The Effect of TiO_2 Coating on Pile Penetration Depth in Clay

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Abstract. Pile driving tests were conducted using models of concrete piles with titanium dioxide (TiO_2) coating and piles without coating. Pile surfaces coated with TiO_2 become superhydrophilic, which enables water molecules in clay pores to be attracted to the pile during the pile driving process. The attraction suppresses the compression of the pore water in the clay soil, hence the result of the pile driving tests showed that piles with TiO_2 coating could penetrate deeper than piles without coating with the same count of hammer strokes. An examination using FTIR confirmed the formation of bonds between water molecules for piles with coating and the absence of such bonding for piles without coating. Furthermore, it was successfully established that pile surface coating gives different results for pile driving in different clay soils.

Keywords: *coating; concrete piles; pile driving; pore water; superhydrophilic; titanium dioxide.*

1 Introduction

The response of pore water pressure in clayey soils has been of great interest in civil engineering [1]. According to Jarushi, *et al.* [2], contractors and engineers experience displacement pile installation problems because the pile driving process induces significant excess pore water pressure in the soil. Jarushi, *et al.* [3] also reported a high pile rebound – an upward pile displacement that occurs during the hammer blow – resulting in a minimal permanent set when large diameter displacement piles were driven at five sites with high pore pressure (greater than 1.92 MPa). Meanwhile, at a site with an acceptable permanent set, the pore pressure was measured in the range of 0.48 and 1.92 MPa. At a site where no rebound occurred, the pore pressure was less than 0.48 MPa.

Pile driving is rather a severe process. The displacement pile is hammered with a heavy mass until it is installed into the ground. The excess pore water pressure induced by pile driving may dissipate slowly in cohesive soils (e.g. clay) or a mixture of fine-grained granular and cohesive soils (e.g. clayey silt or clayey

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fine sand). This is related to the low permeability of the soils [4] and can be caused by creep compression [5], Mandel-Cryer effects, or both [6,7].

Several scientific papers have reported the generation of significant excess pore water pressure in the vicinity of displacement piles during pile driving in cohesive or fine-grained soils [8,9]. Baziar, *et al.* [10] studied the generation of pore pressure during cyclic loading in silty sands and found that the excess pore pressure extended to a distance of 5 to 6 pile diameters around the pile. The results from studies by Moayed [11] and Erten and Maher [12] showed that when silt content exceeded 30%, the excess pore water pressure increased. Obviously, minimal set in pile driving can lead to delays in construction projects and losses in energy and money.

The formation of a depletion layer, $\delta \approx$ 2-4 Å, on a hydrophobic surface [13], as shown in Figure 1, implies compressibility of water over the same distance. We can estimate the force experienced by the pile during the driving process into soil with an excessive pore pressure from the presence of a depletion layer around $F \approx B(\Delta V/V)A$. Let us assume that the diameter of the pile is D = 0.2 m and the bulk modulus of water is $B = 2\times10^9$ N/m^2. The volume of pore containing water in fine-grained soil is in the order of a cubic micrometer (pore diameter $d \approx 1\times10^{-6}$ m). With $A = \pi D^2/4$, $V \approx \pi d^3/6$, $\Delta V \approx (\pi d^2/4)\delta$, we obtain $F \approx 6B\delta D^2/\pi d \approx$ 30,000 N. This value, however, may be overestimated, as the force resulting from the incompressibility of water is very large.

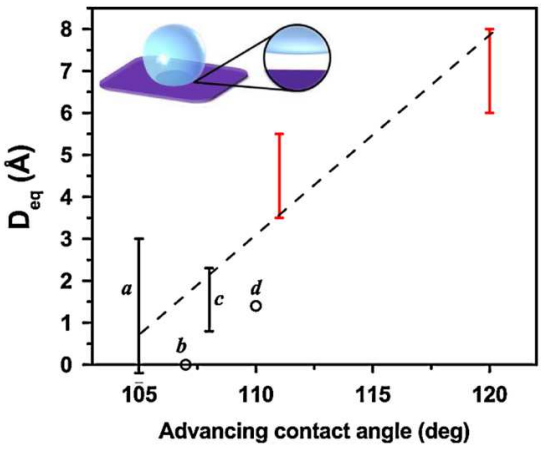


Figure 1 Relationship between the thickness of the depletion layer on a hydrophobic surface and contact angle [14]. Reprinted with permission from [Chattopadhyay *et al.*, How Water Meets a Very Hydrophobic Surface, *Physical Review Letters*, 105(3), 037803 (2010). Copyright (2017) by the American Physical Society.

