Jurnal Teknik Sipil & Perencanaan 25 (1) (2024) p 42 - 53

JURNAL TEKNIK SIPIL & PERENCANAAN

10.15294/jtsp.v26i1.49722

Experimental Study of Cationic-Modified Biopolymer for Increasing the Shear Strength of Sand

Andra Ardiana,[1], Aswin Lim[1, a)], Henky Muljana[2]

[1] *Faculty of Engineering, Department of Civil Engineering, Parahyangan Catholic University,*
[1] *Faculty of Industrial Engineering, Department of Chemical Engineering, Parahyangan Catholic University,*

[a)] aswinlim@unpar.ac.id

Abstract. The application of biopolymers as a more environmentally friendly binding agent has emerged as an exciting research subject to enhance the shear strength of sandy soils. In this article, the selected biopolymer is cationic-modified starch. It is expected that cationic starch will have less water absorption properties since modified starch has cationic groups in place of the OH^- groups found in regular starch. This cationic-modified starch is Amylofax. Five types of samples were made for this test, including samples with a mixture of 2% glucomannan, 2% T(1100), 2% T(2200), 2% T(3300), 2% T(1100) + 2% Beeswax, 2 % T(2200) + 2% Beeswax and 2 % cement. The mixing methods used are hot mixing and cold mixing. The samples were tested using a direct shear test apparatus and UCS to determine the soil shear strength parameters (c) cohesion and (φ) internal friction angle. After conducting the tests on the sand samples with the addition of modified starch biopolymer (cationic starch), it was found that the use of cationic starch provides an increase in shear strength that is greater than natural starch, the cohesion value increases from 215 kPa to 833 kPa and the internal friction angle from 35° to 67°. Increasing the cationic starch code increases cohesion value from 392 kPa to 833 kPa. Still, the shear angle values are almost the same in the three cationic starch samples, ranging between 57° and 67°. The mixing method also influences the cohesion value, which is unique, where cold mixing has a greater cohesion value compared to hot mixing, 392 kPa to 774 kPa for sample A and 588 kPa to 961 kPa for sample B. Samples were also tested with a mixture of 2% cement where this sample was destroyed and could not be formed, so it could be proven that the use of cationic biopolymers was superior to the use of cement with the same ratio.

Keywords: modified-cationic biopolymer, soil improvement, soil shear strength, biopolymer

INTRODUCTION

According to Plank[1], cement manufacturing negatively influences the environment since it releases 2% of all CO_2 emissions, increasing greenhouse gas emissions. Some researchers have looked for alternative materials for binding the soil particle, such as using Fungi-Mycelium Treated Soil [2][3][4] [5] or biopolymer. Using biopolymers aims to replace the role of cement as a hydraulic binder that can enhance soil shear strength while being more environmentally friendly. The use of biopolymers in biopolymer-based soil treatment (BPST) can be confirmed for its effectiveness in geotechnical engineering when addressing environmental concerns [6] [7][8].

Biopolymers are natural polymers derived from plants, animals, algae, fungi, or bacterial sources, primarily composed of polysaccharides. The addition of the biopolymer Glucomannan to soil samples has been proven to increase the shear strength of the soil. The resulting cohesion significantly increases due to the addition of Glucomannan and Xanthan Gum [9][10]. Based on the results of the Scanning Electron Microscope (SEM) analysis, it is suspected that this increase is caused by the cohesion resulting from the formation of a biopolymer film and the filling of voids by Xanthan gum biopolymer. One of the limitations of biopolymers in their practical application is their propensity to dissolve in water readily. In geotechnical engineering, particularly in soil improvement, it is crucial to find solutions for this issue because soil-related work often encounters water on the surface in the form of surface runoff and within the ground as groundwater.

A polymer is defined as a substance made up of repetitive structural elements. The word "polymer" comes from the Greek terms "Poly," which means many, and "Mer," which means pieces. Consequently, "PolyMer" might be understood to mean numerous pieces. Synthetic polymers, semi-synthetic polymers, and biopolymers, freely available in nature, are the three primary groups of polymers. Although synthetic polymers are frequently utilized, they have negative environmental implications, including creating difficult decomposing garbage. Furthermore, the raw materials for synthetic polymers are derived from petroleum, a non-renewable resource that will eventually be depleted. Meanwhile, biopolymers can be categorized into two types: (1). Polymers are produced by biological systems, such as animals, plants, and microorganisms, (2). Polymers are synthesized chemically but derived from natural compounds produced by biological systems, such as sugars and amino acids.

Research mentions that starch biopolymers need to be modified chemically to produce suitable properties or characteristics of the product [7]. Cationic starch is the result of chemically or enzymatically modifying anionic starch, where the initially negative charge of the starch is transformed into a positive charge. The production process of cationic starch involves using cationic reagents in a natural starch solution under suitable reaction conditions (temperature and pH). Chemically, the negative charge of the starch is converted into a positive charge. Commonly used reagents include 2-chloroethyldiethylamine, 2,3-epoxypropyldiethylamine, and 3-chloro-2-hydroxypropyl [11]. The charge of fibers can be balanced out by cationic starch. Stronger paper sheets result from positively charged cationic starch molecules forming electrostatic and hydrogen connections with fibers.

