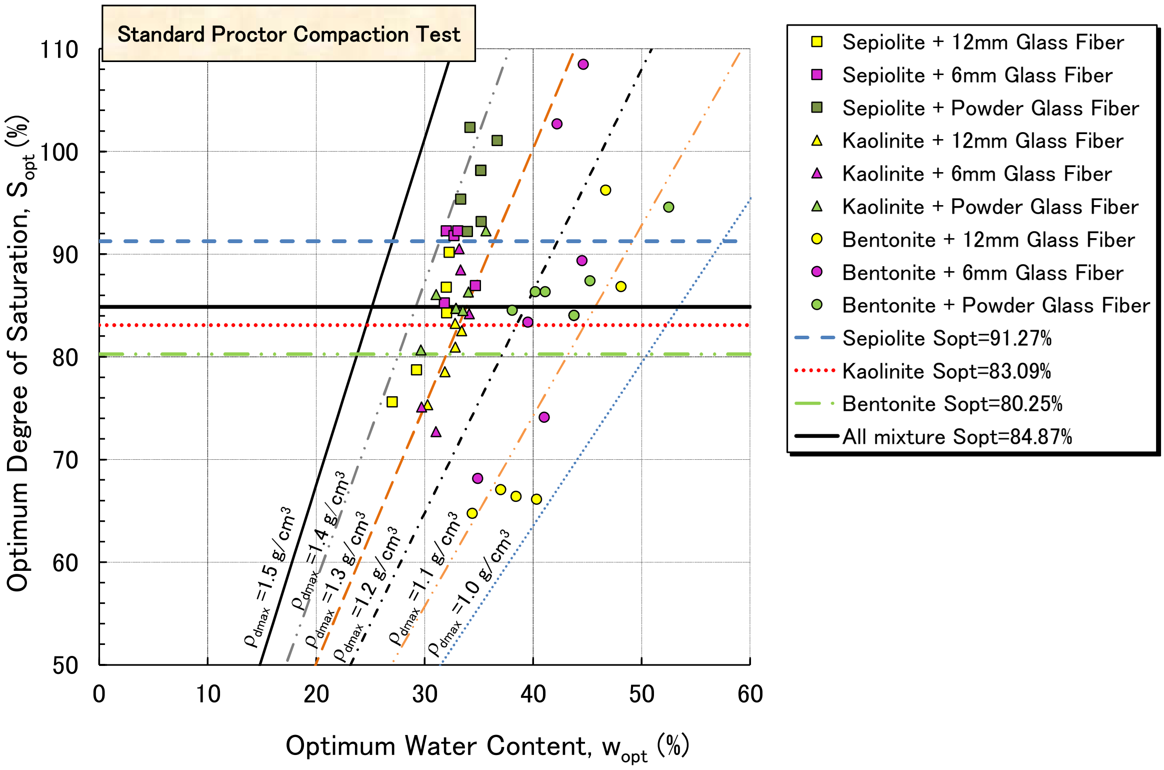

Figure 5. Optimum degree of saturation -optimum water content relationship of the clay+fiber mixtures

3.2 Effect of Fiber ratio on MDD and OWC

The MDD and OWC changes of the powder, 6 mm and 12 mm glass fibers shown in Figure 1 in the standard proctor tests with 1% increments from 0% to 5% are given in Figures 6 and 7, respectively. Figures 6 and 7 show the MDD and OWC changes of the powder, 6 mm, and 12 mm glass fibers, respectively, in the standard proctor tests with 1% increments from 0% to 5%. As a general trend, Figure 6 shows that for all three types of clay and fiber mixtures, higher MDD values are obtained with increasing fiber ratios. Figure 6 illustrates that the highest MDD values were attained at fiber ratios of 5%. The mixture of Sepiolite+5% powder glass had the highest MDD value for the 5% fiber ratio, measuring 1.38 g/cm^3. Compared to the other two clay-fiber mixtures (kaolin+fiber and sepiolite+fiber), bentonite+fiber mixtures have lower MDD values. Depending on the fiber ratio, Figure 7 illustrates how the optimum water content values for three distinct clay+fiber mixtures varied according to the findings of standard proctor tests. The highest OWC value for all three fiber types was found in bentonite clay, as can be seen in Figure 7. Overall, all experiments showed that OWC values were higher at 5% fiber ratios. The OWC value for the bentonite+ 1% powder glass mixture, which was found to be 52.50%, is the only example that deviates from this trend.