Is it possible that the excessive pore pressure causes Archimedean buoyancy? This is given by $F = \rho ghA = \rho gh(\pi d^2/4)$, where h is the depth of pile penetration. Using the mass density of water and a penetration depth of around 10 m, we estimate a force of 3,141 N. This value is very small compared with the force of incompressibility, indicating that the force experienced by the pile because of the excess pore pressure is the incompressibility force of the pore water. Theoretically, if the pile surface exhibits hydrophilic behavior, water molecules can be easily attracted to the pile and the excess pore water pressure can be diminished during the pile driving process.

In 2000, Fujishima, *et al.* [15] introduced an interfacial phenomenon called the superhidrophilicity of titanium dioxide (TiO_2). With a periodic Hartree-Fock procedure, Fahmi and Minot [16] tried to find out the adsorption of water on rutile and anatase surfaces. They concluded that water has a strong preference to dissociate on the TiO_2 surface even though in theoretical studies no geometry relaxation of the surface was established [16,17]. Gu, *et al.* [18] reported a remarkable improvement of surface-modified TiO_2 in load carrying capacity and tribological properties such as friction reduction and anti-wear abilities. TiO_2 has been used as a lubricant additive to a water-based lubricating fluid. The power consumption of drilling optimally decreased with the addition of 6 wt% of TiO_2 nanoparticles in cutting fluid [19,20]. By considering the superhydrophylicity and tribological properties of TiO_2, coating the pile surface with TiO_2 particles can possibly be a solution to the minimal set problem during pile driving in clay. Hence, delays in construction projects can be avoided and significant energy and monetary savings can be achieved.

2 Methods

Models of precast concrete cylinder piles were used in this study. The concrete mixture consisted of cement, sand, gravel, and water at a ratio of 2:2:2:1 in accordance with Indonesian National Standard (SNI) No. 03-2834-2000. A 30 cm long polyvinyl chloride (PVC) pipe with a diameter of 3.175 cm was used as the pile cast. The pile tip was casted with a cone from hard paper and an iron rod with a diameter of 8 mm was inserted along the pile axis. After one week of curing, the cast (PVC and tip cover) was removed, after which curing for a further week was applied prior to coating.

Coating of the pile surfaces with TiO_2 was conducted after the piles were two weeks old. TiO_2 was obtained from Bratachem, Indonesia, which was previously reported as anatase with an average particle size of 160 nm [21]. As the binding agent, an epoxy adhesive physically consisting of two components, resin and hardener, was used. A mixture of epoxy resin and corresponding hardener with a volume fraction of 1:1 was applied uniformly over the pile

surface and then TiO_2 particles were poured over the surface. The coated piles were cured for a further two weeks, giving a total curing period of four weeks.

After the curing period, the wettabilities of the pile surfaces with coating and without coating were characterized by measuring the contact angles of several water droplets on the pile surfaces based on ASTM D7334-08. This is the most commonly used method for determining the wettability of a material. In our case, we needed to confirm the effect of the pile coating with TiO_2 in response to water on the pile surface.

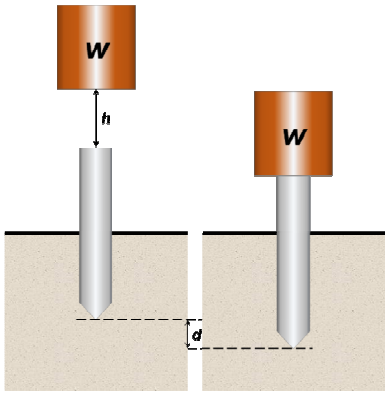


Figure 2 Schematic of pile driving.

Pile driving is a crucial test in this study because the research was carried out primarily to improve pile drivability. The pile driving tests were conducted after the piles were at least four weeks old. Pile driving using an adapted drop hammer is illustrated in Figure 2. A hammer with a mass (w) of 3.2 kg was dropped from a height (h) of 30 cm onto the pile head. As test soils, clays obtained from two locations were used: Plered clay from the Purwakarta region and Sukabumi clay from the Sukabumi region. Both regions are located in West Java Province, Indonesia. For comparison, we also used granular (non-cohesive) soil with three variations of water content. Figure 3 shows photographic images of the soils used in the pile driving tests. The soils were placed inside a container with a diameter of 40 cm and a height of 40 cm.

To characterize the properties of the test soils, the water content or moisture of the soils were determined using gravimetric method ASTM D2216. The mass of water is equal to the difference of wet mass and dry mass of the soil. The dry mass was measured after the soil was dried in an oven at a temperature of 105 °C for 24 hours [22]. This temperature range is based on the temperature of boiling water and without considering the physical and chemical characteristics of the soils. Furthermore, index properties were also analyzed (such as liquid

limit and plastic limit), Atterberg's limit, and grain size of the soils. Fourier transform infrared (FTIR) spectra were obtained with an FTIR Bruker ALPHA spectrometer using a single-reflection diamond attenuated total reflection (ATR) module resolution of 2.0 cm^{-1} and the data from 4000-500 cm^{-1} were recorded to evaluate the minerals in the test soils and the bonding properties between the pile surfaces and the soils.