Cationic starch has strong solubility and can stick to fibers effectively. It has a better retention rate than natural starch, which has its economic value and can help to offset its higher price. Additionally, because it helps lessen water contamination, cationic starch is more environmentally beneficial.

Cationic starch is extensively used as an internal binder in the paper industry, and it is retained in the pulp before forming paper sheets. Cationic starch serves as dry strength, retention aid, and drainage aid. It effectively enhances the physical properties of paper sheets, such as internal bonding, tensile strength, and tearing strength. The addition of CaO (calcium oxide) in the starch modification process can increase efficiency by enhancing the degree of substitution (DS) during the reaction [12].

Sandy soil is a granular soil composed primarily of quartz and feldspar [13]. **Table 1** shows the classification of sandy soil using the USCS system—the particle sizes of this sandy soil range from 4.75 to 0.075 mm. According to the USCS classification system, the particle sizes of this sandy soil are divided into three categories: fine sand, medium sand, and coarse sand. Using a Scanning Electron Micrograph (SEM) helps provide a clearer view of the grain shapes of sand particles. The shapes of sand grains include subrounded, rounded, angular, and subangular [14].

Table 1. Classification of Sandy Soil Based on the USCS System [13]

Organization	**Classification**	**Size Limit [mm]**
Unified, U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, and American Society for Testing and Materials	Coarse sand	4,705 – 2,000
	Medium sand	2,000 – 0,425
	Fine sand	0,425 – 0,075

In this research, the use of modified starch biopolymer will be explored. In addition, granule beeswax is also mixed with some samples. This study aims to assess the changes in shear strength parameters through direct shear testing and unconfined compressive strength (UCT) testing of sandy soil with the admixture of Amylofax and beeswax.

METHODOLOGY

The research was conducted at the Geotechnical Laboratory of Parahyangan Catholic University in Bandung. The testing equipment used in this research included the direct shear test apparatus and the unconfined compressive strength (UCS) test apparatus. The direct shear test specimens were prepared with a diameter of 50 mm and a height of 20 mm, while the unconfined compressive strength test specimens had a diameter of 38 mm and a height of 76 mm. The sand used in the research was silica sand, commonly used for field soil density testing with a sand cone or Sand Cone Test apparatus. The modified starch used was Amylofax, which was derived from potato starch. Amylofax used in the study consisted of three types with codes T1100, T1200, and T3300. The Beeswax used was processed into granular form. Figure 1 depicts the photo of Silica sand, Amylofax, and Beeswax, respectively.

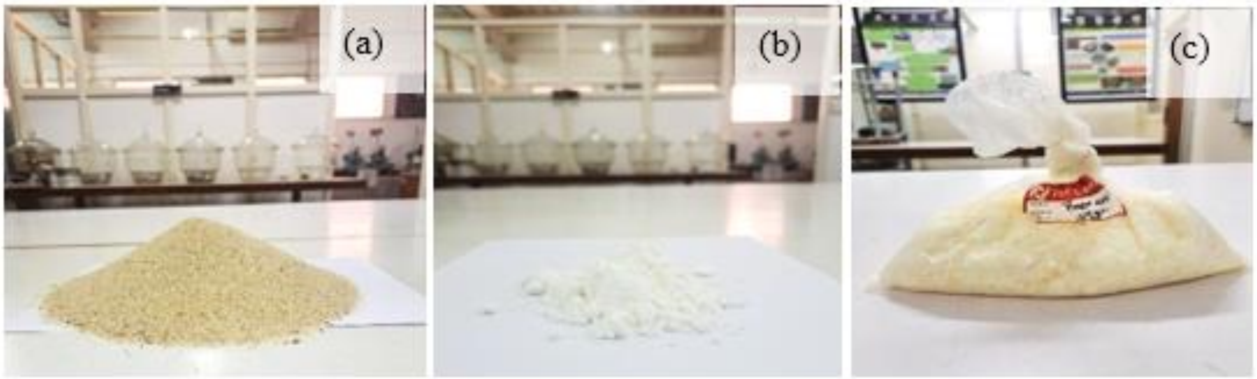


Figure 1. Picture of (a) Silica sand, (b) Amylofax, (c) beeswax
(Source: Amylofax from Chemical UNPAR Laboratory, Beeswax Palet from T&T Chemical)

Index Properties Testing

This testing was conducted to determine the physical properties of silica sand. The tests included the minimum and maximum soil unit weight, specific gravity test, and sieve analysis.

Density test for sand soil

This testing is carried out on initial conditions of Silica sand samples. The equipment required to conduct the soil bulk density test includes a Small-sized compaction mold. Figure 2 shows the Vernier caliper, Scale with an accuracy of 0.01 grams, Spatula, and Funnel.