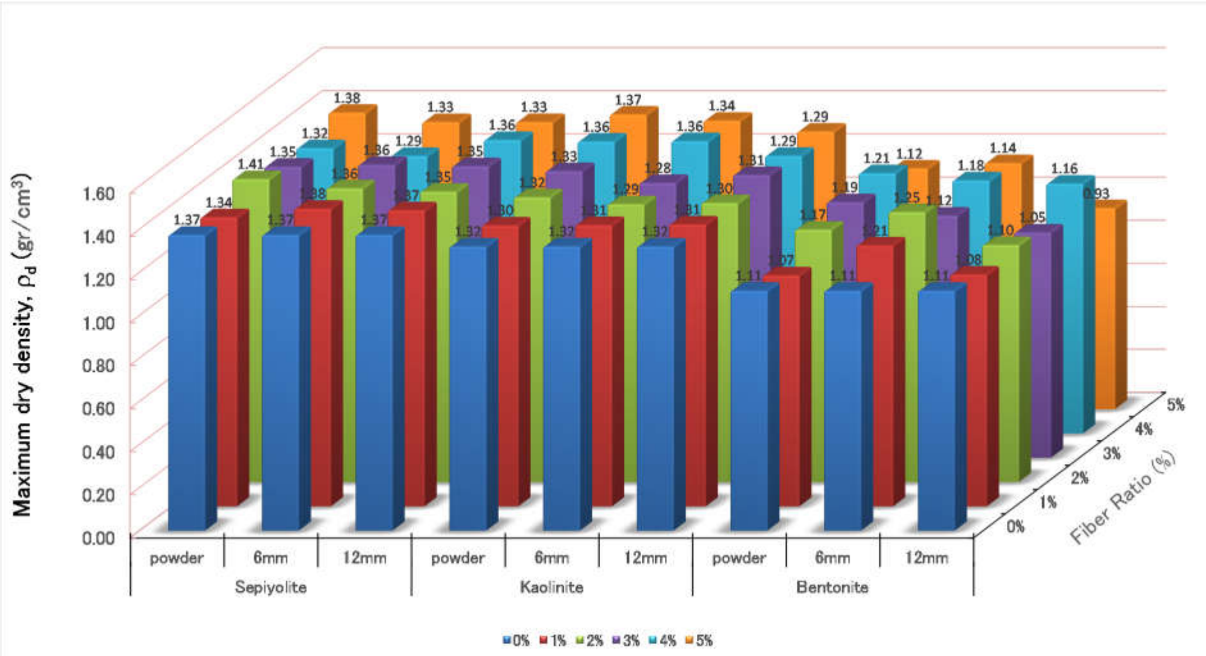

Figure 6. Relationship between MDD-fiber ratio of the clay+fiber mixtures

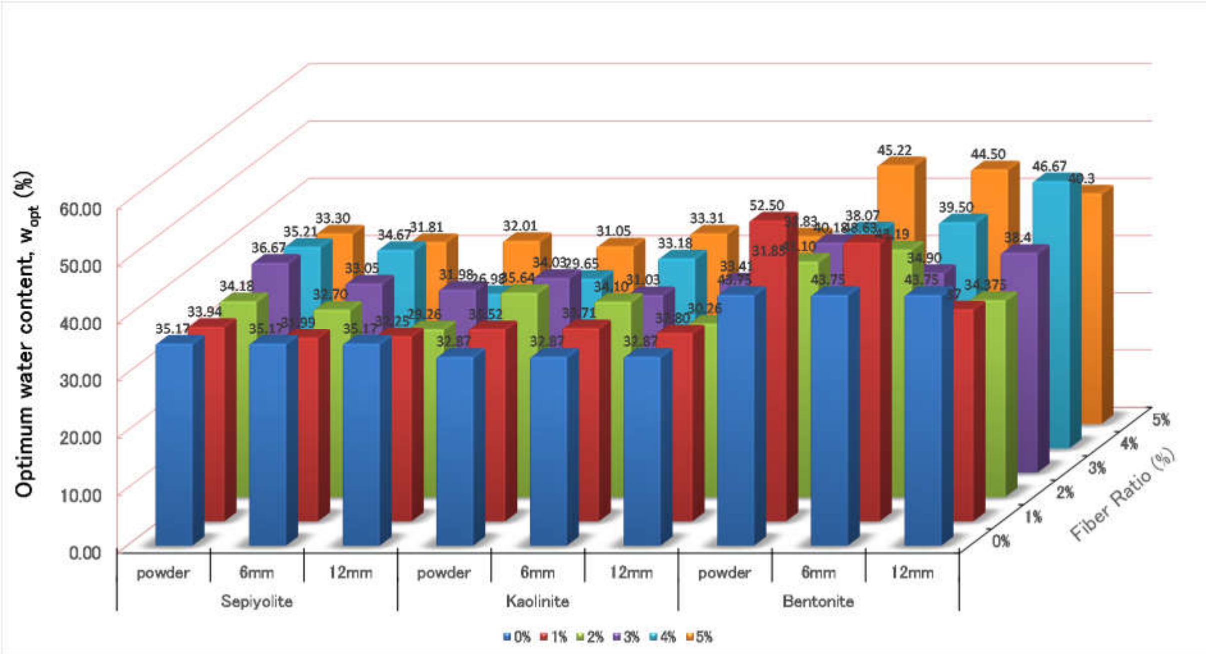

Figure 7. Relationship between OWC-fiber ratio of the clay+fiber mixtures

3.3 Effect of fiber Length on MDD and OWC

Three different fiber types were used to examine the impact of fiber length: powder, 6 mm, and 12 mm. For three distinct fiber lengths, Figure 8 displays the variation of MDD values obtained for Bentonite, Kaolin, and Sepiolite clays with a 1% increase from 0% to 5%. The MDD values found in the standard proctor test with powder glass fiber are higher than those found in the standard proctor experiments with glass fiber lengths of 6 mm and 12 mm, according to the study. Sepiolite+powder glass fiber mixtures generally had the highest MDD values, whereas bentonite+12 mm fiber glass mixtures had the lowest MDD values.