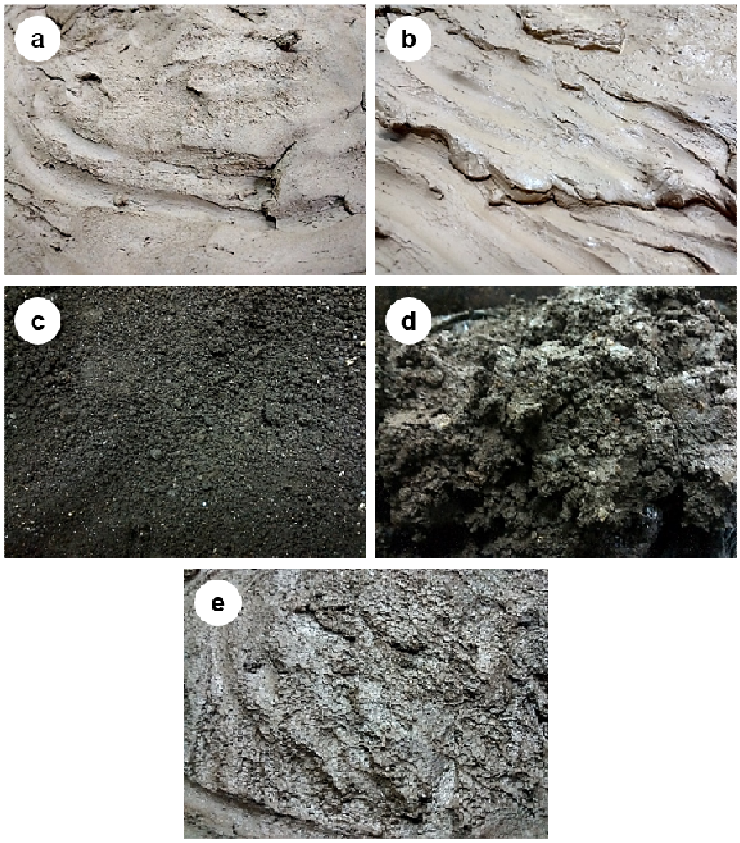


Figure 3 Photographic images of the test soils: (a) Plered clay, (b) Sukabumi clay, (c) granular soil 1, (d) granular soil 2, and (e) granular soil 3.

3 Results and Discussion

3.1 Effects of Pile Coating on Pile Surface Wettability and Penetration Depth

Epoxy adhesives physically consists of two components, namely resin and hardener. It is a family of thermoset materials widely used as adhesives,

coatings, and polymer matrix composites due to the low viscosity of the formulation, good insulation properties of the final material even at high temperature, and good chemical and heat resistance. Resin and hardener were mixed properly at a ratio of 1:1 and then applied on the clean surface of the model pile. TiO_2 powder was applied directly to the pile surface after the epoxy. Epoxy curing is the conversion of the liquid components into plastic material. Figure 4 shows the pile without coating (top) and the pile with TiO_2 coating (bottom).

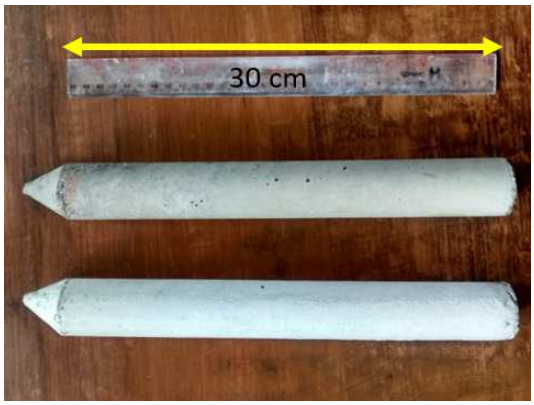


Figure 4 Pile without coating (top) and pile with TiO_2 coating (bottom).

As mentioned earlier, a wettability test was conducted by dropping water onto the pile surface: piles without coating and piles with TiO_2 coating, as well as concrete slabs without coating and concrete slabs with TiO_2 coating. Approximately 10% of the piles in this study had a contact angle (CA) of 80-120°, corresponding to the CA of water on concrete slabs without coating. However, the remaining 90% had a CA of 20-70°. Meanwhile, the CA measured on the surfaces of the piles with TiO_2 coating was < 10°. This indicates that the surfaces of the piles with TiO_2 coating exhibited superhydrophilicity. The result of the wettability test on a concrete slab with TiO_2 coating produced a corresponding CA, as shown in Figure 5. Some recorded images are shown in the figure where the contact angle initially was very small and then vanished after 2 seconds.

