Int. J. of GEOMATE, June, 2014, Vol. 6, No. 2 (Sl. No. 12), pp. 910-918
Geotech., Const. Mat. & Env., ISSN:2186-2982(P), 2186-2990(O), Japan

CHARACTERISTICS OF WATER-SWELLING FRICTION REDUCING MATERIALS ON THE PULLING-OUT REMOVAL OF TEMPORARY WORKS

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ABSTRACT: Water-swelling friction reducing materials (WSFRMs) are commonly used as a “pulling-out assisting material” for temporary works such as steel sheet-piles and H-steels that are required to be removed and collected after use. Generally, WSFRMs are coated to steel sheet-piles and H-steels before these are driven into the ground or placed in mortar fluid. The WSFRMs absorb moisture in the ground or mortar to swell and form a swelling membrane over the piles. Then, the membrane works also as a lubricating membrane and as a result it can reduce friction. The authors pay attention to these characteristics of WSFRMs and try to develop a special material that can swell only when soaked in an alkaline moisture environment without swelling in acid or a neutral water environment, in addition to the conventional material that swells in any type of moisture environment. In this paper, considering that both types (alkaline and conventional) of WSFRMs are used as “pulling-out assisting material” for temporary steel sheet-piles and H-steels, we perform through experiments on the swelling ratios of the materials as well as on the pulling-out characteristics of the steel flat-bar to which the WSFRMs are coated in advance.

Keywords: Pulling-out, Swelling, Temporary work, Water-swelling friction reducing material (WSFRM)

1. INTRODUCTION

Water-swelling friction reducing materials (WSFRMs) are expected to prevent soil adhesion and reduce friction dramatically on the surface of steel sheet-piles and H-steels of temporary works [1-4]. At the same time, the WSFRMs are used more often as “pulling-out assisting material” to facilitate the pulling-out of various materials (such as steel sheet-piles and H-steels) where temporary works are required to be pulled out or collected [4-6]. Generally speaking, coated on the steel sheet-piles and H-steels in advance, and installed into the ground or buried in cement fluid, the WSFRMs absorb the water contained in the ground or cement fluid to swell and form the swelling membrane. Then, such a membrane works as a lubricant layer (swelling membrane layer). As a result, it is effective at reducing the friction on the contact surfaces between the ground or cement fluid, and the temporary steel sheet-piles and H-steels.

In recent years, construction works have become diversified. There is a construction method in which digging is implemented in a stable liquid before core materials such as steel sheet-piles or H-steels, on which the WSFRM is coated in advance, are installed, and then replaced (filled) with soil cement and so on. In this method, because the conventional WSFRM swelling is completed in a stable liquid, one of the problems is the lubricant layer (swelling membrane) is likely to be detached from the core material during the process of filling the soil cement. As a result, the effectiveness of the material is limited during the pulling-out of the temporary materials (steel sheet-piles and H-steels). Therefore, the authors are developing and testing a WSFRM that does not swell in acid or neutral immersion water but only in alkaline immersion water (hereinafter called “alkaline WSFRM”), as well as a conventional WSFRM (hereinafter called “amphoteric WSFRM”) for the purpose of applying WSFRM to this method [7, 8].

In this paper, given the amphoteric and alkaline WSFRMs are coated to the temporary materials, to facilitate the pulling-out, the authors undertook experiments to review the fundamental characteristics such as the swelling ratios of the amphoteric and alkaline WSFRMs and the forces to pull out the iron flat-bars on which such WSFRMs were coated in advance.

2. CURRENT STATUS REGARDING THE PULLING-OUT OF TEMPORARY MATERIALS FOR CONSTRUCTION

Today, many steel materials are used for temporary works in construction. On the other hand, although being temporary materials, the steel materials are often hard to pull out due to problems related to the construction premises, surrounding ground. Furthermore, although there are various methods of pulling-out, all of them require powerful, large, and heavy machines. Therefore, there are cases in which H-steel materials are hard to pull out and are buried on the site [6]. Because such left steel sheet-piles and H-steels, accumulate every year, they have become a major problem as obstacles at the later stages of construction.