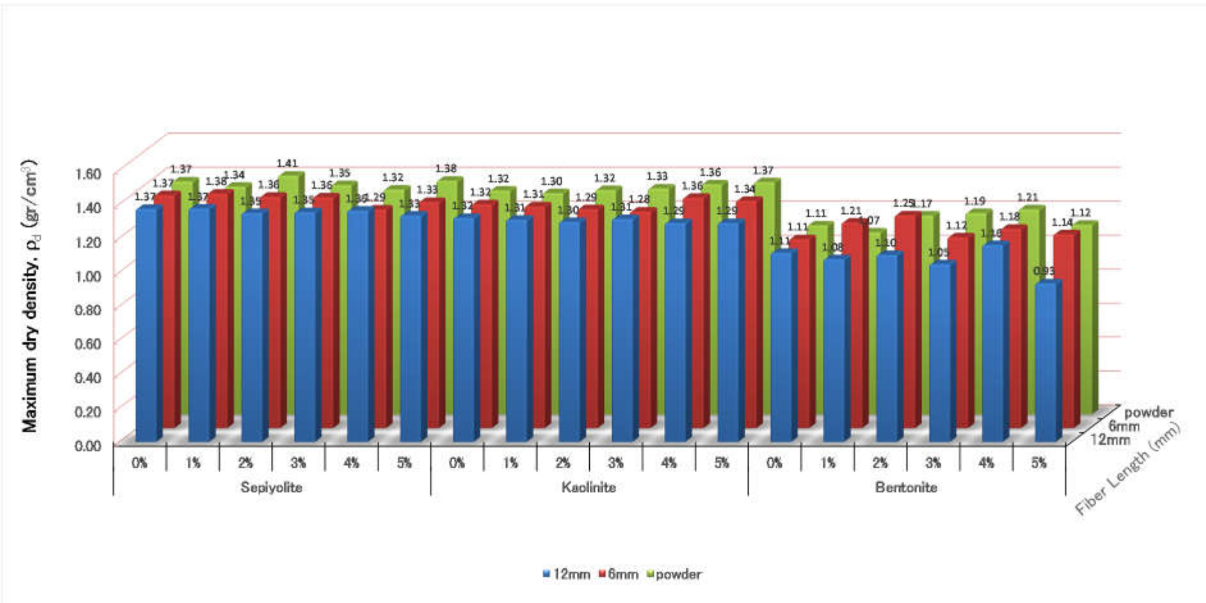

Figure 8. Relationship between fiber length and MDD

The variation of OWC values for Bentonite, Kaolin, and Sepiolite clays using three different fiber lengths (powder, 6 mm, and 12 mm) with a 1% increase from 0% to 5% is depicted in Figure 9. Regardless of the type of clay, it is observed that powder glass fibers have substantially higher OWC values. The OWC values typically decrease as the fiber length increases. For all three fiber lengths, the OWC values of bentonite+fiber mixtures are generally higher than those of Sepiolite+fiber and Kaolinite+fiber mixtures. In general, when the OWC value is viewed as a function of fiber length, it is discovered that as fiber length increases, decreasing OWC values are obtained.

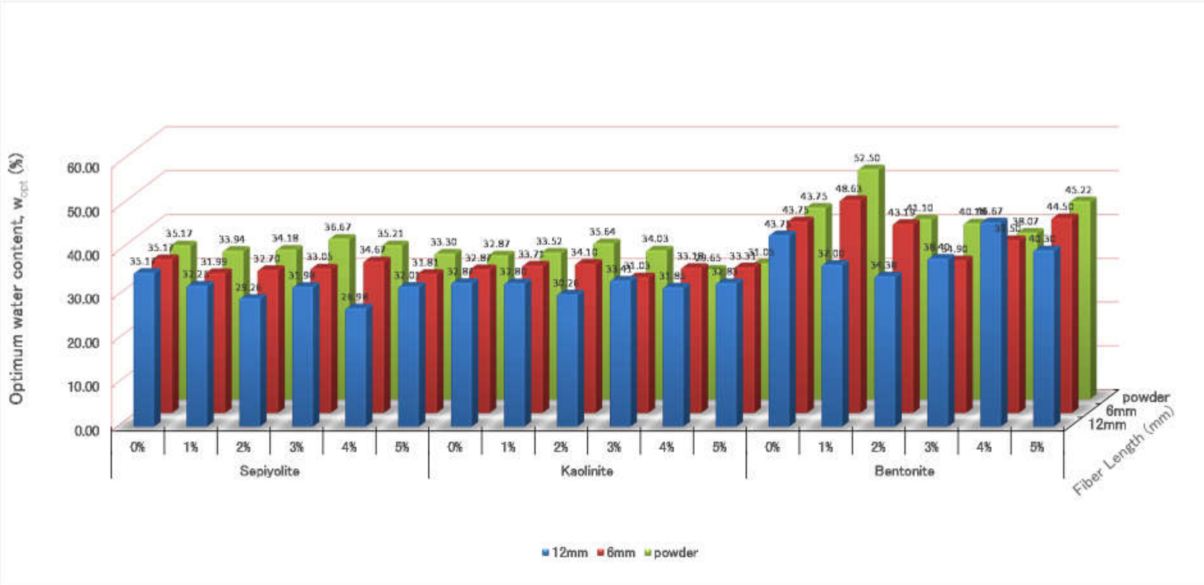

Figure 9. Relationship between fiber length and OWC

3.4 Effect of Clay type on MDD and OWC

The variation of MDD values for the three types of clay is depicted in Figure 10. In the same circumstances, with the same fiber lengths and ratio, the MDD values are kaolinite, bentonite, and sepiolite, respectively. The results of the experiments demonstrated that clay type had a significant impact on MDD values. This is also because different types of clay have different chemical compositions. For instance, when no fiber was used in the experiments, the MDD values for the types of clay that were sepiolite, kaolinite, and bentonite were 1.11 g/cm^3, 1.32 g/cm^3, and 1.37 g/cm^3, respectively. However, MDD values of 1.12 g/cm^3, 1.37 g/cm^3, and 1.38 g/cm^3 were determined for clay+5% powder glass fiber, respectively.