The pile driving tests on each soil type used as pile driving media were carried out at least three times for piles without coating and piles with coating in different containers. The soil density in each container was maintained the same (~994 kg/m^3) at the beginning of each session of each pile driving test. This was achieved by removing the soil from the container after finishing each pile driving test and then filling the container again with the soil in such a way that

initial volume of the soil was reached again. Therefore, the iterations of our experiment were conducted under the same initial conditions.

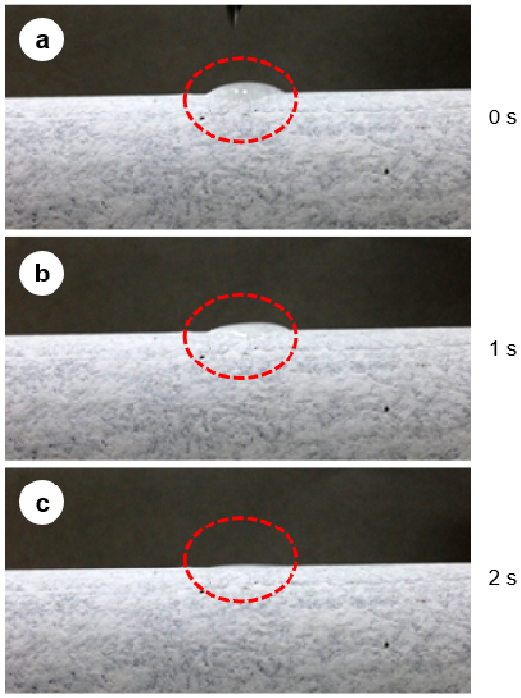


Figure 5 Development of the contact angle of a water droplet on a TiO_2-coated pile. The droplets were recorded at different times: 0 s (a), 1 s (b), and 2 s (c).

In the pile driving test, the maximum count of hammer strokes was different for each different soil type used as the pile driving media. When one pile tested in a certain soil type reached its maximum penetration depth after *n* hammer strokes, even though other piles tested in the same soil type did not yet reach maximum depth, and was still able to be driven, the maximum count of hammer strokes was restricted to *n*. A comparison of penetration depths at each stroke for piles without coating and piles with TiO_2 coating in the Sukabumi and Plered clays is shown in Figure 6. It can be observed that the piles penetrated more readily in the Sukabumi clay as the water content was higher than in the Plered clay.

It needed to be confirmed that the difference in penetration depths between piles without coating and piles with coating occurred only in clay soils and not in granular soils. The results of the pile driving tests in granular soils, Figure 6, clearly show that the piles also penetrated more readily in soils with higher water content. For penetrating granular soil 1 with a pile to a depth of 30 cm, nearly 60 strokes were required, whereas pile driving in granular soil 1 and 2

required 13 and 5 strokes respectively. Similar results were observed for the Plered and Sukabumi clays with the piles penetrating the latter more easily as the water content was higher.

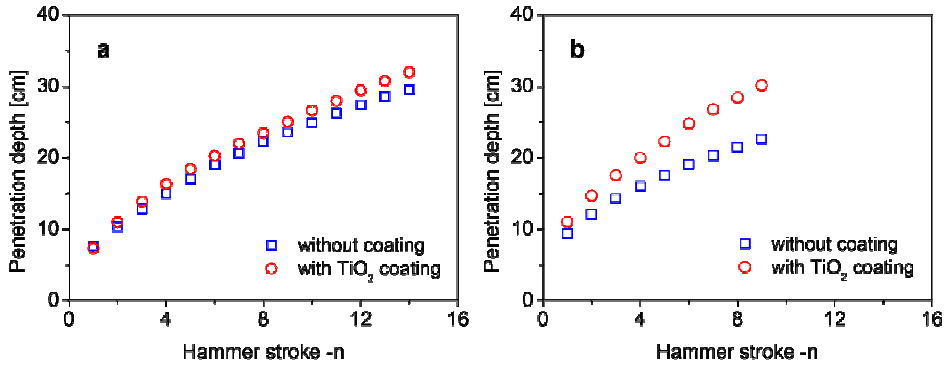


Figure 6 Penetration depths of uncoated and TiO_2-coated piles in (a) Plered and (b) Sukabumi clays.

In Figure 7 we can see an interesting phenomena. There is almost no difference in penetration depth between piles without coating and piles with TiO_2 coating for pile driving in granular soils. This indicates the absence of a coating effect in granular soil since water molecules can move freely in the soil [23]. The pile penetration depth benefit for piles with TiO_2 coating compared to piles without coating can be calculated with the following Eq. (1):

$$\eta = \left(\frac{d - d'}{l} \right) \times 100\% \tag{1}$$

where l is the pile length, d and d' are the final penetration depths of piles with TiO_2 coating and without coating respectively. The complete results can be seen in Table 1.