Figure 2. A mini compaction mold
(Source: UNPAR Laboratory Mini Mold)

Soil density testing at maximum and minimum density conditions [15] & [16]

This testing is conducted on silica sand twice to ensure consistent results. The testing aims to obtain emin and emax values, where the sand is most densely and loosely compacted. The testing equipment consists of a Small-sized compaction mold, Rubber mallet, Scale with an accuracy of 0.1 grams, Vernier caliper, and Funnel.
Specific gravity test [17]**.**

This test aims to determine the specific gravity of soil using an Erlenmeyer flask. Testing Equipment includes an Erlenmeyer flask, Distilled water (Aquades), a Scale with an accuracy of 0.01 grams, a Thermometer, an Electric stove, a Glass stirring rod, an Evaporating dish or porcelain dish, a Pipette, and an Oven. The complete set of testing tools is shown in Figure 3.

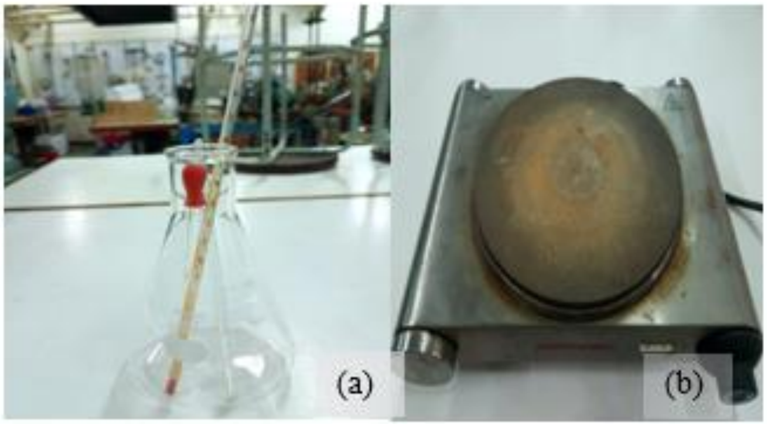


FIGURE 3. Soil Specific Gravity Testing Equipment (Erlenmeyer Flask, Thermometer, Glass Stirring Rod, Pipette (a)), (Electric Stove (b))
(Source: UNPAR Laboratory)

Grain size analysis [18]

This test aims to determine the particle size distribution of soil particles larger than 75 µm or retained by the No. 200 sieve. The used testing equipment is as follows:

1. A set of sieves with standard sizes: No. 4 - 10 - 20 - 40 - 80 - 120 - 200 - Pan.
2. Scale with an accuracy of 0.01 grams.
3. Sieve shaker or vibrating sieve apparatus.
4. Brush.

TABLE 2. Standard Sieve Mesh Sizes [18].

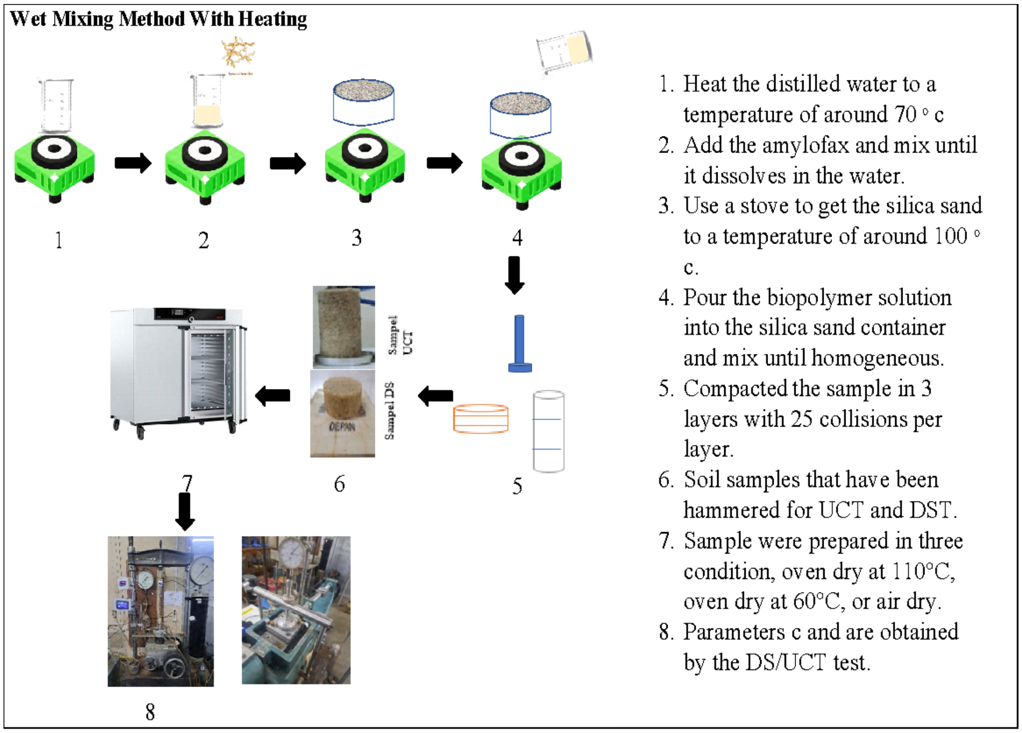
Sieve no	Sieve size (mm)
4	4.750
10	2.000
20	0.850
40	0.425
80	0.180
120	0.125
200	0.075

Soil Sample Mixing

The mixing of samples is conducted with variations in the use of biopolymer, hot mixing method, cold mixing method, and variations in normal stress [19].