Three different clay types' changes in OWC values are depicted in Figure 11. This time, bentonite clay had the highest OWC values, in contrast to the MDD values shown in Figure 11. In every experiment, bentonite clay produced the highest OWC values, while sepiolite clay produced the lowest, irrespective of the fiber type and ratio. Higher OWC values were attained because bentonite clay had a greater capacity to retain water than the other two clays.

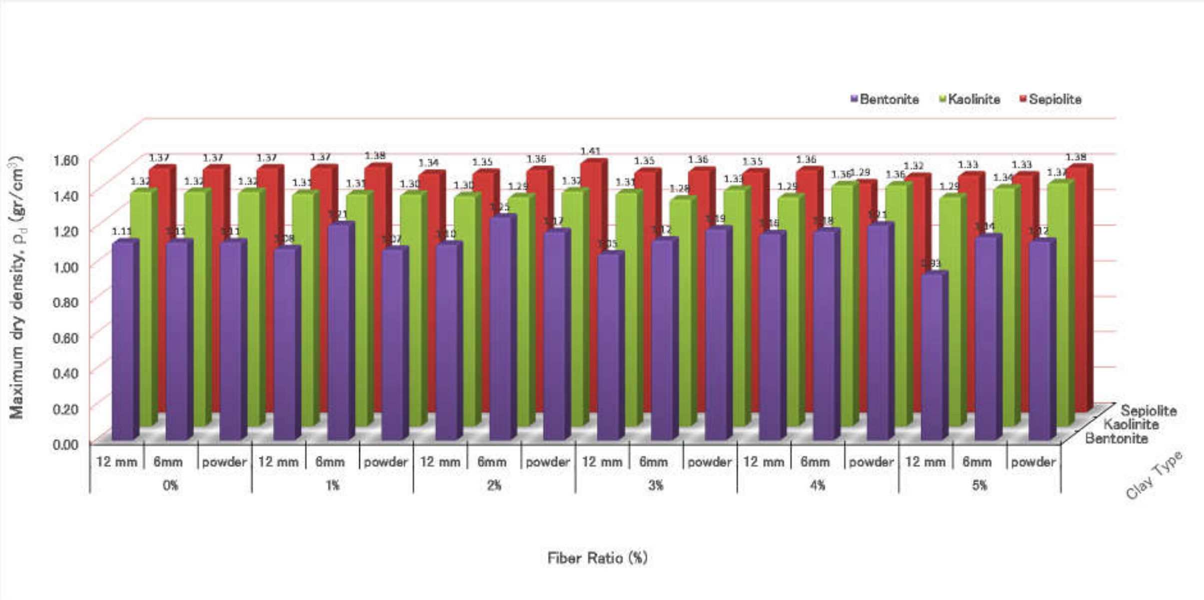

Figure 10. Relationship between clay type and MDD

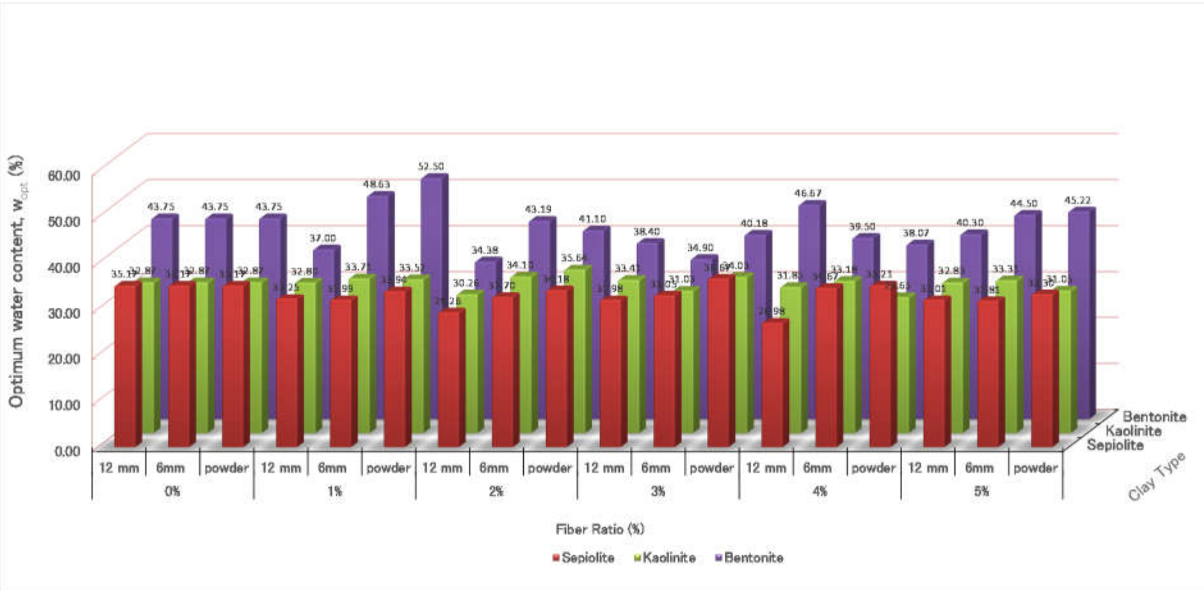

Figure 11. Relationship between clay type and OWC

3.5 Relationship between saturation level and water content.

Figure 12 displays the water content degree of saturation relationship for each clay+fiber mixture according to the standard compaction test results. The second-order polynomial relationships for the water content-degree of saturation derived from mixtures of bentonite+powder glass fiber, bentonite+ 6 mm glass fiber, and bentonite+12 mm glass fiber are displayed in Figure 12a, respectively. The degree of saturation-water content relationships for the data from the tests involving kaolinite+powder glass fiber, kaolinite+6mm glass fiber, and kaolinite+12 mm glass fiber are also displayed in Figure 12b, while Figure 12c displays the degree of saturation water content relationships for the data obtained from the tests involving sepiolite+powder glass fiber, sepiolite+6mm glass fiber, and sepiolite+12 mm glass fiber. The results of the second order polynomial equations derived from mixtures of bentonite+powder, bentonite+6 mm fiber, and bentonite+12 mm fiber are extremely similar, as shown in Figure 12a. It is evident that the compaction tests for bentonite+glass fiber mixtures began with a minimum water content of roughly 3–5%, and the resulting degree of saturation levels were roughly 2–7%. Nevertheless, it can be observed from the best fit lines that mixtures of bentonite+glass fiber begin with an average water content of about 10%. Additionally, standard compaction tests demonstrate that even at 55–60% water content, bentonite+glass fiber mixtures can reach degree of saturation levels of approximately 