From Table 1 we can conclude that coating the pile surface with TiO_2 particles did deliver an effect in accordance with the initial objective of this study, where pile coating caused pile drivability in clay soils to increase. Meanwhile, pile coating did not have a significant impact on pile drivability in granular soils, because basically water molecules can move freely in granular soil and can be displaced instantaneously during pile driving. In the same table, even a negative benefit value for pile driving in granular soil 2 can be seen. This means that the driving of piles with coating in granular soil 2 did not give a better result than for piles without coating but instead more hammer strokes were needed to achieve the same penetration depth.

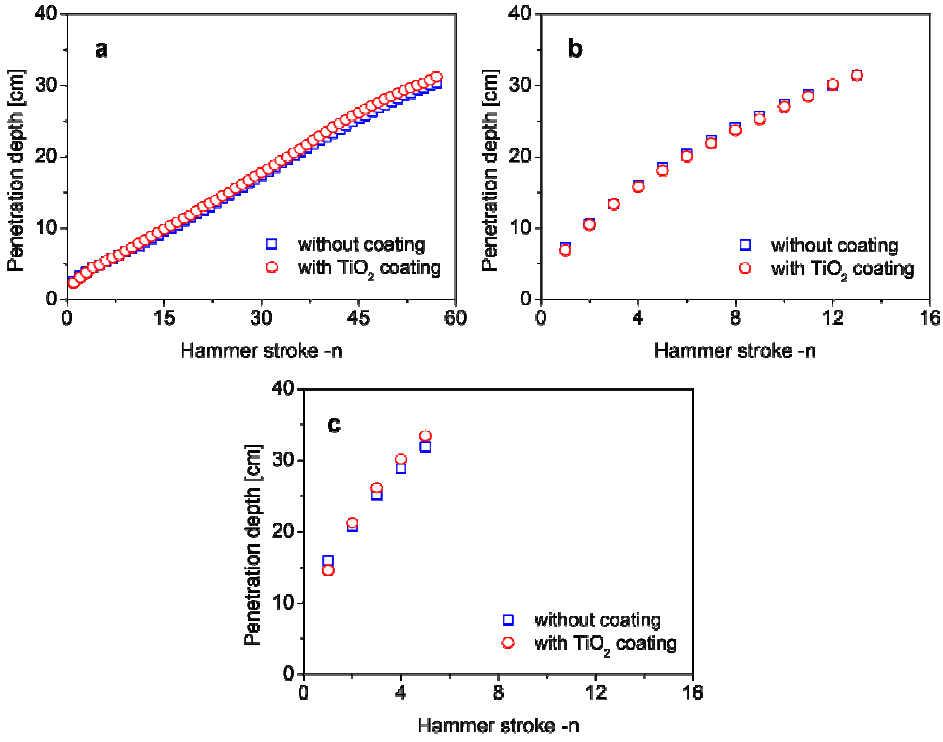


Figure 7 Penetration depths of uncoated and TiO_2-coated piles in granular soil 1 (a) granular soil 2 (b), and granular soil 3 (c).

Table 1 Pile penetration depth benefit for piles with TiO_2 coating over piles without coating.

Soil	Benefit (%)
Plered clay	7.337
Sukabumi clay	22.102
Granular soil 1	2.552
Granular soil 2 (less water added)	-0.199
Granular soil 3 (more water added)	4.312

3.2 Index Properties of Soils for Pile Driving Media

In accordance with the ASTM D2216-Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil, Rock, and Soil-Aggregate Mixtures, the gravimetric method was used to determine the water content in the soils used as pile driving media in this study. Water contents on wet weight basis were calculated using the following Eq. (2) [22]:

$$\theta_w = \frac{\text{water mass}}{\text{wet soil mass}} = \frac{\text{wet soil mass} - \text{dry soil mass}}{\text{wet soil mass}} \quad (2)$$

To optimize the drying process, samples of Plered clay, Sukabumi clay, granular soil 1, granular soil 2, and granular soil 3 were prepared into small parts placed in aluminum containers. After drying for 24 hours, the dry masses of the soil samples were immediately measured to prevent adsorption of water in the atmosphere. Furthermore, additional drying was conducted for 3 hours and the sample masses were re-measured to verify their dry mass. Based on the data and the calculated water contents in the soils, as shown in Table 1, granular soil 1 had the lowest water content. Meanwhile, the water content of the Sukabumi clay was slightly higher than that of the Plered clay. This corresponds with the direct observation that Sukabumi clay was qualitatively softer than Plered clay. The water content value of the granular soils was around the water content value of the clays, hence the granular soils could be used as control.

