

Insights into potential of banana leaf powder as a mud soil stabilizer

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ABSTRACT

This study proposes a novel method for managing surplus soil in urban construction projects by investigating the use of banana leaf powder (BLP) as an eco-friendly and efficient mud-soil stabilizer. This study is pioneering in its focus on the use of an agricultural waste product, BLP, as an alternative to conventional methods that frequently rely on cement or lime, which pose environmental concerns owing to their high alkalinity and carbon emissions. BLP, derived from dried and pulverized banana leaves, traditionally used in various industries, was evaluated for its suitability as a stabilizer against orange peel biopolymer (OBP) and fly ash (FA). The findings of this study are groundbreaking. BLP's water absorption capacity, W_{ab} , although lower than that of OBP, was significantly higher than that of FA, demonstrating its potential as a mud soil stabilizer. BLP increased the compaction and strength of the treated clay, whereas OBP made it more challenging to compact the clay owing to gelatinization. The ease of compaction with BLP is attributed to the absorption of free water into the pores of the particles. These results suggest that differences in the stabilizer's water absorption mechanism affect the effectiveness of the post-treatment compaction process on the treated soil. An analysis of the impact of water absorption capacity on the cone index, q_c , revealed a material-independent relationship between the parameter β ($=W_{ab} \times A$, where A denotes stabilizer addition content) and q_c for BLP and FA. This is because, in contrast to OBP, BLP and FA did not gelatinize the free water that was not absorbed by the stabilizer and remained in the same form within the treated clay. This indicates that understanding the water absorption capacity and mechanism of organic- or inorganic-based stabilizers is important for predicting the strength of treated soil. The same relationship between β and q_c holds true for the hybrid-treated clay using both BLP and FA, with β considered to be the sum of β for both BLP and FA. Furthermore, this study innovatively addresses the concern of BLP decay in treated soil by creating a hybrid stabilizer with FA and conducting experiments to accelerate BLP decay using fungal mycelia. These experiments revealed that the hybrid-treated clay exhibited a more gradual decrease in carbon content and stabilized pH levels, implying that FA could inhibit decay by fungal mycelia, improving the BLP-treated soil's long-term durability. These findings suggest that agricultural wastes with high organic content can be effectively used for soil stabilization and ground improvement in civil engineering construction and maintenance projects by combining inorganic materials and taking advantage of their properties, such as high water absorbency. This can address the issues (such as high alkalinity and high carbon dioxide emissions) associated with cement- and lime-based stabilizers, which were previously widely used.

1. Introduction

During construction and maintenance activities, large quantities of soil are frequently excavated, creating "surplus soil" that requires proper disposal in regulated areas [1–3]. Owing to limited space, securing disposal sites is particularly difficult in urban areas [4–6]. With

increasing urbanization, the transportation of surplus soil to distant disposal locations incurs substantial costs and delays. In a recycling-oriented society, it is becoming more desirable to reuse surplus soil in the same or other construction projects [6,7]. High-quality excavated soil can be used as fill or backfill material. However, surplus soil from dredging operations in rivers, ports, and irrigation

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facilities is frequently characterized by high water content and fine particles, rendering it unsuitable for immediate reuse [8].

High-water-content sludge is commonly used as a construction material using dewatering methods such as drying or consolidation. However, these methods are time-consuming and produce soil with low strength, limiting their use in applications such as vegetative bases [9–11]. Alternatively, chemical stabilization with additives such as cement or lime can significantly improve the soil strength and support structural stability [12,13]. However, the use of these stabilizers frequently results in the production of alkaline byproducts such as calcium hydroxide, necessitating the installation of additional neutralization facilities [14–17]. Moreover, the environmental impact of cement and lime production, which emits considerable amounts of carbon dioxide, has become a major concern in the context of global warming [18–20].

Recent advances in sustainable materials have emphasized the importance of reducing the environmental impact of industrial processes [21]. reviewed sustainable transformations in soda ash production, highlighting innovative methods such as microbial-assisted and modified Solvay processes that use external CO₂ sources to reduce waste and emissions [22]. demonstrated the potential for geopolymerization of construction and demolition waste to produce sustainable building materials, aligning with global efforts to reduce environmental harm. Additionally [23], showed the eco-friendly synthesis of nanostructures using natural fuels such as grape juice to improve pollutant degradation, while [24] investigated novel materials for hydrogen storage, emphasizing the widespread adoption of eco-friendly technologies.

In line with these sustainable methods, recent research has focused on using waste and byproducts such as steel slag, coal ash, and biomass ash as alternatives to traditional stabilizers such as cement and lime for sludge treatment. Examples include steel slag, coal ash, paper mill incineration ash, sewage sludge incineration ash, and biomass incineration ash [25–31], some of which have been successfully commercialized. These wastes and byproducts are inorganic materials with relatively stable quality; therefore, verification is required. They are expected to provide long-term stability to treated soils. Organic polymer-based materials are used as stabilizers for muddy soils in the form of polymer-based materials [32–34]. However, the use of polymers raises environmental concerns. Other organic materials, such as agricultural waste without polymers, can be used as stabilizers to a limited extent. Agricultural waste, as an organic material, is less concerned with heavy metals than inorganic materials and is more environmentally friendly because it occurs naturally. However, its potential as a sludge stabilizer remains unknown.

Considering the above, this study focused on banana leaf powder (BLP) as an agricultural waste and investigated its potential as a mud stabilizer without the use of polymers. BLP is produced by drying and pulverizing banana leaves and is primarily used as a food additive, cosmetic, and health supplement [35–45]. It is also used as a fertilizer to improve soil nutrients [41,46]. Furthermore, its application to the soil may improve its water retention capacity [47–49]. Recently, it was

reported that the water absorption capacity of stabilizer materials (such as paper sludge ash and palm ash) significantly influences the post-treatment strength and consistency of mud [50–52]. Therefore, this study attempted to use the water retention capacity of BLP as a mud stabilizer.

Table 1 lists a comparison of the properties of the proposed BLP-based stabilizer and conventional lime- or cement-based stabilizers. As listed in the table, the proposed BLP-based stabilizer aims to address the issues with cement- and lime-based stabilizers, such as their high alkalinity and carbon footprint. The BLP is organic, whereas cement and lime are inorganic. Although there is no issue when BLP is used as a fertilizer, it is necessary to overcome the unprecedented challenge of controlling the deterioration of durability caused by soil degradation when a BLP-based stabilizer is used as a construction material for structures.

In this study, BLP was produced in the laboratory, and its water absorption capacity was assessed using a newly developed method. This assessment included a comparison of its water absorption capacity to that of orange peel biopolymer (OBP), an organic polymer material, and fly ash (FA), an inorganic material, as well as an analysis of the differences in their mechanisms of action. The effect of BLP addition on the compaction and strength development of treated clay was investigated, with comparisons to OBP and FA treatments. The effects of the water absorption capacity of BLP-treated clay were explored. Concerns about BLP decay led to the production of soil treated with both BLP and FA to investigate the impact of the hybrid stabilizer’s water absorption capacity on its strength. Experiments were conducted to accelerate BLP decay using fungal mycelia and to compare the weight, strength, carbon content, and pH levels of BLP- and hybrid-treated clays.

2. Materials

Ao clay, which is commercially available in Japan, was used to simulate surplus clay. This clay falls under the low liquid limit (CL) category according to the Unified Soil Classification System [53]. Table 2 (a) lists the chemical composition of the Ao clay as determined using an X-ray fluorescence analyzer. Its physical and chemical properties include particle density (ρ_s) of 2.716 g/cm³, liquid limit (w_L) of 40.7 %, plastic limit (w_p) of 23.7 %, plasticity index (I_p) of 17.0, and pH value of 7.0. These properties were ascertained following the JGS standards [54,55]. Fig. 1 shows the particle size distribution (PSD) of Ao clay, as per the JGS standard [56].