90%. In comparison to bentonite+glass fiber mixtures, kaolinite + glass fiber mixtures in Figure 12b exhibit a significantly higher degree of saturation at very low water contents when the degree of saturation - water content relationships are analyzed. For example, the degree of saturation of kaolinite+glass fiber mixtures approach 100% at a water content of approximately 40–45%. After 50% water content, the degree of saturation in bentonite+glass fiber mixtures increase in a roughly horizontal line as the water content rises. Compared to bentonite+glass fiber and kaolinite+glass fiber mixtures, the degree of saturation water content behavior of the sepiolite+glass fiber mixtures shown in Figure 12c is significantly different. The sepiolite+glass fiber mixtures show a convex increase in the water content degree of saturation relationships when compared to the other two clay+fiber mixtures. In this instance, sepitolite+fiber mixtures reach full saturation at water content levels below 40%. However, even at significantly lower increases in water content, the degree of saturation of sepiolite+fiber mixtures increase much more quickly. Each type of clay and the glass fibers used with it are shown in Table 2 along with the water content degree of saturation correlation equations, R^2 values, and the quantity of data used in the experiments. Between 79 and 93 data points are used in the computations. The determined R^2 values, which varied from 0.88 to 0.96, showed that the correlations were fairly strong.

Table 2. Degree of saturation water content relationship for clay+glass fiber mixtures

No	Clay Type	Fiber Type	Data (n)	Equation	R^2
1	Bentonite	Powder	80	$S_r = -0.0025w^2 + 2.1985w - 17.841$	0.88
2	Bentonite	6 mm	91	$S_r = -0.0166w^2 + 3.0642w - 27.439$	0.90
3	Bentonite	12 mm	93	$S_r = -0.0173w^2 + 3.1752w - 31.078$	0.95
4	Kaolinite	Powder	79	$S_r = -0.0207w^2 + 3.7531w - 21.853$	0.96
5	Kaolinite	6 mm	80	$S_r = -0.0285w^2 + 4.0678w - 24.745$	0.96
6	Kaolinite	12 mm	78	$S_r = -0.012w^2 + 3.0697w - 11.365$	0.98
7	Sepiolite	Powder	81	$S_r = 0.0293w^2 + 1.6679w - 10.514$	0.92
8	Sepiolite	6 mm	79	$S_r = 0.0216w^2 + 2.0059w - 9.9788$	0.94
9	Sepiolite	12 mm	79	$S_r = -0.0023w^2 + 2.8261w - 11.657$	0.93