Table 2 Water content of clays and granular soils measured using Gravimetric method.

Soil	Average θw (wt%)
Plered clay	31.7
Sukabumi clay	33.1
Granular soil 1	29.9
Granular soil 2 (less water added)	36.1
Granular soil 3 (more water added)	39.9

If we compare the water content of the test soils in Table 2 and the pile penetration depth benefits in Table 1, it can be inferred that the effect of pile coating with TiO_2 on pile drivability does not solely depend on the water content of the soils used as the pile driving media. In both clays, with water contents that are not much different, pile coating allowed high pile penetration depth benefits. Meanwhile, in granular soils, the same soils but with different water contents, the coating did not have a significant impact on pile drivability in the soils. Thus, we need to get a deeper understanding of the properties of the clays used. The results of further analysis of index properties, Atterberg limits, and grain size of the Plered and Sukabumi clays can be seen in Table 3.

As can be noticed in Table 3, the Plered clay can be categorized as a clay with low plasticity (CL), while the Sukabumi clay is a clay with high plasticity (CH). As for the grain size, the Sukabumi clay contained more fine particles than the Plered clay. Based on studies and references mentioned earlier, we know that excess pore water pressure commonly appears during pile driving in areas with a high content of fine-grained soils [8,9]. Therefore, the effect of the coating,

which was more obvious in the pile driving of the Sukabumi clay, is in accordance with the references. Greater pore water pressure may have arisen when piles without coating were driven into the Sukabumi clay than into the Plered clay. When pile driving was carried out for piles with TiO_2 coating, the pore water pressure could be minimized and consequently the pile drivability increased.

Table 3 Results of index properties, atterberg limits and grain size analyses of Plered and Sukabumi clays.

Soil	Plered clay	Sukabumi clay
Index properties	Average unit weight = 1.79 Specific gravity = 2.6 Void ratio (e) = 0.45 Porosity (n) = 0.31	Average unit weight = 1.75 Specific gravity = 2.57 Void ratio (e) = 0.47 Porosity (n) = 0.32
Atterberg limit	Liquid limit = w_L = 45.67 Plastic limit = w_P = 18.76 Plasticity index = $I_P = w_L - w_P$ = 26.90 Soil type (Casagrande) = CL (low plasticity) unified classification	Liquid limit = w_L = 56.46 Plastic limit = w_P = 20.71 Plasticity index = $I_P = w_L - w_P$ = 35.75 Soil type (Casagrande) = CH (clay of high plasticity) unified classification
Grain size	Gravel (%) = 0 Sand (%) = 8.30 Silt (%) = 60.72 Clay (%) = 30.98 D30 = 0.0045 D60 = 0.0138 Specific gravity (Gs) = 2.5954 Percent passing No. 200 = 91.70 %	Gravel (%) = 0 Sand (%) = 3.24 Silt (%) = 61.81 Clay (%) = 34.95 D30 = 0.0031 D60 = 0.0118 Specific gravity (Gs) = 2.5750 Percent passing No. 200 = 96.76 %

3.3 FTIR Characterization

To understand more profoundly what may affect the changes of drivability of piles with TiO_2 coating in clay soils, the FTIR spectra of Plered clay, concrete, and mixture of Plered clay and concrete were recorded to investigate whether there was new or lost bondings at the interface of the concrete and the clay. The FTIR spectra of the concrete do not show any significant peaks (Figure 8), whereas the spectra of the clay and the mixture of clay and concrete are nearly the same. The clay spectrum shows stretching and bending of both Si–O and OH in the range of 1300-1400 cm^{-1} [24].

The peak location and relative intensity between peaks appearing in the spectra of the clay and the clay-concrete mixture are identical, indicating that their

absorption spectra are also identical. This also indicates the absence of any new bonds created between the concrete and the clay. This result demonstrates likely hydrophobicity or non-hydrophilicity of the concrete because the water molecules did not make bonds with any atoms in the concrete.