The BLP used in this study had a particle density (ρ_s) of 1.540 g/cm³. Fig. 2 outlines the BLP production process. This process starts with purchasing commercially available banana leaves, followed by drying at 110 °C for seven days, shredding, and milling into BLP. Table 3 lists the organic components of BLP, determined by a CNH organic elemental analyzer. Fig. 1 shows the BLP PSD, with a mean particle diameter (D_{50}) of 0.069 mm. Fig. 3(a) shows the physical appearance of BLP.

In this study, for comparison with BLP, two other types of stabilizers were used: OBP, an organic material with $\rho_s = 1.538$ g/cm³, and FA, an inorganic material with $\rho_s = 2.581$ g/cm³. OBP consists of a hydrogel —

Table 1

Comparison of characteristics between the proposed BLP-based stabilizer and conventional lime/cement-based stabilizer.

	BLP-based stabilizer	Lime-based stabilizer	Cement-based stabilizer
Compound features	Organic compound	Inorganic compound	Inorganic compound
Carbon dioxide emission	Low emission associated with production	High emissions associated with production	High emissions associated with production
Hazard, Risk	Low alkalinity and non-toxic	Generation of rapid heat and high alkalinity when reacted with water	Concerns about the leaching of hexavalent chromium and an increase in pH
Soil treatment mechanism	Free water content of soil reduced by the water absorption of BLP	Free water content of soil reduced by the water absorption and heat generation of lime	Free water content of soil reduced by the hydration and solidification of cement
Strength of treated soil	Sufficient strength expected when combined with compaction, but concern about durability	Sufficient strength expected when combined with compaction	Sufficient strength expected with hardening

Table 2
Chemical composition of Ao clay and fly ash (FA) determined using X-ray fluorescence analysis [57].

(a) Ao clay										
Chemical Composition	CaO	SiO ₂	Al ₂ O ₃	K ₂ O	Fe ₂ O ₄	TiO ₂	MgO	P ₂ O ₅	MnO	Others
Mass Percentage (%)	2.83	56.96	15.27	4.41	15.41	1.54	2.36	0.54	0.31	0.55
(b) FA										
Chemical Composition	CaO	SiO ₂	Al ₂ O ₃	SO ₃	K ₂ O	Fe ₂ O ₄	TiO ₂	MnO	P ₂ O ₅	Others
Mass Percentage (%)	6.62	56.71	14.69	0.73	2.30	13.70	2.38	0.21	1.93	0.74

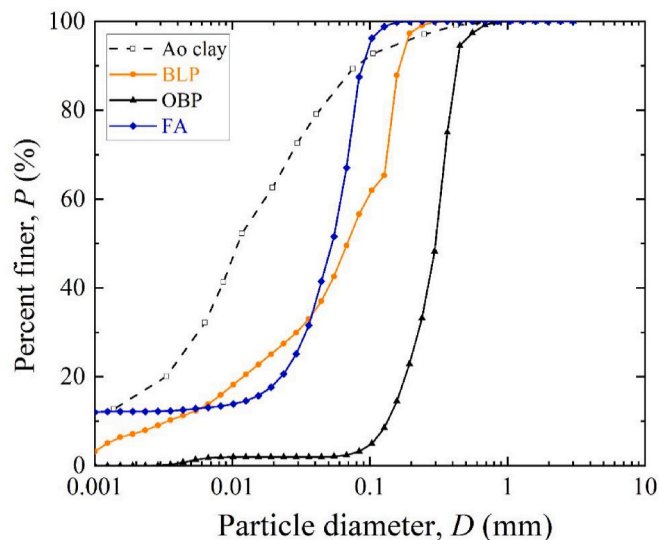


Fig. 1. Particle size distributions of Ao clay, banana leaf powder (BLP), orange peel biopolymer (OBP), and fly ash (FA). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

an organic super absorbent polymer derived from orange peel bio-waste, widely used in agriculture to reduce water and fertilizer requirements. FA is a byproduct of coal-fired power generation, classified as F-type. Table 2(b) lists the chemical composition of FA. Table 3 lists the organic components in OBP. Fig. 1 shows the PSDs of OBP and FA, measured using a laser diffraction-type PSD device. Fig. 3(b) and (c) show the physical appearances of OBP and FA, respectively.

Researchers, including [52,58], have identified the free water content in cement-treated soils as a key indicator of strength development. The role of water absorption in soil stabilizers is crucial for determining the free water content of soils treated with cement and ash, as emphasized by Ref. [59]. Therefore, before examining the characteristics of the treated soils, we examined the water absorption of the three stabilizers (BLP, OBP, and FA) using the suction filtration method. Fig. 4 shows the

Table 3
Organic element content of banana leaf powder (BLP) and orange peel biopolymer (OBP) determined using CHN organic element analysis.

(a) BLP			
Element concentration	Carbon (C)	Nitrogen (N)	Hydrogen (H)
Mass ratio (%)	48.02	2.81	6.22
(b) OBP			
Element concentration	Carbon (C)	Nitrogen (N)	Hydrogen (H)
Mass ratio (%)	35.79	0.12	6.14

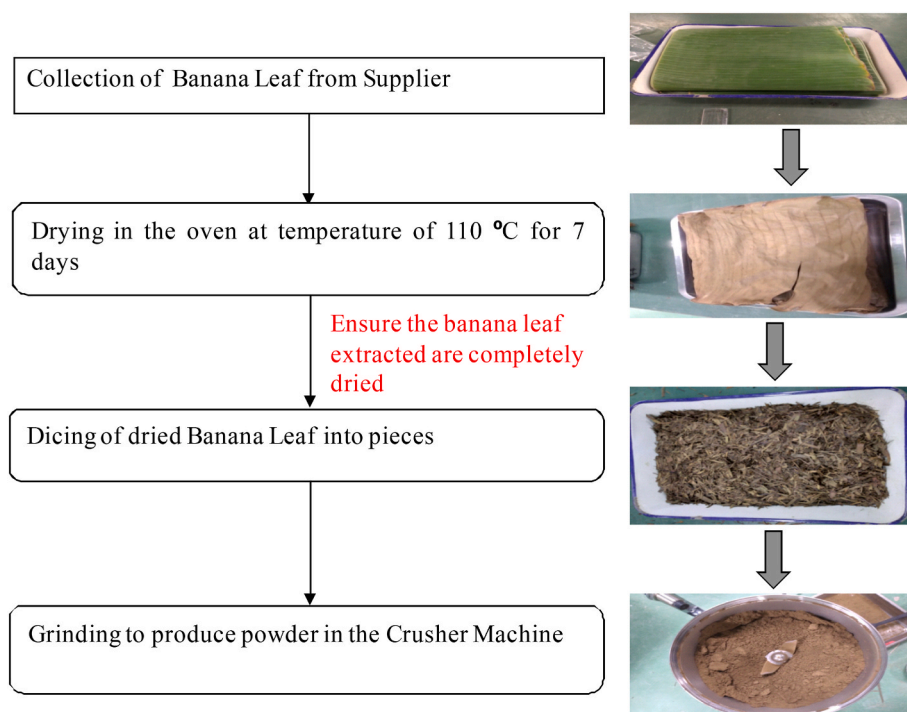


Fig. 2. Preparation process of banana leaf powder (BLP).