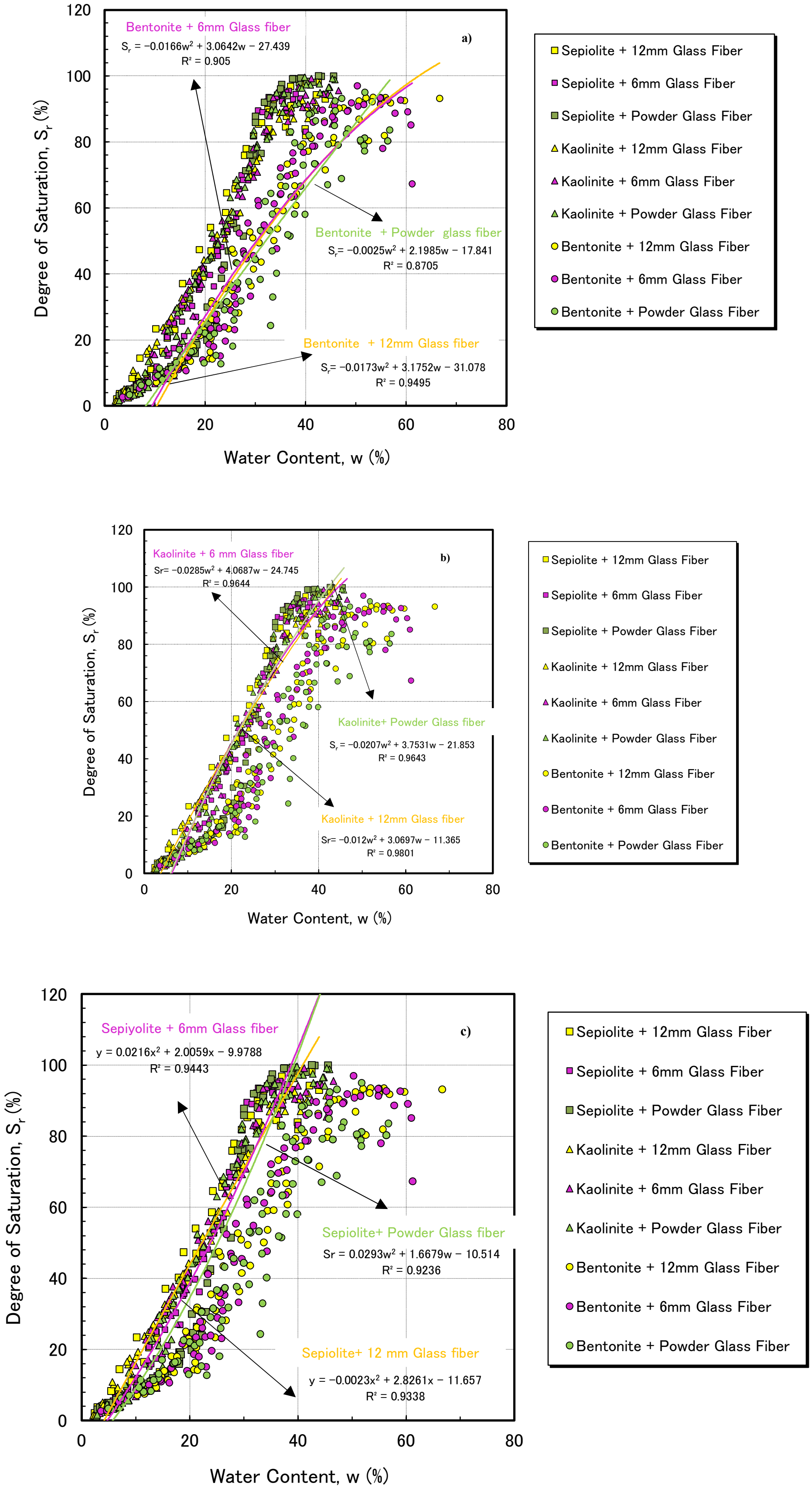

Figure 12. Relationship between degree of saturation and water content a) Bentonite+Glass fiber mixtures, b) Kaolinite+Glass fiber mixtures, c) Sepiolite+ Glass fiber mixtures

3.6 Dry density-Degree of saturation relationship

Figure 13 shows the independently calculated degrees of saturation for the Bentonite+Fiber, Kaolinite+Fiber, and Sepiolite+Fiber mixtures that correspond to the dry density values. Data sets 225, 230, and 264 were used for the experimental investigation for mixtures of Bentonite+Fiber, Kaolinite+Fiber, and Sepiolite+Fiber, respectively. Equations 2, 3, and 4 contained the second-order polynomial with the highest R^2 values. Standard compaction test results from clay+fiber mixtures showed that the degrees of saturation increased at different rates as the water content increased, even though the dry density values were closer to one another at low saturation levels. Dry density values increased as a result of this rise. Bentonite+fiber mixtures had the lowest dry density values, while Sepiolite+fiber mixtures had the highest dry density values. The dry density values of the Sepiolite+Fiber, Kaolinite+Fiber, and Bentonite+Fiber mixtures were 1.27 g/cm^3, 1.118 g/cm^3, and 1.13 g/cm^3 at a constant saturation level, such as 60% saturation. The degree of saturation required for the dry densities to take the highest value varied between 89% and 92% on average in sepiolite+fiber and kaolinite+fiber mixtures, whereas it was only 81% in bentonite+fiber mixtures.

$$\rho_d = -0.00009 \times S_r^2 + 0.0165 \times S_r + 0.5876 \quad (n = 225, R^2 = 0.898) \tag{2}$$

$$\rho_d = -0.0001 \times S_r^2 + 0.0178 \times S_r + 0.4829 \quad (n = 230, R^2 = 0.878) \tag{3}$$

$$\rho_d = -0.0001 \times S_r^2 + 0.0162 \times S_r + 0.4453 \quad (n = 264, R^2 = 0.882) \tag{4}$$