Soil Sample Mixing (Hot Mixing Method)

Mixing soil samples using the wet method involves mixing water and Amylofax, heating until Amylofax dissolves, stirring until homogeneous and slightly thickened, then mixing with preheated silica sand samples. This mixture is stirred until well-blended and compacted into a direct shear test and unconfined compressive strength test molds. A schematic representation of sample preparation using the wet mixing method can be seen in Figure 4.

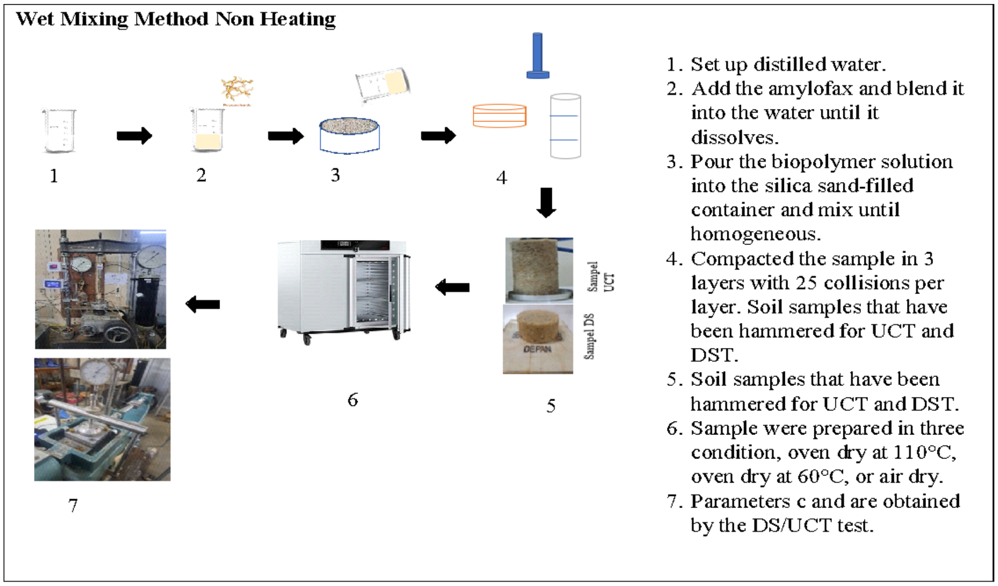


1. Heat the distilled water to a temperature of around 70 ° c
2. Add the amylofax and mix until it dissolves in the water.
3. Use a stove to get the silica sand to a temperature of around 100 ° c.
4. Pour the biopolymer solution into the silica sand container and mix until homogeneous.
5. Compacted the sample in 3 layers with 25 collisions per layer.
6. Soil samples that have been hammered for UCT and DST.
7. Sample were prepared in three condition, oven dry at 110°C, oven dry at 60°C, or air dry.
8. Parameters c and are obtained by the DS/UCT test.

FIGURE 4. Schematic of Sample Preparation Using the Wet Mixing Method with Heating Process

Soil Sample Mixing (Cold Mixing Method)

Mixing soil samples using the wet method involves mixing water and Amylofax without heating until Amylofax dissolves, stirring until homogeneous and slightly thickened, then mixing with preheated silica sand samples. This mixture is stirred until well-blended and then compacted into the direct shear test and unconfined compressive strength test molds. A schematic representation of sample preparation using the wet mixing method can be seen in Figure 5.



1. Set up distilled water.
2. Add the amylofax and blend it into the water until it dissolves.
3. Pour the biopolymer solution into the silica sand-filled container and mix until homogeneous.
4. Compacted the sample in 3 layers with 25 collisions per layer. Soil samples that have been hammered for UCT and DST.
5. Soil samples that have been hammered for UCT and DST.
6. Sample were prepared in three condition, oven dry at 110°C, oven dry at 60°C, or air dry.
7. Parameters c and are obtained by the DS/UCT test.

FIGURE 5. Schematic of Sample Preparation Using the Wet Mixing Method without Heating Process

Direct Shear Test [20]

The direct shear test aims to obtain the shear resistance value of soil at a specific everyday stress. This test is conducted with variations in normal stress. The normal stress variations used in this direct shear test are 50, 100, and 150 kPa.

Unconfined Compressive Strength Test [21]

The unconfined compressive strength test is conducted by placing the sample on the pedestal of the compression apparatus and then applying a direct axial load to the sample without any confining stress until the sample undergoes failure.

Soaking Test

This experiment involves submerging the sample in a container until failure happens. The process of failure or degradation due to water is visually observed. This testing is performed to determine the durability of the sample under submerged conditions.

RESULTS AND DISCUSSIONS

The index properties test is conducted to obtain the behavior or characteristics of the tested soil sample, as shown in Table 3. The index properties tests performed in this study include specific gravity, dry unit weight test, and sieve analysis. The specific gravity value obtained is 2.66, close to the specific gravity value of silica sand obtained from the test Mousavi and Ghayoomi, [22] which is 2.65.