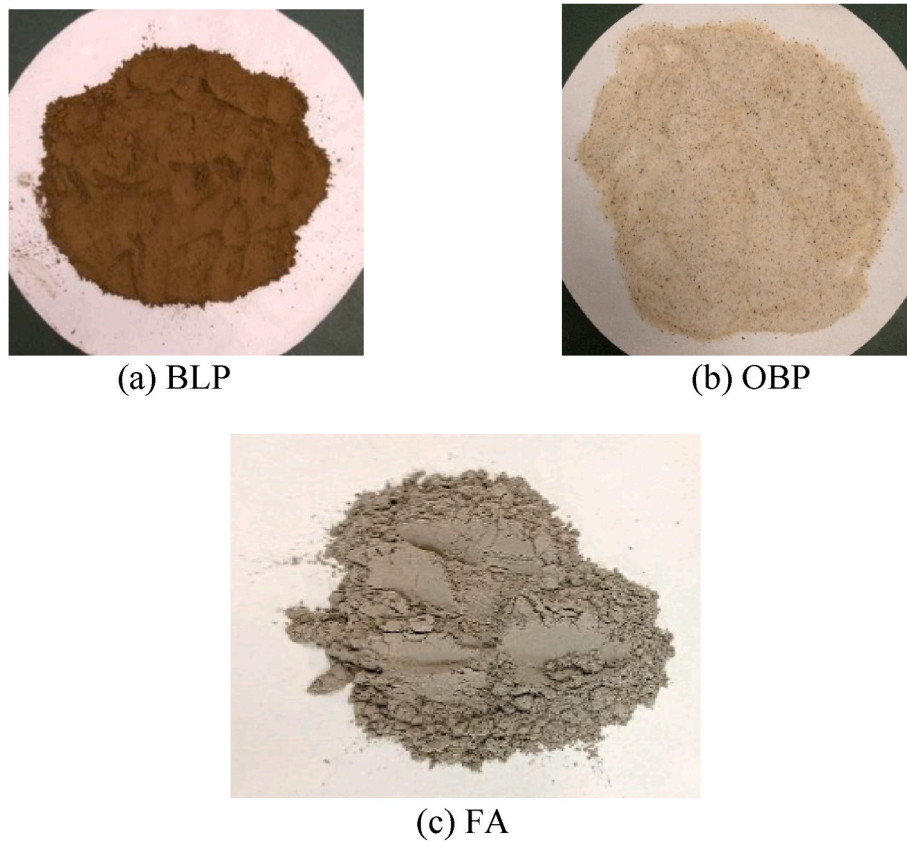


Fig. 3. Appearances of banana leaf powder (BLP), orange peel biopolymer (OBP), and fly ash (FA). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

suction filtration method [60].

For the suction filtration test, 5 g of BLP or FA and 0.03 g of OBP were mixed with 100 and 20 mL of distilled water, respectively. We placed the mixtures in round plastic containers and shook them on an electronic shaker at room temperature ($20 \pm 1 \text{ }^\circ\text{C}$) for different durations, ranging from 4 to 672 h. We connected the suction filtration setup to a vacuum pump and set the pressure gauge to -90 kPa . This pressure enables the liquid to pass through the filter membrane and trap the solid. We used a 90-mm-diameter filter membrane with $0.45 \text{ }\mu\text{m}$ pores and $125 \text{ }\mu\text{m}$ thickness. After the curing period, each stabilizer mixture was poured

into a funnel to ensure that no residue remained in the containers and excess water was filtered out. We then measured the weight of the solids captured by the membrane. Using this weight, we calculated the water absorption capacity of each stabilizer, W_{ab} , which is defined as the mass of water absorbed and retained per gram of stabilizer.

Fig. 5 shows the W_{ab} relationship with curing time. The empirical equation suggested in Ref. [60] expresses the water absorption capacity of a stabilizer over time as follows:

$$W_{ab} = d - e \times (f)^t \quad (\%) \tag{1}$$

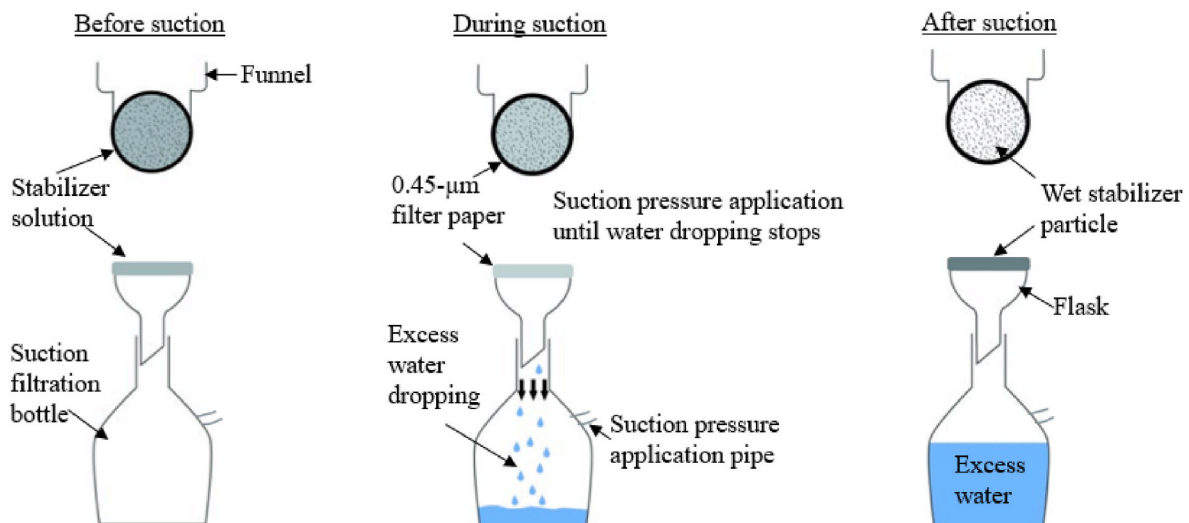


Fig. 4. Laboratory testing procedure for determining the water absorption performance of waste-based stabilizers using the suction filtration method [60].

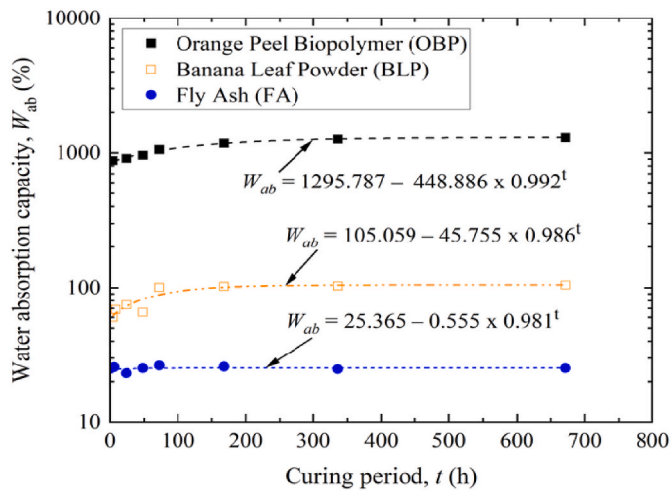
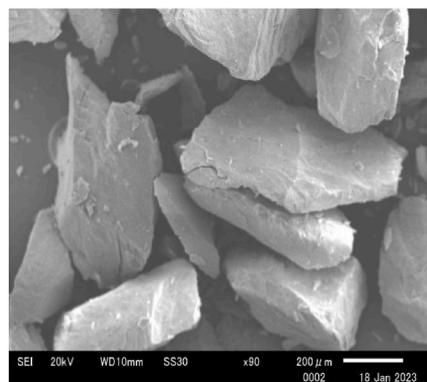


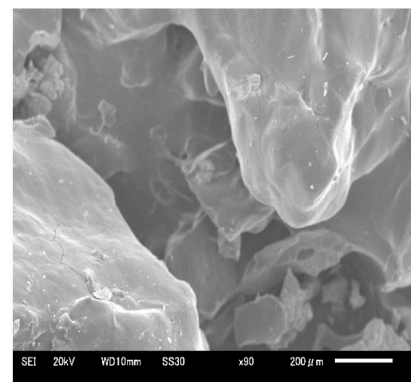
Fig. 5. Water absorption capacity W_{ab} of banana leaf powder (BLP), orange peel biopolymer (OBP), and fly ash (FA) at different curing periods. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

where d , e , and f are empirical constants, and Fig. 5 shows these constants and the corresponding equations for BLP, OBP, and FA.