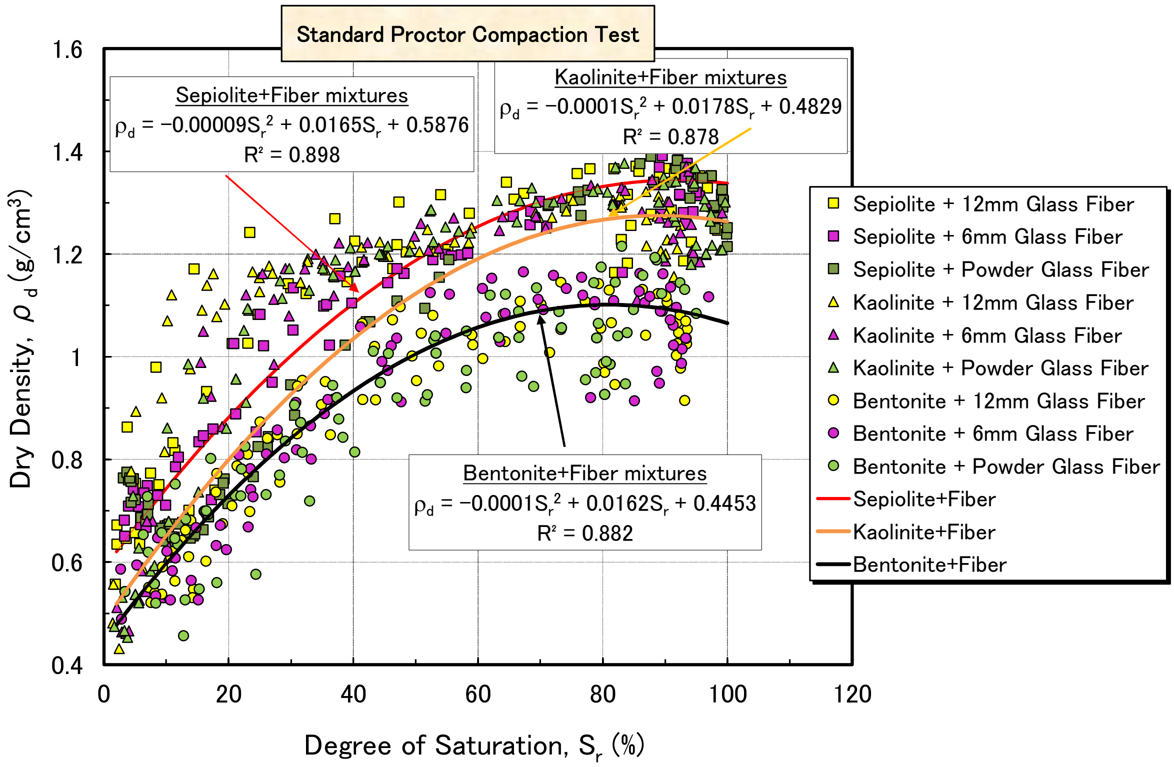

Figure 13. Degree of saturation-dry density relationships for Clay (Sepiolite/Kaolinite/ Bentonite) + Glass fiber (powder/6mm/12mm) mixtures

Conclusions

Three different types of clay with varying plasticity properties (Sepiolite, Benyonite, and Kaolinite) were combined with three different types of glass fibers (powder, 6 mm, and 12 mm) as part of this experimental study to examine the compaction behavior of clay + glass fiber mixtures. Standard compaction tests were then conducted. The experiments employed six different fiber ratios, with a 1% fiber increase rate, ranging from 0% to 5% by weight. Three different types of clay, three different types of fiber, and six different fiber ratios were used in the experimental study's fifty-four standard proctor tests.

The experimental results shows that the mixtures of kaolin+fiber and sepiolite+fiber that were closest to the ZAV curve had water contents of about 40%. The degree of saturation in the Sepiolite+Fiber and Kaolin+Fiber mixtures was less than 20% at very low water contents of approximately 2% to 15%. When the water content in Bentonite+Fiber mixtures ranges from 2% to 22%, the saturation level stays below 20%.

Sepiolite+fiber mixtures had the highest optimum degree of saturation, while bentonite+fiber mixtures had the lowest optimum degree of saturation. The average optimum degree of saturation level (S_{opt}=85.78) was determined for every clay+fiber combination. Generally, higher OWC values were obtained at 5% fiber content in all experiments. Sepiolite+powder glass mixtures generally had the highest MDD values, whereas bentonite+12 mm fiber glass mixtures had the lowest MDD values.

Overall, it can be concluded that when the OWC value is viewed as a function of fiber length, decreasing OWC values are obtained as the fiber length increases. As opposed to bentonite+fiber mixtures, which only needed 81%, sepiolite+fiber and kaolinite+fiber mixtures needed an average of 89% and 92% degree of saturation for the dry densities to take the highest value.

Funding: The authors did not receive support from any organization for the submitted work.

References

Akbulut, S., Arasan, S., & Kalkan, E. (2007). Modification of clayey soils using scrap tire rubber and synthetic fibers. *Applied Clay Science*, *38*(1), 23–32. https://doi.org/10.1016/j.clay.2007.02.001

Anagnostopoulo, C. A., Tzetzis, D., & Berketis, K. (2014). Evaluation of the Shear Strength Behaviour of Polypropylene and Carbon Fibre Reinforced Cohesive Soils. *Research Journal of Applied Sciences, Engineering and Technology*, *7*(20), Article 20. https://doi.org/10.19026/rjaset.7.805

Bell, F. G. (1996). Lime stabilization of clay minerals and soils. *Engineering Geology*, *42*(4), 223–237. https://doi.org/10.1016/0013-7952(96)00028-2

Benziane, M. M., Della, N., Denine, S., Sert, S., & Nouri, S. (2019). Effect of randomly distributed polypropylene fiber reinforcement on the shear behavior of sandy soil.

Studia Geotechnica et Mechanica, *41*(3), 151–159. https://doi.org/10.2478/sgem-2019-0014

Çelik, S., Ghalehjough, B. K., Majedi, P., & Akbulut, S. (2017). Effect of randomly fiber reinforcement on shear failure surface of soil, behind flexible retaining walls at different conditions. *Indian Journal of Geo-Marine Sciences*, *46*(10), 2097–2104. Scopus.