The value of the soil-to-volume ratio (dry unit weight) obtained consists of two values: first, the maximum dry unit weight γdmax = 17.6 kN/m^3, while the minimum dry unit weight γdmin = 14.5 kN/m^3. The results of γ_{dmax} and γ_{dmin} from the experiment are close to the values of γdmax and γdmin obtained from the testing conducted by Mousavi and Ghayoomi [22].

According to the Unified Soil Classification System (USCS), the soil used falls into the poorly graded sand or SP (Poor Graded Sand) category.

TABLE 3. Results of Sand Soil Index Properties Test

Parameter	**Results**	**Reference**
Specific gravity, *Gs*	2.66	ASTM D 1429
Soil classification	SP (Poorly Graded Sandy)	USCS
Max, dry density, γ_{dmax}	17.6 kN/m^3	ASTM D 4253
Min, dry density, γ_{dmin}	14.5 kN/m^3	ASTM D 4254

Table 3 shows the properties and characteristics of the sand samples used in this research. The sand sample, as the basic material, is classified as silica sand, and the results of the index properties test are supported by research conducted by Mousavi and Ghayoomi [22].

The Influence of Amylofax Addition on the Increase in Soil Shear Strength Value

Table 4 presents the collection of test results conducted to determine the effects of adding Amylofax with codes (A) = Amylofax T1100, (B) = Amylofax T2200, and (C) = Amylofax T3300 to silica sand samples. Additionally, in this test, an attempt was made to mix Amylofax with a natural biopolymer, specifically glucomannan. Direct shear testing was performed to determine the changes in shear strength values of the soil samples.

From the test results, the addition of modified starch had a significant positive effect on the increase in soil shear strength values compared to the addition of glucomannan biopolymer. The cohesion values increased from 215 kPa added 2 % glucomannan to 961 kPa added 2 % T(3300), and the internal friction angle ranged from 35° to 57°respectively. This is consistent with previous research conducted by Muguda et al. [23], where the increase in cohesion due to the addition of biopolymer was attributed to the formation of hydrogels that bind soil particles through hydrogen bonding, with or without ion bonding, depending on the type of biopolymer used.

TABLE 4. Shear Strength of Soil with Amylofax Mixture Variation

Method	Composition	c, kPa	φ, (°)	γ_{dry}, (kN/m^3)
Wet, hot mixing, oven dry	2 % glucomannan	215	35	16.18
Wet, hot mixing, oven dry	2 % (A)	392	64	16.47
Wet, hot mixing, oven dry	2 % (B)	588	67	16.54
Wet, hot mixing, oven dry	2 % (C)	833	57	16.95
Wet, cold mixing, oven dry	2 % (A)	774	58	16.94
Wet, cold mixing, oven dry	2 % (B)	961	58	16.65
Wet, hot mixing, oven dry	2 % (A) + 2 % (BW)	140	35	15.94
Wet, hot mixing, oven dry	2 % (B) + 2 % (BW)	127	16	15.11
Dry, cold mixing, oven dry	2 % Cement	Untestable (Unable to be formed)		

The addition of cement components to the sand sample cannot be done because the ratio of 2% cement is not strong enough to create bonds between sand grain particles so that the sand cannot be molded and crushed.

The Influence of Adding Amylofax with a Wet and Hot Mixture

Figure 6 shows the results of shear strength testing by adding Amylofax using the wet and heated mixing method. The wet mixing method is employed based on a previous study conducted by Seo et al. [23], where their research suggested that wet mixing results in a more uniform distribution of the biopolymer mixture in the soil. The use of modified starch demonstrates a significant improvement in shear strength, reaching up to 833 kPa with an angle of internal friction of 57°. The greater the code number of the Amylofax used, the higher the cohesion value of the soil. Amylofax with code C yields the highest cohesion compared to B and A. The code number in Amylofax indicates the extent to which OH$^-$ groups are replaced by cations. The increase in shear strength due to adding modified starch is attributed to replacing hydrophilic OH$^-$ groups with cationic groups. This test shows that adding cation starch can increase the cohesion value, which is greater than natural starch and better than adding cement in the same composition. This has proven that biopolymers can be used as a substitute for more environmentally friendly cement.

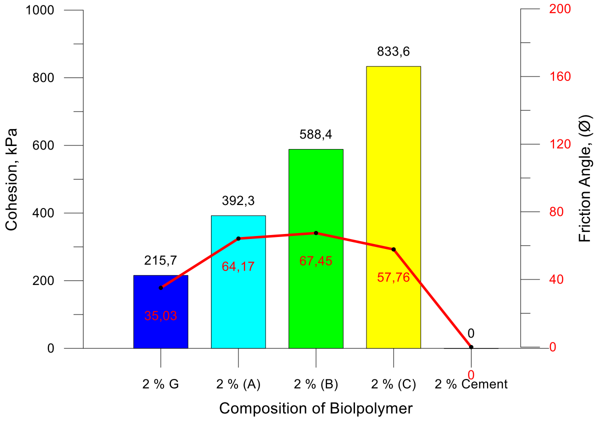


FIGURE 6. Obtained soil cohesion and internal friction angle with the composition of the biopolymer hot mix.