As one of the solutions for the above problem, there are technologies leveraging amphoteric and alkaline WSFRMs. After they are coated to steel materials, a dry membrane is formed. And, by installing or burying the dry membrane in cement fluid or the ground, the super-absorbent polymer contained in the dry membrane absorbs the water from the cement fluid or the ground. Finally, the amphoteric and alkaline WSFRMs form a swelling membrane. Because this swelling membrane works as a lubricant layer and reduces the friction on the steel materials, the pulling-out can be done with less force using medium- or small-sized heavy machines rather than with large-sized heavy machines (*see* Fig. 1).

In the technology utilizing the amphoteric and alkaline WSFRMs, such WSFRM is required to be coated in advance before the temporary materials are installed. In other words, it is currently impossible to apply such WSFRMs on the temporary materials, once they are installed. However, even after the temporary materials are installed, it is possible to pour such WSFRM around the installed steel sheet-piles and H-steels. Therefore, the details should be studied and reviewed in the future.

3. BASIC CHARACTERISTICS OF THE WSFRM

3.1 Basic Composition

The amphoteric WSFRM is fluid (coating material) and consists of the synthetic resin, elastomer, as the parent material, mixed with a super-absorbent polymer, filling material, solvent, and so on. Also, the alkaline WSFRM has a similar composition. However, unlike that of the amphoteric WSFRM, the super-absorbent polymer of the alkaline WSFRM hardly swells in fresh or saline water Instead, it uses a special polymer that swells in alkaline water.

The amphoteric and alkaline WSFRMs can be coated easily with a brush, roller, and so on, in advance. In addition, they dry relatively fast (approximately 12 hours at 20°C) and form a 1-2mm thick layer (dry membrane) after drying [9]. Furthermore, because the dry membrane made of such WSFRMs is hard, the temporary materials, on which such WSFRM is coated in advance can be installed or pushed directly into the ground. In the meantime, the quality of the extracted water from the swelling membrane of the amphoteric and alkaline WSFRMs comply with “Environmental Standard for Groundwater Based on Soil Contamination Countermeasures Act” [10], making it eco-friendly.

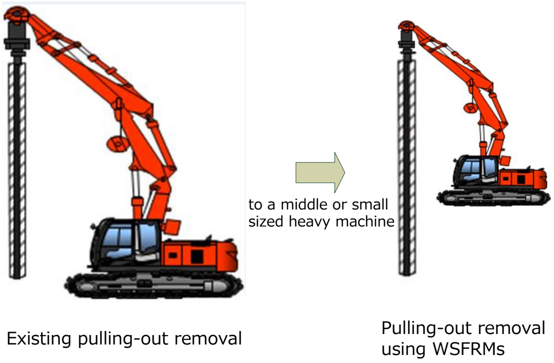


Fig. 1 Scale comparison of machines used for pulling-out removal of temporary works

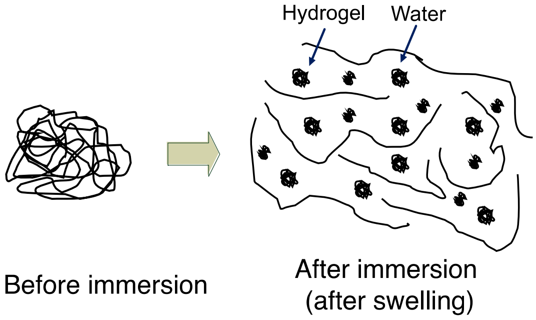


Fig. 2 Swelling mechanism of a super-absorbent polymer

3.2 The Swelling Mechanism

The swelling of the amphoteric and alkaline WSFRMs depends on the super-absorbent polymer incorporated in such WSFRM. The super-absorbent polymer consists of bridged polyelectrolytes with ionic bases and a 3D network, and absorbs water to form hydrogel when immersed in water (*see* Fig. 2). The bridge bonds prevent free movement of the high-energy molecules. As a result, these water molecules are retained inside the 3D network and the 3D network swells. On the other hand, the elastic effect of the high-energy molecule chain generates force to contract the 3D network and achieves equilibrium with the force to expand the network through the imbibition. This absorbing force depends on the osmotic pressure arising from the concentration difference of the movable ions inside and outside of the hydrogel [11].