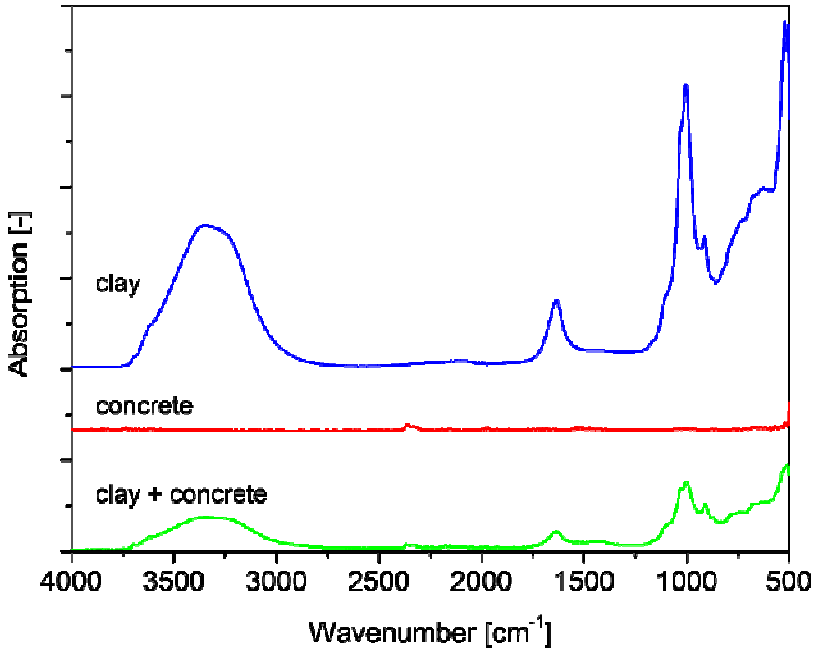


Figure 8 FTIR spectra of clay, concrete, and mixture of clay and concrete.

Figure 9 shows the FTIR spectra of the clay, the TiO_2, and a mixture of clay and TiO_2. The spectrum of the TiO_2 powder used in this study is the same as that for standard TiO_2 powder, with a broad main Ti–O–Ti peak from 500-900 cm^{-1} [24]. Comparing the spectra of the clay and the mixture of clay and TiO_2, no new peaks appear but an interesting phenomenon can be observed.

The OH band in the spectrum of the clay-TiO_2 mixture is wider than that belonging to clay only. In the spectrum of the clay-TiO_2 mixture, the OH band widens up to 2500 cm^{-1}, whereas in the clay sample, the OH band spreads up to only 2850 cm^{-1}. This widening is attributed to increments in the density of the OH bonds in the clay-TiO_2 mixture and can be understood if in this mixture some water molecules were bounded to the surface of the TiO_2, thereby enhancing its superhydrophilicity. This implies that the surface of the TiO_2-coated pile is superhydrophilic. The surface of the pile will attract water molecules, halting the compression of water in the clay pores.

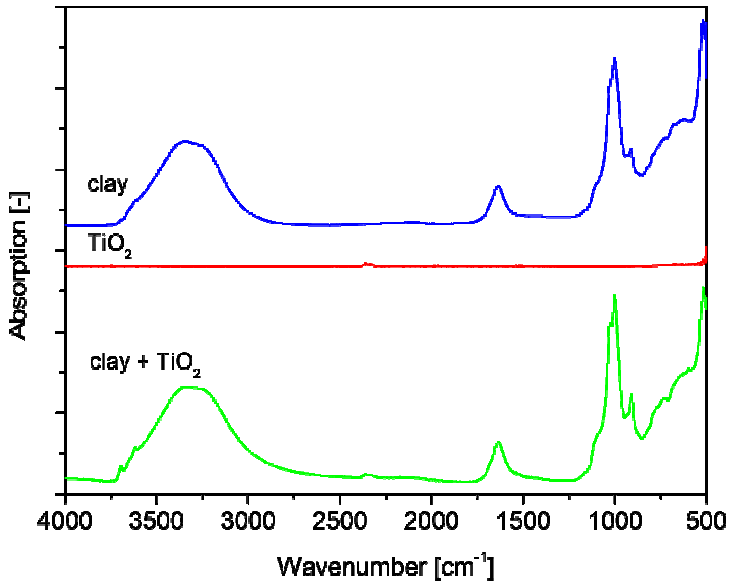


Figure 9 FTIR spectra of clay, concrete, and mixture of clay and TiO_2.

Water has three vibrational modes associated with OH bond stretching (≈ 3800-3600 cm-$^{-1}$ in the liquid state) and bending (≈ 1650-1590 cm^{-1} in the liquid state). The 1638 cm^{-1} band indicates the presence of OH groups. The position of the molecular band is very sensitive to interactions like hydrogen bonding, which encourages the shift towards lower wave numbers (< 3600 cm^{-1}), creating differences between water-free, hydrogen-bonded, and intramolecular hydrogen bonds [25].

In the Sukabumi clay, the intensive band at 1028 cm^{-1} is related to Si–O stretching. The OH-bending kaolinite demonstrates the presence of surface groups over the OH inner surface at bands 911.6 and 934.2 cm^{-1} [26]. A vibration band at 911.6 cm^{-1} indicates the possible presence of hematite [27]. The presence of bands at 3690, 3618, 2358, 1636, 1028, 911.6, and 794.1 cm^{-1} indicate the possible presence of illite [26], and the bands at 3618, 1636, and 1028 cm^{-1} indicate the presence of gypsum [27]. Two IR bands were also observed in the Sukabumi clay at 1645 and 1628 cm^{-1}. These two bands are associated with water H–O–H bending and show that there was water in the soil structure. They are related to hydroxyl stretching wavenumbers, the higher/lower band being related to strong/weak hydrogen bonds of water, both in accordance with the positions of the liquid bending modes [27].