The Influence of Adding Amylofax Wet Method Without Heating (Cold Mixture)

Figure 7 shows the test results, slightly different from the previous testing method. In this test, the Amylofax mixing method is done wet but without the heating process. This experiment was conducted to determine whether modified starch with a cold mixture can increase the soil shear strength value, similar to conventional mixtures using heating, following the properties of biopolymers, where the gelatinization process requires heating.

The results obtained with the cold mixture provide better shear strength values than the hot mixture. The cohesion values increased from 392 - 588 kPa, and the internal friction angle ranged from 64° to 67° when using Amylofax T1100 and the cohesion values increased to 774 - 961 kPa, and the internal friction angle ranged from 58,5° to 58,7°. The internal friction angle ranged from 64° to 67° when using Amylofax T2200, which is higher than those achieved with the hot mixing method. Therefore, applying this modified starch may be more straightforward in the future as it does not require a heating process. This is very important for ease of operation in field-scale experiments.

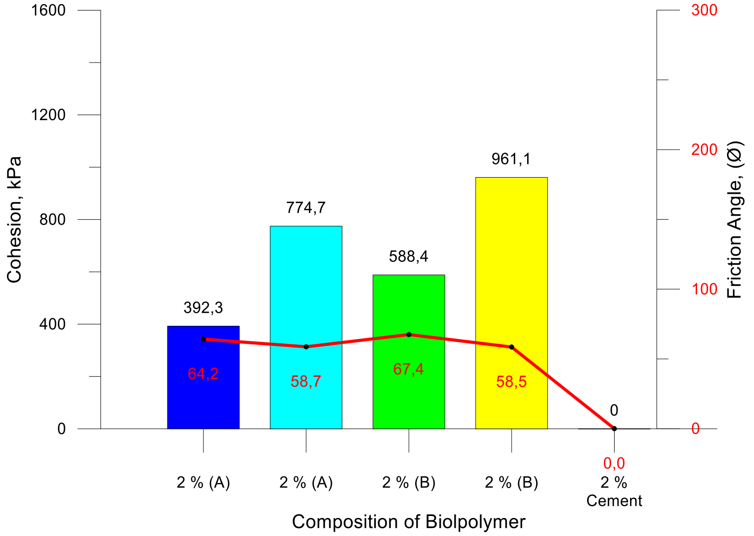


FIGURE 7. Obtained Soil Cohesion and Internal Friction Angle Values Versus Composition of Cold Mixed Biopolymer

The Effect of Adding Beeswax to Amylofax

Figure 8 illustrates how adding beeswax to the Amylofax mixture affects the shear strength values. In this test, beeswax was added in the same concentration as the modified starch (Amylofax), which is 2% of the weight of the silica sand used. The test with the addition of beeswax was conducted using the hot mixing method. This was done because beeswax does not dissolve in cold water, so it needs to be heated to ensure even mixing with Amylofax solution. Once the beeswax was evenly mixed with Amylofax, it was mixed with silica sand and stirred until well-distributed. The results of the test showed that Amylofax with codes A and B experienced a decrease in cohesion from 392 kPa to 140 kPa with amylofax T(1100) and 588 kPa to 127 kPa with amylofax T(2200). As for the internal angle of friction, it increased from 64° to 67°, and it decreased from 35° to 16° for T(1100) and T(2200). The addition of beeswax to the mixture of sand and cationic starch has not shown positive results, so it is necessary to find other substitute materials with hydrophobic properties and good bonds with cationic starch.

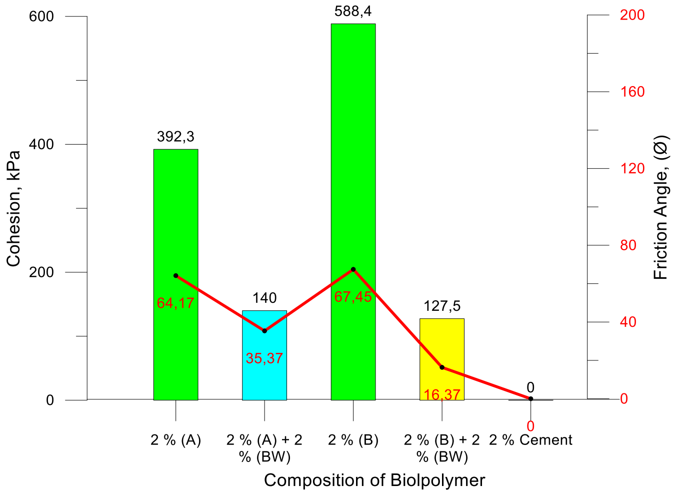
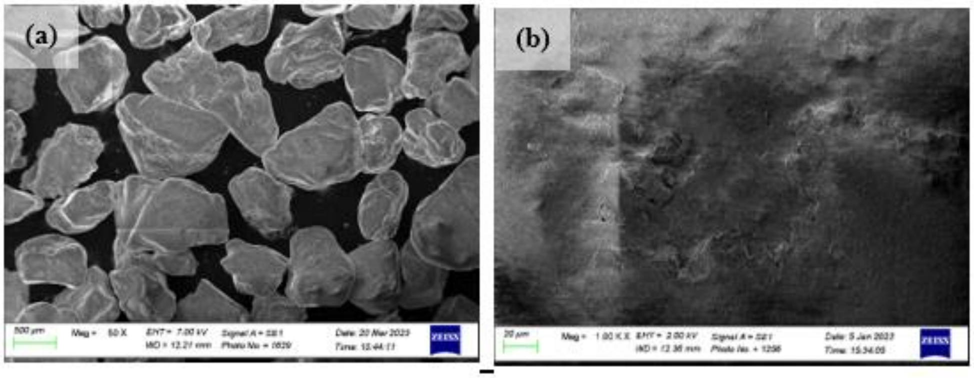