As shown in Fig. 5, OBP had the highest W_{ab} , followed by BLP. The W_{ab} of BLP was observed to be approximately 60–100 %. The obtained W_{ab} of BLP was slightly lower than that of paper sludge ash reported in Ref. [60], however similar to those of palm kernel shell ash and rice husk ash. This indicated that the water absorption of BLP was comparable to that of biomass combustion ash. OBP's superior performance is probable because of its organic hydrogel polymer, which forms three-dimensional networks that absorb and retain large amounts of water. Fig. 6 shows scanning electron microscopic (SEM) images of the changes in the OBP particles after soaking. The SEM images of BLP shown in Fig. 7 show particles with clumping, laminar plate shapes, and thin layers, which could improve water absorption. Although BLP is the same type of organic material as OBP, its water absorption mechanism is completely different. It is believed that in BLP, particle pores contribute significantly to physical water absorption. The water absorption capacity of the BLP was higher than that of the FA. This suggests that BLP, as a mud stabilizer, may be more effective than FA in absorbing free water in clay.



(a) Without soaking



(b) With soaking

Fig. 6. SEM images of orange peel biopolymer (OBP).

3. Strength characteristics of BLP-treated clay

3.1. Strength characteristics of BLP-treated clay compared with other treated clays

The strength properties of clay treated with BLP were investigated and compared to clay treated with OBP and FA. In Japan, surplus soils from construction activities are categorized based on their strength. Specifically, second-grade surplus soil must have a cone index value of 0.8 MPa or higher. Second-grade surplus soil has the potential to be used as embankment material [61]. Consequently, in this study, to investigate the strength characteristics of the treated clay, cone index tests were conducted in accordance with the Japanese standard [62], rather than unconfined compression or California bearing ratio tests.

First, samples treated with BLP, OBP, or FA were prepared for cone index tests using the mixture. The curing conditions are listed in Table 4. After adjusting the water content to the liquid limit (w_L) in the Ao clay, BLP, OBP, and FA were added to the predetermined dry mass ratios A_{BLP} , A_{OBP} , and A_{FA} , respectively, and thoroughly mixed. The mixtures were then cured in a sealed plastic bag for 7 d. The dry mass ratio is the mass of each stabilizer to the dry mass of the Ao clay. After curing, each mixture was placed in a mold with an internal diameter of 100 mm and a capacity of 1000 cm³ in three layers, with each layer being compacted 25 times with a 2.5 kg rammer. Finally, the mold containing the treated samples was subjected to cone index testing. In the cone index test, a cone penetrated the compacted soil specimen into the mold at a rate of 1 cm/s. The cross-sectional area of the cone base was 3.24 cm² (diameter, 20.3 mm), and the tip angle was 30°. The penetration resistance force was recorded when the cone tip reached depths of 5, 7.5, and 10 cm from the top surface of each specimen. The average penetration resistance force (Q_c) was calculated as the mean of three measurements. The cone index (q_c) was determined by dividing Q_c by the bottom of the cone tip area (A).

Fig. 8 shows the cone index values (q_c) of the treated clays with respect to stabilizer content. As shown in Fig. 8, the BLP-treated clay exhibits a higher q_c than the FA- and OBP-treated clays. The clay treated with BLP exceeded the q_c value of 0.8 MPa, unlike the clay treated with OBP and FA. The results indicating a lower q_c for the FA-treated soil (Fig. 8(a)) are consistent with the lower W_{ab} shown in Fig. 5. Fig. 8 shows that the q_c of the FA-treated clay with a 20 % addition ratio is less than 0.2 MPa, which is insufficient to support construction equipment such as bulldozers. In contrast, the q_c of BLP-treated clay is approximately 1.5 MPa, allowing it to support not only bulldozers but also heavier machinery, including dump trucks. Moreover, if long-term durability is ensured, BLP-treated clay can be used as a material for road and river embankments, as well as for backfilling in civil engineering structures.

In contrast, the OBP-treated clay, which showed a higher W_{ab} ,

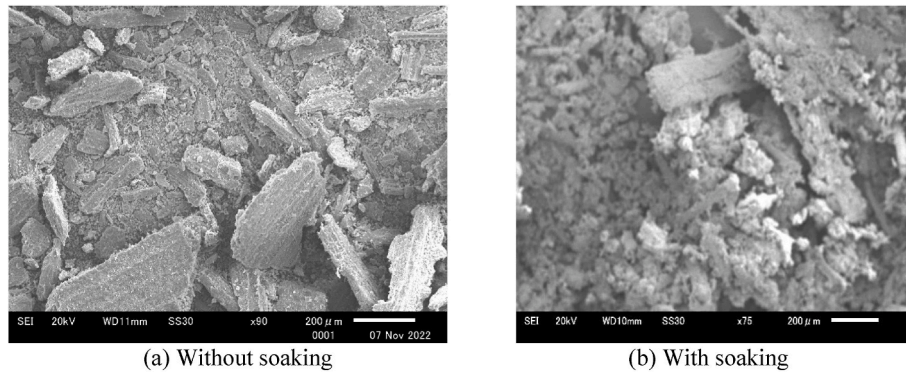


Fig. 7. SEM images of banana leaf powder (BLP).

Table 4

Mixture and curing conditions of the treated clay for cone index test.

Type of treated clay	Water content of Ao clay (%)	Banana Leaf Powder content, A_{BLP} (%)	Orange Peel Biopolymer content, A_{OBP} (%)	Fly Ash content, A_{FA} (%)	Pre-compaction sealed-curing period, t
Banana Leaf Powder (BLP)-treated clay	40.7 % (w_L)	10, 15, 20, 30	–	–	3 d, 7 d
Orange Peel Biopolymer (OBP)-treated clay	–	–	2, 4, 6, 8, 10, 30, 50	–	7 d
Fly ash (FA)-treated clay	–	–	–	10, 20, 30, 35, 40,45,50	7 d, 14 d

yielded a lower q_c than the BLP-treated clay. The q_c value of OBP-treated clay did not significantly increase as the addition rate increased (A_{OBP}). This can be attributed to BLP absorbing water in the soil through its particle pores, thereby reducing free water, whereas OBP causes the soil to remain in a state with larger voids by gelatinizing the water in the soil. Consequently, OBP made the treated clay more difficult to compact, whereas BLP made it easier. It can be suggested that differences in the stabilizer's water absorption mechanism influence the effectiveness of the post-treatment compaction process on treated soil. Fig. 8(b), which presents the dry density (ρ_d) of the cone index test specimens relative to the stabilizer content, shows that ρ_d of the OBP-treated clay is lower than that of the other treated soils, reducing to a water density of 1.0 g/cm^3 at a relatively low stabilizer content. The ρ_d of the BLP-treated clay also decreased with increasing addition rate, although not as considerably as that of the OBP-treated clay. According to Section 2, one reason for this trend could be that ρ_s of the organic materials (BLP and OBP) were lower than those of the inorganic materials (Ao clay and FA). Section 2 shows that BLP has the same water absorption capacity as palm kernel shell ash and rice husk ash. However, the q_c of clay treated with PKSA and RHA reported by Ref. [63] was approximately 3.0 MPa at 20 % addition ratio, whereas the q_c of the BLP-treated clay in this study was 1.5 MPa at the same addition ratio in Fig. 8(a). This difference could also be caused by the difference in the particle densities of the additives.