In the Plered clay, the band at 520.9 cm^{-1} is related to SiOAl (octahedral Al) vibration [24]. The OH-bending kaolinite demonstrates the presence of OH inner surface groups at 913 cm^{-1} and an OH surface group near 935.6 cm^{-1} [28]. The vibration band at 913 cm^{-1} shows possible hematite presence [27]. The Plered clay had weak absorbance peaks at 3696 and 3619 cm^{-1} related to out-of-plane stretching, specifically an external vibration of the OH group and stretching vibrations of internal OH groups [25,29]. These two absorption peaks intensify when the clay interacts with the concrete and intensify further when they interact with the TiO_2. The same pattern occurred in the Sukabumi clay with a strong new absorbance peak at 3648 cm^{-1} observed in the mixture of TiO_2-Sukabumi clay, which is related to the vibration of external O–H groups. A summary of clay minerals in the Plered and Sukabumi clays can be seen in Table 4.

Table 4 Summary of clay minerals in Plered and Sukabumi clays.

Plered clay	Sukabumi clay
3696 and 3619 cm^{-1}: out-of-plane stretching OH 913 and 935.6 cm^{-1}: kaolinite 913 cm^{-1}: hematite 520.9 cm^{-1}: SiOAl (octahedral Al)	3690, 3618, 2358, 1636, 1028, 911.6, and 794.1 cm^{-1}: illite 3618 cm^{-1}, 1636 cm^{-1}, 1028 cm^{-1}: gypsum 1645 and 1628 cm^{-1}1: H–O–H bending 1028 cm^{-1}: Si–O stretching 911.6 and 934.2 cm^{-1}:kaolinite 911.6 cm^{-1}: hematite

As final confirmation that the superhydrophilicity of TiO_2 was what caused the piles with TiO_2 coating to penetrate more facilely in clay soils than piles without coating, we conducted additional pile driving tests in the Plered clay for piles with graphite [30] and talc-powder coatings [31]. Both graphite and talc-powder are hydrophobic. The results are shown in Figure 10. The piles even reached much more shallow depths than piles with TiO_2 coating with the same count of hammer strokes. Clearly this was because hydrophobic surfaces tend to repel water and lead to the excess pore pressure becoming even more significant. Therefore, piles with a hydrophobic coating are even more difficult to be driven than piles without coating in clay soil.

We have successfully improved pile drivability in clay soils by coating the pile surface with TiO_2. However, we do not know its influence on pile shaft resistance. The increase or decrease of shaft resistance is still in question, which is an important factor in the installation of pile foundations. Thus, further investigation on studying pile shaft resistance as a result of coating is needed.

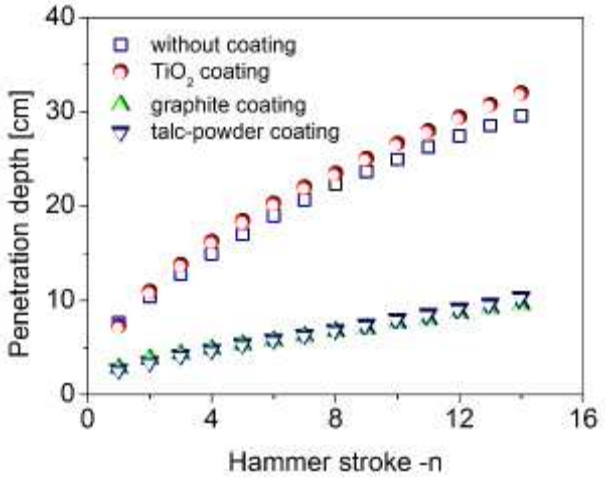


Figure 10 Result of pile driving tests for piles graphite and talc powder coatings.

4 Conclusions

Titanium dioxide (TiO_2) coating on models of precast concrete piles was implemented in this study to overcome pile driving problems in clay soils by utilizing the superhydrophilicity of TiO_2. Pile surfaces with TiO_2 coating are able to attract pore water in the clay during the pile driving process. Hence, the excess pore water pressure that is always a problem while driving displacement piles in clay can be avoided. Based on the experimental results, TiO_2 coating could improve pile penetration depth up to 7.337% and up to 22.102% compared to without coating with the same count of hammer strokes in Plered clay and Sukabumi clay, respectively. However, in regular soils, the coating showed nearly no effect on penetration depth because in fact excess pore pressure only appears in cohesive or fine-grained soils.

Acknowlegdements

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