FIGURE 8. Obtained cohesion and internal friction angle values due to the addition of beeswax

Results of Digital Microscope and Sem Tests

This testing was conducted on specific sample variations to understand the bonding between sand particles and the biopolymers Amylofax, glucomannan, and Beeswax. These particle-to-particle bonds contribute to the increase in the shear strength of the sand. The SEM test results in Figure 9 (a) show the shape of the silica sand used in the experiment. Figure 9 (b) displays the surface morphology of solid Beeswax before dissolution in water. Figure 9 (c) exhibits images of samples mixed with Amylofax. These images illustrate that the biopolymer Amylofax coats the silica sand grains, forming interconnections and bonds between individual sand grains coated by the biopolymer.



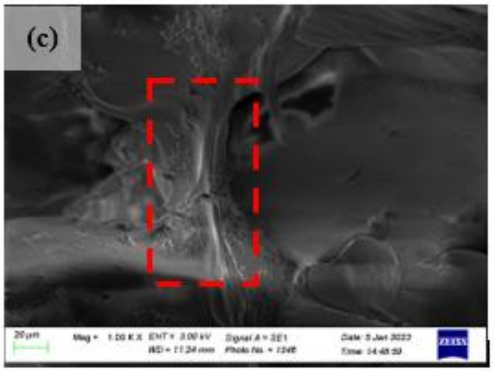


FIGURE 9. (a) SEM of silica sand, Figure 8 (b) SEM of beeswax. Figure 8 (c) SEM of Amylofax sample C.

The Results of The Unconfined Compressive Strength (Ucs) Test [24]

Table 5 displays the results of unconfined compressive strength (UCS) tests conducted to determine undrained shear strength values for each soil mixture with varying amounts of Amylofax. The cohesion values for undrained shear strength are as follows:

1. Amylofax with Sample A: Cohesion value of 302 kPa and modulus E_{50} of 94.6MPa.
2. Amylofax with Sample B: Cohesion value of 479 kPa and modulus E_{50} of 149.8 MPa.
3. Amylofax with Sample C: Cohesion value of 1278.7 kPa and modulus E_{50} of 440.9 MPa.

TABLE 5. Undrained Shear Strength Values with Various Amylofax Variations from Unconfined Compressive Strength Tests

Method	**Sample**	**S_u [kPa]**	**E_{50} [MPa]**	**γ_{dry}, [kN/m^3]**
W, HM, OD	A	302	94.6	15.68
W, HM, OD	B	479	149.8	15.64
W, HM, OD	C	1278	440.9	15.64

*W: Wet mixing, *HM: Hot mixing, *OD: Oven dry

*A: T1100, *B: T2200, *C: T3300

Those undrained shear strength values are very high. For comparison, the undrained shear strength of very stiff clay is around 250 kPa.

Soaking Test Results

This test assessed the durability of sand samples modified with beeswax, which exhibits hydrophobic properties. In this experiment, the resistance of modified starch as a biopolymer, combined with beeswax, did not yield the expected results. The samples still easily disintegrated when immersed in water. Consequently, the hydrophobic nature of beeswax as an additive had a negative impact.

CONCLUSIONS

Using modified starch or cationic starch has been proven to enhance the shear strength of sandy soil. During the mixing process, cationic starch dissolves more quickly than natural starch, ensuring a more even distribution of biopolymer in the sample. The test results indicate that using modified starch, such as Amylofax, yields higher shear strength than glucomannan. Furthermore, the higher the Amylofax code used, the greater the cohesion value obtained. Sample C achieved the highest cohesion value of 833 kPa, surpassing Sample B and A, with 588.4 kPa and 392.3 kPa, respectively. The internal friction angle varied between 64° and 67°. The cold-water mixing method resulted in higher cohesion values than the hot-water mixing method, with a cohesion value of 961 kPa compared to 588.4 kPa. At the same time, the internal friction angle slightly decreased from 58° to 67°. Adding beeswax to the Amylofax mixture decreased cohesion, which contrasts the effect observed when combining glucomannan with beeswax.

ACKNOWLEDGMENTS

The authors would like to express our gratitude to Parahyangan Catholic University for all the support they have been providing to complete this research.