To further investigate the impact of the stabilizer's water absorption capabilities on the strength of the treated soils, specimens with varying curing periods before compaction were prepared for the BLP and FA, as listed in Table 4. OBP was excluded from this analysis because, as previously stated, the gelation of water significantly altered the characteristics of free water in the specimen, differentiating it from the other treated soils.

Fig. 9 shows the relationships between the obtained q_c and A_{BLP} and A_{FA} . The difference in q_c owing to the curing period was minimal in both BLP- and FA-treated soils. However, longer curing times tended to result in higher q_c values. These trends are consistent with the observation in Fig. 5, which showed that, while W_{ab} increased slightly with longer curing periods, the change was not significant. Therefore, to consider the impact of W_{ab} of each stabilizer, in addition to the stabilizer content, we examined the correlation between β and q_c , as expressed by the

following equation.

$$\beta = \frac{W_{ab}}{100} \times \frac{A_{st}}{100}, \quad (2)$$

where A_{st} denotes A_{BLP} or A_{FA} .

Fig. 10 shows the q_c values from Fig. 9 plotted against β . The significant differences between BLP and FA observed in Fig. 9 are not evident here. This implies that using β , rather than the stabilizer content, reduces q_c variations caused by stabilizer differences. This is because, in contrast to OBP, BLP and FA did not gelatinize the free water that was not absorbed by the stabilizer and remained in the same form within the treated clay. The results shown in Fig. 10 reveal a material-independent relationship between β and q_c for both the BLP and FA. Regardless of whether the stabilizer is inorganic or organic, it can be concluded that understanding its water absorption capacity and mechanism is important for predicting the effect of treatment on the soil, such as the strength of the treated soil. Thus, the data plotted in Fig. 10 can be approximated using an equation based on the formula proposed by Ref. [57] as follows:

$$q_c = \frac{ab\beta^{1-c}}{1 + b\beta^{1-c}} \text{ (MPa)}, \quad (3)$$

where a , b , and c are empirical constants with values of 3.07, 284.90, and -2.46 , respectively, as shown in Fig. 10.

3.2. Strength characteristics of BLP-treated clay combined with FA

We investigated the strength properties of BLP-treated clay combined with FA. The reason for combining BLP and FA was to address durability concerns with BLP alone, and the addition of FA was thought to inhibit the BLP's microbial decomposition. Hereafter, the BLP-treated clay combined with FA is referred to as hybrid-treated clay.

To assess the strength of hybrid-treated clays, parameter β was used to design the mix composition. In the previous section, it was understood that using parameter β , the q_c could be relatively uniquely determined regardless of using BLP- or FA-treated clay. Based on this, the water absorption capacity of the hybrid stabilizer (BLP combined with FA) at the addition rate A_{st} was assumed to be the sum of the water absorption

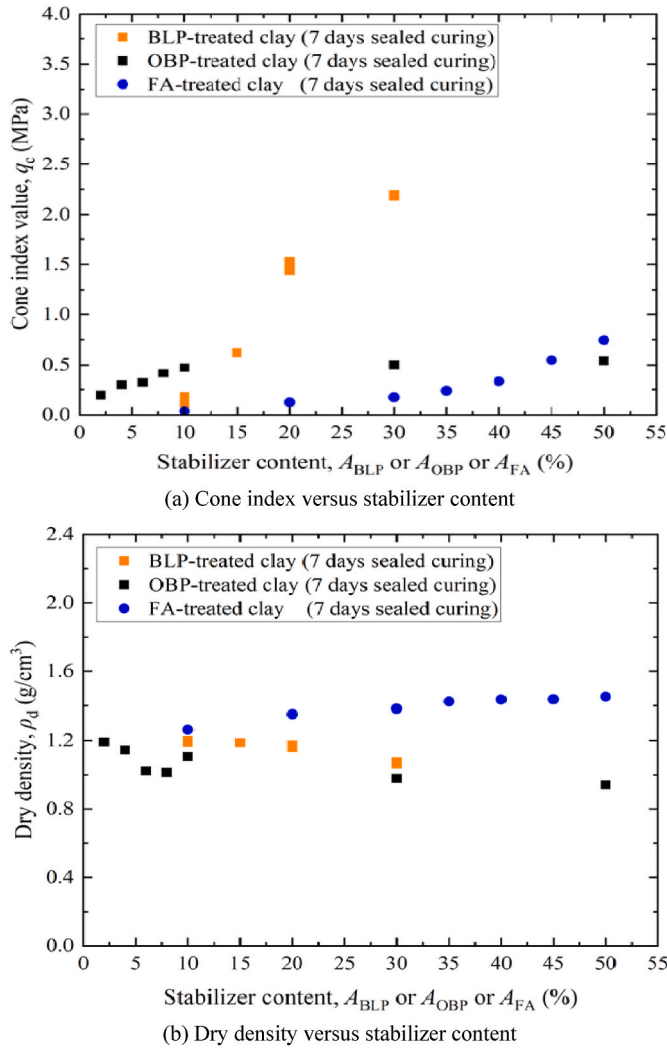


Fig. 8. Cone index and dry density versus stabilizer content for seven-day pre-compaction sealed curing clays.

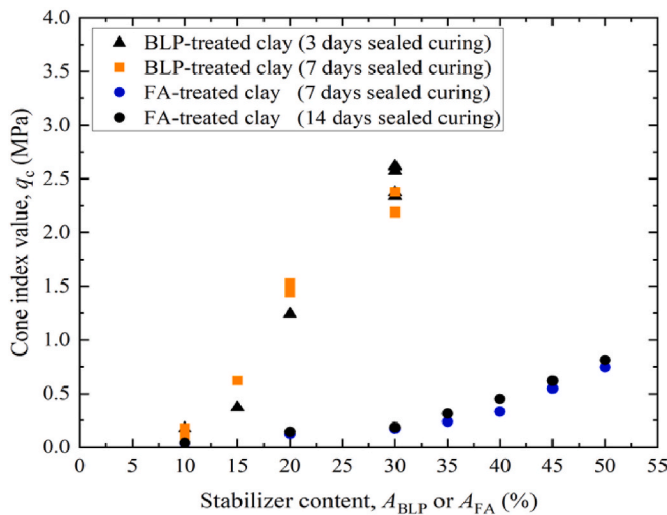


Fig. 9. Cone index versus stabilizer content of BLP- and FA-treated clays with different pre-compaction curing periods.