Chen, M., Shen, S.-L., Arulrajah, A., Wu, H.-N., Hou, D.-W., & Xu, Y.-S. (2015). Laboratory evaluation on the effectiveness of polypropylene fibers on the strength of fiber-reinforced and cement-stabilized Shanghai soft clay. *Geotextiles and Geomembranes*, *43*(6), 515–523. https://doi.org/10.1016/j.geotexmem.2015.05.004

Choobbasti, A. J., Kutanaei, S. S., & Ghadakpour, M. (2019). Shear behavior of fiber-reinforced sand composite. *Arabian Journal of Geosciences*, *12*(5), 157. https://doi.org/10.1007/s12517-019-4326-z

Choobbasti, A. J., Samakoosh, M. A., & Kutanaei, S. S. (2019). Mechanical properties soil stabilized with nano calcium carbonate and reinforced with carpet waste fibers. *Construction and Building Materials*, *211*, 1094–1104. https://doi.org/10.1016/j.conbuildmat.2019.03.306

Consoli, N. C., Arcari Bassani, M. A., & Festugato, L. (2010). Effect of fiber-reinforcement on the strength of cemented soils. *Geotextiles and Geomembranes*, *28*(4), 344–351. https://doi.org/10.1016/j.geotexmem.2010.01.005

Consoli, N. C., Casagrande, M. D. T., Prietto, P. D. M., & Thomé, A. (2003). Plate Load Test on Fiber-Reinforced Soil. *Journal of Geotechnical and Geoenvironmental Engineering*, *129*(10), 951–955. https://doi.org/10.1061/(ASCE)1090-0241(2003)129:10(951)

Dhar, S., & Hussain, M. (2019). The strength behaviour of lime-stabilised plastic fibre-reinforced clayey soil. *Road Materials and Pavement Design*, *20*(8), 1757–1778. https://doi.org/10.1080/14680629.2018.1468803

Estabragh, A. r., Namdar, P., & Javadi, A. a. (2012). Behavior of cement-stabilized clay reinforced with nylon fiber. *Geosynthetics International*, *19*(1), 85–92. https://doi.org/10.1680/gein.2012.19.1.85

Gao, L., Hu, G., Xu, N., Fu, J., Xiang, C., & Yang, C. (2015). Experimental Study on Unconfined Compressive Strength of Basalt Fiber Reinforced Clay Soil. *Advances in Materials Science and Engineering*, *2015*, e561293. https://doi.org/10.1155/2015/561293

Jiang, H., Cai, Y., & Liu, J. (2010). Engineering Properties of Soils Reinforced by Short Discrete Polypropylene Fiber. *Journal of Materials in Civil Engineering*, *22*(12), 1315–1322. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000129

Karakan, E. (2018). Factors Effecting the Shear Strength of Geotextile Reinforced Compacted Clays. *Dokuz Eylül Üniversitesi Mühendislik Fakültesi Fen ve Mühendislik Dergisi*, *20*(60), Article 60.

Kutanaei, S. S., & Choobbasti, A. J. (2015). Prediction of combined effects of fibers and cement on the mechanical properties of sand using particle swarm optimization algorithm. *Journal of Adhesion Science and Technology*, *29*(6), 487–501. https://doi.org/10.1080/01694243.2014.995343

Kutanaei, S. S., & Choobbasti, A. J. (2016). Triaxial behavior of fiber-reinforced cemented sand. *Journal of Adhesion Science and Technology*, *30*(6), 579–593. https://doi.org/10.1080/01694243.2015.1110073

Lemaire, K., Deneele, D., Bonnet, S., & Legret, M. (2013). Effects of lime and cement treatment on the physicochemical, microstructural and mechanical characteristics of a plastic silt. *Engineering Geology*, *166*, 255–261. https://doi.org/10.1016/j.enggeo.2013.09.012

Shen, Y., Tang, Y., Yin, J., Li, M., & Wen, T. (2021). An experimental investigation on strength characteristics of fiber-reinforced clayey soil treated with lime or cement. *Construction and Building Materials*, *294*, 123537. https://doi.org/10.1016/j.conbuildmat.2021.123537

Tajdini, M., Hajialilue Bonab, M., & Golmohamadi, S. (2018). An Experimental Investigation on Effect of Adding Natural and Synthetic Fibres on Mechanical and Behavioural Parameters of Soil–Cement Materials. *International Journal of Civil Engineering*, *16*(4), 353–370. https://doi.org/10.1007/s40999-016-0118-y

Tang, C.-S., Shi, B., Cui, Y.-J., Liu, C., & Gu, K. (2012). Desiccation cracking behavior of polypropylene fiber–reinforced clayey soil. *Canadian Geotechnical Journal*, *49*(9), 1088–1101. https://doi.org/10.1139/t2012-067

Tran, K. Q., Satomi, T., & Takahashi, H. (2018). Improvement of mechanical behavior of cemented soil reinforced with waste cornsilk fibers. *Construction and Building Materials*, *178*, 204–210. https://doi.org/10.1016/j.conbuildmat.2018.05.104

Wang, D., Abriak, N. E., & Zentar, R. (2013). Strength and deformation properties of Dunkirk marine sediments solidified with cement, lime and fly ash. *Engineering Geology*, *166*, 90–99. https://doi.org/10.1016/j.enggeo.2013.09.007