REFERENCES

[1] J. Plank, "Applications of biopolymers in construction engineering. In Biopolymers," *N Biopolym. Online; Wiley-VCH Verlag GmbH Co. KGaA*, 2005.

[2] Yosuardi Y, Lim A, Renggaman A, and Wijaya M, "Pengaruh Nutrisi Terigu Terhadap Perbaikan Tanah Pasir Silika dengan Miselium Jamur," *J. Arsip Rekayasa Sipil dan Perenc. 6*, 2023.

[3] Lim A, Sunaryo J.Y, Wijaya M, Satyanaga A, and Kristijarti A.P, "Hydraulic characteristics and incubation methods for enhancing durability of Fungi-Mycelium treated silica sand using Rhizopus oligosporus and Rhizopus oryzae combination," *Biogeotechnics*, 2024.

[4] Lim A, Henzi P, and Arvin O, "Comparison of pleurotus ostreatus and rhizopus oligosporus fungi for loose sand improvement," *J. Geoengin.*, vol. 18(1), pp. 1–10, 2023.

[5] Lim A and Pianica L, "Efek gradasi tanah pasir pada penggunaan jamur Rhizopus Oligosporus untuk perbaikan tanah pasir lepas," *J. Apl. Tek. Sipil*, vol. 20(2), pp. 157–163, 2022.

[6] C. G. Chang Ilhan, Lee Minhyeong, Tran An Thi Puong, Lee Sojeong, Kwon Yeong-Man, Im Jooyoung, "Review on biopolymer-based soil treatment (BPST) technology in geotechnical engineering practices," *ELSEVIER*, vol. 24, 2020, doi: diu.org/10.1016/j.trgeo.2020.100385.

[7] Hamidah, Marzuki H, and Kholidah N, "Rice Flour Potential As Biodegradable Plate (Bioplastic) In Terms Of It's Characteristics," *J. Sains dan Terap. Kim.*, 2021.

[8] Kumara S A and Sujatha E R, ""Performance evaluation of β-glucan treated lean clay and efficacy of its choice as a sustainable alternative for ground improvement," *Geomech. Eng*, doi: http://doi.org/10.12989/gae.2020.21.5.413.

[9] Lim A, Montol Y.A, and Rustiani S., "Improvement of soil shear strength using glucomannan biopolymer for loose sand," earth and envirionmnetal science, 2021.

[10] Lim A, Montol YA, and Rustiani S., "Soil Improvement Using Xanthan Gum Biopolymer for Loose Sand: Experimental Study," Springer, 2021.

[11] S.M Butrim and Et.al, "SYNTHESIS AND PHYSICOCHEMICAL PROPERTIES OF CATIONIC STARCHES," *Chem. Nat. Compd.*, 2011.

[12] Almonaityte K and Et.al, "Structure and properties of cationic starches synthesized by using 3-chloro-2-hydroxypropyltrimethylammonium chloride," *Int. J. Biol. Macromol.*, 2020.

[13] Das B.M, *Principles Of Geotechnical Engineering*, Seventh Ed. Canada: Cengage Learning, 2010.

[14] Holtz W.D and Kovacs R.D, *An Introduction to Geotechnical Engineering*. New Jersey: Prentice-Hall, 1981.

[15] [ASTM] American Society for Testing and Material (2000). *ASTM D-4253 Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table1*.

[16] [ASTM] American Society for Testing and Material. (2000). *ASTM D-4254 Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density.*

[17] [ASTM] American Society for Testing and Material. (2010). *ASTM D-1429 Standard Test Methods for Specific Gravity of Water and Brine.*

[18] [ASTM] American Society for Testing and Material. (2009). *ASTM D-6913-04. Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis1*.

[19] Ardiana A, Lim A, Muljana H, Putra H, and Widjaja B, "Studi Laboratorium Campuran Biopolimer Glukomanan dan Beeswax untuk Meningkatkan Kuat Geser Tanah Pasir," *J. Tek. Sipil*, vol. 17, pp. 197–208, 2023, doi: DOI: 10.24002/jts.v17i3.6968.

[20] [BSN] Badan Standardisasi Nasional. (2016). *SNI 3420:2016 Metode Uji Kuat Geser Langsung Tanah Tidak Terkonsolidasi dan Tidak Terdrainase. In Standar Nasional Indonesia (SNI). www.bsn.go.id*.

[21] [BSN] Badan Standardisasi Nasional. (2012). *SNI 3638:2012 Metode Uji Kuat Tekan-Bebas Tanah Kohesif . In Standar Nasional Indonesia (SNI). www.bsn.go.id*.

[22] Mousavi S and Ghayoomi M, "Dynamic shear modulus of microbial induced partially saturated sand," 2018. doi: 335703423.

[23] S. Muguda, G. Lucas, P. . Hughes, and Et.al, "Durability and hygroscopic behaviour of biopolymer stabilised earthen construction materials," *Constr. Build. Mater.*, 2020, doi: 10.1016/j.conbuildmat.2020.119725.

[24] [ASTM] American Society for Testing and Material (2016).*Standard Test Method for Unconfined Compressive Strength of Cohesive Soil*.