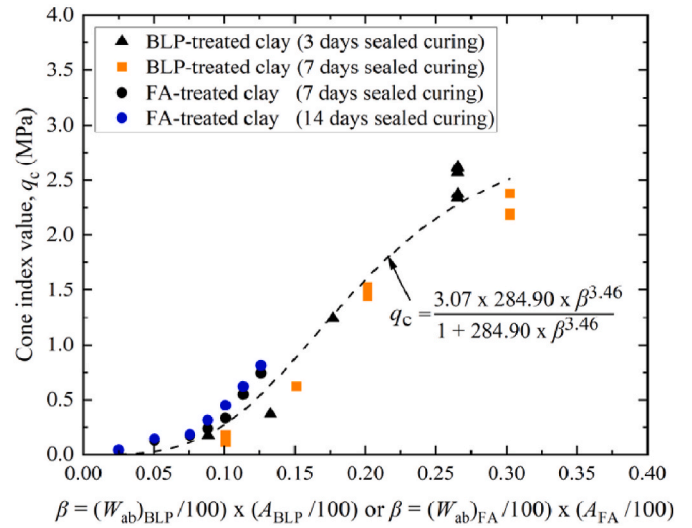


Fig. 10. Relationship between parameter β and cone index q_c of BLP- and FA-treated clays.

capacities of BLP and FA at their respective addition rates, A_{BLP} and A_{FA} . Consequently, the β for the hybrid stabilizer is defined as follows:

$$\beta = \frac{(W_{ab})_{BLP}}{100} \times \frac{A_{BLP}}{100} + \frac{(W_{ab})_{FA}}{100} \times \frac{A_{FA}}{100}, \quad (4)$$

where $(W_{ab})_{BLP}$ and $(W_{ab})_{FA}$ are the water absorption capacities of BLP and FA at the corresponding curing period t , respectively. The hybrid stabilizer content A_{st} can be defined by the following equation:

$$A_{st} = A_{BLP} + A_{FA} \quad (5)$$

By finding β for a predetermined target q_c value using Eq. (3), and subsequently solving Eqs. (4) and (5) for the calculated β under the desired A_{st} , the A_{BLP} and A_{FA} were determined. Fig. 11 shows straight lines with different values of β , enabling the determination of composite A_{BLP} and A_{FA} ratios for $A_{st} = 30\%$, aimed at achieving q_c values of 400, 1000, 1250, and 1600 kN/m² after 3 d of sealed curing. Table 5 lists the mixture design proportions for hybrid-treated clays with two stabilizers.

To validate the mixture design, multiple samples of hybrid-treated clay were prepared under the conditions outlined in Table 5. Following a three-day sealed curing period in zip-lock plastic bags, laboratory cone index tests were conducted. The designed q_c was plotted

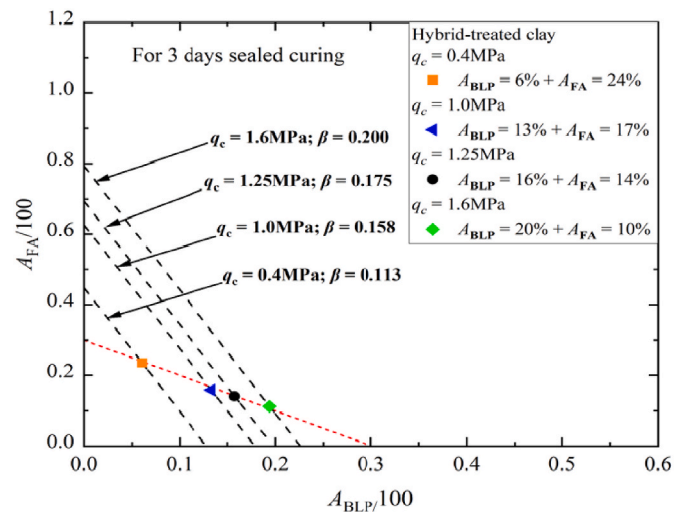


Fig. 11. Determination of stabilizer ratio of hybrid-treated clays for different targeted cone indices.

Table 5
Designed mixture conditions for hybrid-treated clays and measured cone index test results.

Water content of Ao clay, w (%)	Total stabilizer content, A_{st} (%)	Banana Leaf Powder content, A_{BLP} (%)	Fly Ash content, A_{FA} (%)	Targeted q_c at $t = 3$ days(MPa)	Measured q_c at $t = 3$ days(MPa)	Measured dry density, ρ_d (g/cm^3)
40.7 % (w_t)	30	6	24	0.40	0.31	1.34
	30	13	17	1.00	0.93	1.27
	30	16	14	1.25	1.17	1.20
	30	20	10	1.60	1.77	1.08

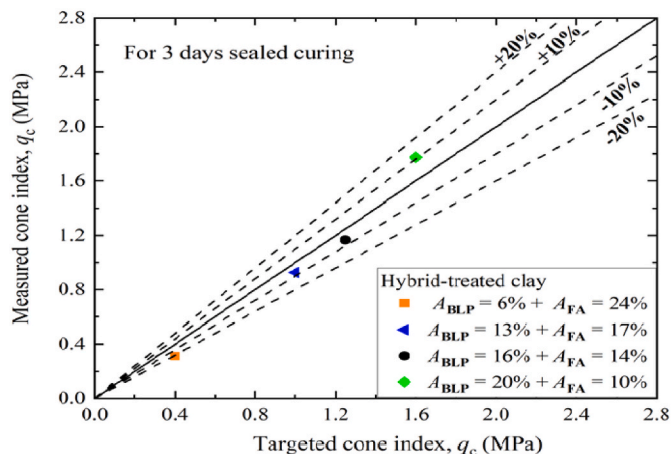


Fig. 12. Relationship between targeted and measured cone index of hybrid-treated clays.

against the measured q_c (Fig. 12), revealing a generally close match with an accuracy of $\pm 20\%$, indicating the feasibility of achieving the target q_c for the hybrid-treated clay. The good agreement between the designed and measured q_c values suggests that β significantly influenced the strength properties of the hybrid-treated clay. This suggests that the relationship between β and q_c represented by Eq. (3) holds true for hybrid-treated clays.

Fig. 13 shows ρ_d of hybrid-treated clay plotted against q_c . ρ_d decreases with an increase in q_c , that is, with an increase in the proportion of BLP in the hybrid stabilizer. However, compared to the clay treated with BLP alone, the ρ_d value of the hybrid-treated clay tended to be higher.

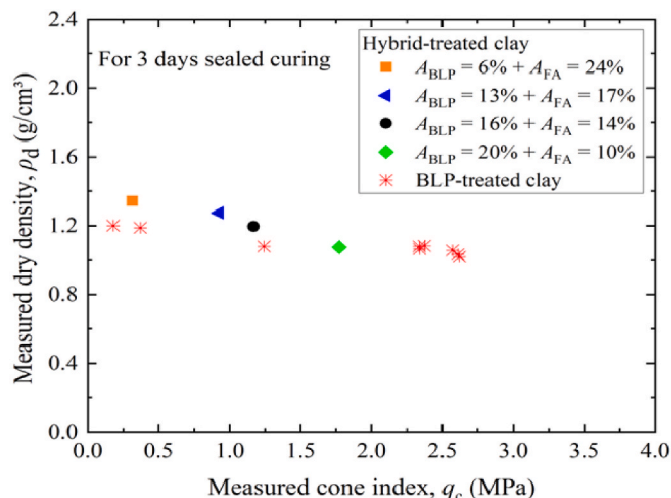


Fig. 13. Relationship between ρ_d and q_c of hybrid-treated clays.

4. Assessment of durability and contribution to the environment

4.1. Change in physicochemical and mechanical properties with fungal decay curing

BLP is an organic material; therefore, its decay in soil is a concern. To examine the changes in the BLP- and hybrid-treated clays against decay, the clays were cured in an environment containing Kwaratake mycelia, which accelerates decay. The changes in the quality of the treated clays were examined. Kwaratake mycelia, also known as Coriolus versicolor and white rot fungi, primarily rot broad-leaved trees. Although bananas are not broad-leaf trees, rather, grasses with wide leaves, Kwaratake mycelia, were used as the decay fungus. After preparing each treated clay sample, curing was conducted according to the Performance Standards and Test Methods for Wood Preservatives [64].

Kwaratake fungal mycelia were cultured in an incubator with an outer diameter of 15.0 cm and a height of 16.5 cm, as shown in Fig. 14 (a). Commercially available Potato Dextrose Agar (PDA) was used as the culture medium for fungal mycelia. PDA was mixed and dissolved properly in sterilized water at the manufacturer’s prescribed ratio (39 g in 1000 mL), then sterilized at 121 °C for 15 min. After sterilization, the prepared agar medium was transferred to an incubator and inoculated with Kwaratake fungal mycelia. The inoculated agar medium was incubated at a relative humidity of 70 % and a room temperature of 26 °C for 14 d. After 14 d, the hyphae grew on the surface of the rotting fungus medium, as shown in Fig. 14(a).

The BLP- and hybrid-treated clays were prepared using the mixture and pre-compaction curing conditions listed in Table 6. After pre-compaction curing, each treated clay sample was transferred to a steel-split mold with an internal diameter of 5 cm and a height of 10 cm. Compaction was performed in three layers, with 12 blows per layer using a 1.5 kg rammer falling from a height of 20 cm. Subsequently, the specimens were removed from the mold and placed in an incubator containing the fungal medium for degradation, as shown in Fig. 14(b).

After the specified fungal decay-curing period, the specimen was removed from the incubator, its mass was determined, and an unconfined compression test [65] was conducted to determine the unconfined compressive strength (UCS). As previously stated, the classification of treated surplus soil in Japan is based on the cone index. Ideally, a cone index test should be conducted. However, because of the incubator’s size constraints, it was difficult to cure larger specimens; therefore, an unconfined compression test was performed. The unconfined compression test involved placing each cylindrical soil specimen in a testing machine and applying an axial load at a constant axial strain rate (1 %/min) until the specimen failed or deformed significantly. The maximum axial stress experienced by the specimen during the test was recorded as UCS. Fig. 15 shows the appearance of BLP- and hybrid-treated clay specimens. Regardless of the type of treated clay, the specimens’ surfaces turned white after fungal decay curing. Following the unconfined compression tests, the water content and pH of the specimens were determined. The aforementioned investigations were also conducted on BLP- and hybrid-treated clays that were not subjected to fungal decay curing.

Fig. 16 shows the changes in mass loss, UCS, water content, and pH of the specimens during fungal decay curing. Both BLP- and hybrid-treated clays exhibited a decrease in mass after the onset of curing; however, no further reduction in mass was observed after approximately



(a) Kawaratake fungal mycelia in the incubator (b) Treated clay specimens in the incubator

Fig. 14. Preparation of Kawaratake fungal mycelia and treated clay specimens for fungal decay curing.

Table 6

Mixture and curing conditions of BLP- and hybrid-treated clays for curing using decay fungus.

Type of treated clay	Water content of Ao clay (%)	Banana Leaf Powder content, A_{BLP} (%)	Fly Ash content, A_{FA} (%)	Pre-compaction sealed-curing period, t	Predetermined fungal decay curing, (days)
BLP-treated clay	40.7 % (w_L)	20	–	3 d	0, 14, 28, 42, 56, 70, and 84
Hybrid (BLP combined with FA)- treated clay		16	14		

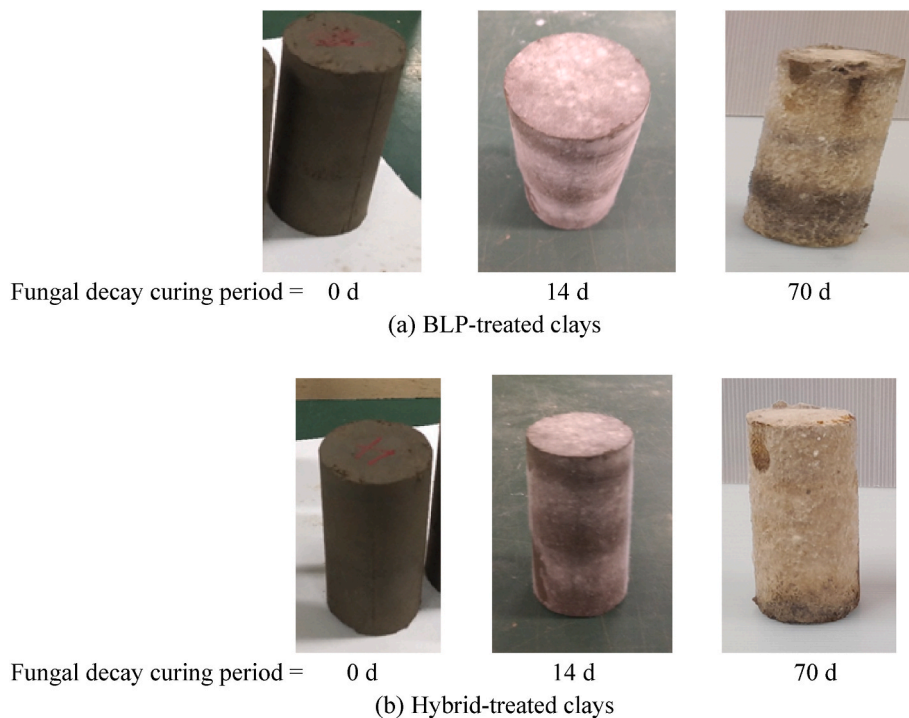


Fig. 15. Treated clay specimens after curing in a Kawaratake fungal mycelia medium.

four weeks. Regardless of the type of treated clay, the UCS decreased significantly at the start of fungal decay curing and then gradually decreased as curing progressed. The rapid decrease in UCS at the start of curing was most likely owing to the increase in water content, as shown in Fig. 16(c). This was thought to be because of the high water content of the PDA used to cultivate Kawaratake fungal mycelia, resulting in water transfer to the treated clays, increasing the water content and lowering the UCS. Therefore, caution is necessary when analyzing the UCS; however, no significant differences were observed in the changes in mass or UCS between the two types of treated clay. The pH values (Fig. 16(d)) increased slightly at the start of the curing process, regardless of the type of treated clay, and only minor changes were

observed after four weeks. The pH of BLP-treated clay increased by approximately 10.2 % between 0 and 84 d, whereas the pH of hybrid-treated clay increased by approximately 19.1 %. Once the pH changes were minimal, the pH of the hybrid-treated clay was slightly higher than that of the BLP-treated clay owing to the presence of FA. However, the alkalinity was low, indicating that concerns regarding the alkalinity of the leachate were relatively low.

4.2. Changes in carbon storage capacity

In recent years, carbon storage in the soil has garnered attention [49, 66,67]. As listed in Table 3, BLP contains a significant amount of carbon,

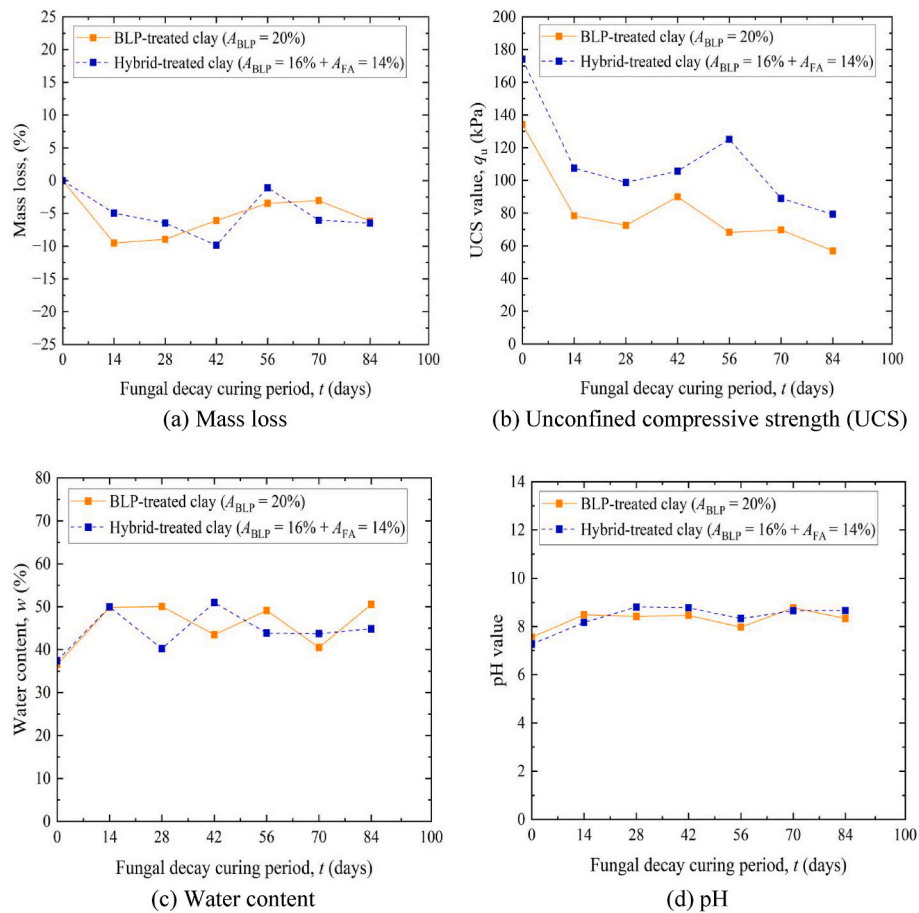


Fig. 16. Mass loss, unconfined compressive strength (UCS), water content, and pH of treated specimens versus fungal curing period.

and its use in treated clays is expected to improve the carbon storage. Therefore, we investigated the changes in carbon storage in BLP- and hybrid-treated clays during the curing process. Except for the pre-compaction sealed curing period, the survey samples' mixture conditions and curing conditions were identical to those described in Section 4.1. The sealed curing period for compaction was set at 14 d. The amount of carbon in the treated clay was determined using a CNH

organic elemental analyzer.

Fig. 17 shows the carbon content changes from immediately before the start of sealed curing prior to compaction, through 14 d of sealed curing, and up to 70 d of fungal decay curing. As shown in the figure, both the hybrid- and BLP-treated clays exhibited a decrease in carbon content with curing. However, the carbon content of the hybrid-treated clay decreased more gradually than that of the BLP-treated soil. The carbon content of BLP-treated clay decreased by approximately 28.8 % between 0 and 84 d, whereas the carbon content of hybrid-treated clay decreased by approximately 19.4 %. This was likely because, as shown in Fig. 16(d), the hybrid-treated clay had a slightly higher pH than the BLP-treated clay, which may have inhibited fungal activity. In other words, the combination with FA may have caused a slight pH increase, resulting in a more gradual decrease in carbon content. However, as shown in Fig. 17, the reduction in carbon content continued beyond 84 d, suggesting that further investigation is required.

5. Conclusions

In this study, the potential of BLP as a mud soil stabilizer was examined experimentally, with a focus on its water absorption performance. The findings led to the following conclusions.

1. The water absorption capacity W_{ab} of BLP, evaluated using the suction filtration method, was approximately 60–100 % of its own mass. Although this value was lower than OBP's absorption capacity, it was significantly higher than FA. The obtained W_{ab} of BLP was slightly lower than that of paper sludge ash, but similar to that of palm kernel shell ash and rise husk ash reported in previous studies, suggesting

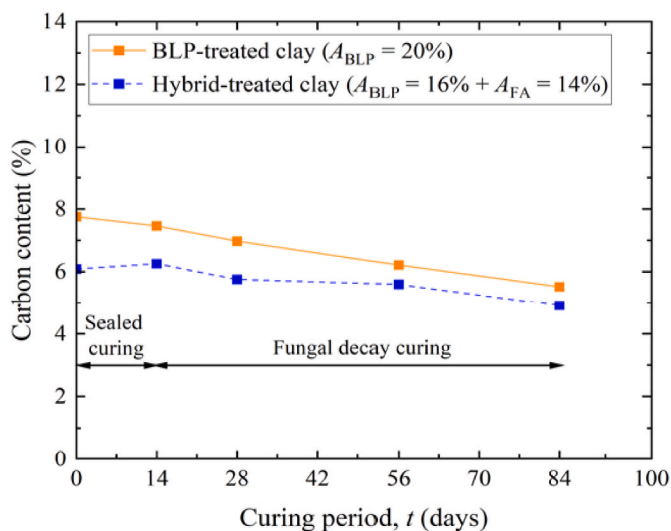


Fig. 17. Change in carbon content of treated clay subjected to sealed and fungal decay curing.

the potential of using the water absorption capability of BLP as a mud soil stabilizer.

2. The cone index (q_c) of BLP-treated clay is sufficient for its effective use as a construction material. The cone q_c of the FA-treated clay with a 20 % addition ratio was less than 0.2 MPa, which is insufficient to support construction equipment such as bulldozers. In contrast, the q_c of BLP-treated clay is approximately 1.5 MPa, making it capable of supporting not only bulldozers but also heavier machinery, including dump trucks. Moreover, if long-term durability is ensured, BLP-treated clay can be used as material for road and river embankments, as well as backfilling in civil engineering structures.
3. In contrast, the cone index of clay treated with highly absorbent OBP showed no significant increase with increasing addition rate (A). This is because OBP gelatinizes and absorbs free water in the clay, making it more difficult to compact the treated clay, whereas BLP increases the treated clay's compactness by absorbing free water into the pores of BLP particles. Differences in the stabilizer's water absorption mechanism affected the effectiveness of the post-treatment compaction process in the treated soil.
4. Analyzing the impact of water absorption capacity on the cone index revealed a material-independent relationship between β ($=W_{ab} \times A$) and q_c for both BLP and FA. This is because, in contrast to OBP, BLP and FA did not gelatinize the free water that was not absorbed by the stabilizer and remained in the same form within the treated clay. This indicates that, regardless of whether the stabilizer is inorganic or organic, understanding its water absorption capacity and mechanism is important for predicting the effect of treatment on the soil, such as the strength of the treated soil. The hybrid-treated clay with BLP and FA followed the same relationship between β and q_c , with β considered as the sum of β for BLP and FA.
5. Because of concerns regarding the decay of BLP in treated clay, experiments were conducted to accelerate the decay of BLP using fungal mycelia, and changes in the properties of BLP- and hybrid-treated clays were examined. The results showed that, while the water content increased and the unconfined compression strength decreased with accelerated curing, weight loss stabilized regardless of the type of clay used. In contrast, the pH increased slightly at the start of curing but remained below nine for both BLP- and hybrid-treated clays.
6. Controlling the deterioration of durability caused by soil degradation when using BLP-based stabilizer as a construction material for structures is challenging owing to its organic nature. The test results showed that the carbon content of the treated clays decreased with accelerated curing; however, this decrease was more gradual in hybrid-treated clays than in the BLP-treated clays. This could be because the presence of FA in the hybrid-treated clay slightly increased the pH above that in the BLP-treated clay, inhibiting fungal mycelia decay. These findings indicate that BLP can be used effectively for soil stabilization and ground improvement in civil engineering construction and maintenance projects to address issues (e. g., high alkalinity and high carbon dioxide emissions) associated with cement- and lime-based stabilizers that were previously used.

CRediT authorship contribution statement

Amulie Jarjusey: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Kimitoshi Hayano:** Writing – review & editing, Supervision. **Alula Araya Kassa:** Methodology. **Shovon Raihan:** Methodology. **Yoshitoshi Mochizuki:** Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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