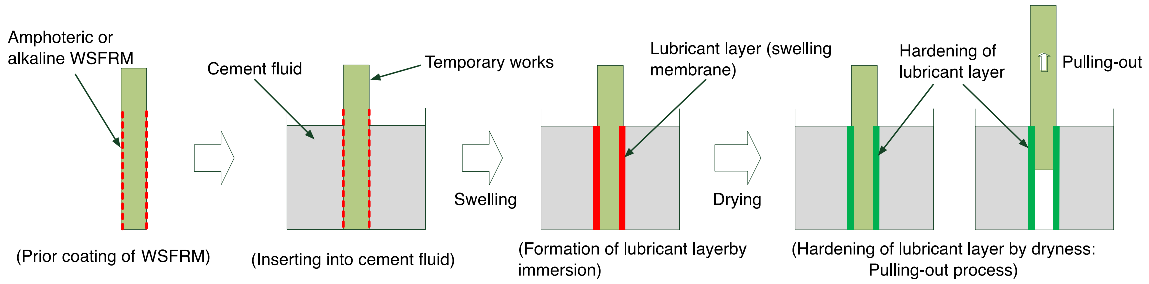


Fig. 3 Simple overview for pulling-out removal of temporary works using amphoteric and alkaline WSFRMs

Hydrogel formed inside the 3D network (*see* Fig. 2) works as the lubricant layer. It is the main factor to induce the friction reducing effect by the amphoteric and alkaline WSFRMs. Also, because the generated volume of the hydrogel can be controlled through changing the amount of the super-absorbent polymer, it is possible to produce the amphoteric and alkaline WSFRMs that swell to the appropriate extent according to each purpose [9].

The super-absorbent polymer incorporated in the amphoteric and alkaline WSFRMs change those dissolution characteristics by replacing the end of the structural formula with various cations [11]. In general, in a super-absorbent polymer, the end of the structural formula is replaced with a Na+ ion, and the amphoteric WSFRM contains this super-absorbent polymer. On the other hand, the alkaline WSFRM contains a special super-absorbent polymer in which the end of the structural formula is replaced with an H+ ion. Because the end of the formula is replaced with an H+ ion, the super-absorbent polymer does not dissolve and swell in a neutral area, but gelates and swells in an alkaline area after the alkaline water is absorbed into the 3D network.

For the WSFRM incorporating the super-absorbent polymer, a variety of studies have been reported already [4-7]. Among them [4] is a representative report about the development of a super-absorbent polymer (water-absorbing polymer material) and WSFRM.

3.3 The Role

The role of the amphoteric and alkaline WSFRMs is to form a continuous swelling membrane on the surface of the temporary materials. Such WSFRMs coated in advance to the temporary materials, absorb the water in the cement fluid or ground to swell on the contact surface between temporary materials, and the cement fluid or ground. This swelling membrane becomes a dry membrane to form a lubricant layer (swelling membrane) on the contact surface between temporary materials, and the surrounding area. The formed lubricant layer can reduce friction on the contact surface of temporary materials. Therefore, applying the amphoteric and alkaline WSFRMs in advance is effective to reduce the friction on the surface of the temporary materials, and it is expected that it should facilitate the pull out of temporary materials (*see* Fig. 3).

The alkaline WSFRM for pulling out temporary steel sheet-piles and H-steels is thought to be especially suitable for the construction method to build a continuous wall in the ground platform (digging method with stabilizing fluid). For example, after the ground is drilled while the stabilizing fluid such as bentonite suspension is filled in there, the temporary materials, onto which the alkaline WSFRM is coated in advance, are installed. Then, after the stabilization, soil cement, mortar, concrete, and so on are filled. The alkaline WSFRM coated in advance absorbs water under an alkaline environment such as soil cement, mortar, and concrete before swelling starts from the contact surface to form the continuous swelling membrane on the surface of the temporary materials. This lubricant layer works in a similar way to the lubricant layer of the amphoteric WSFRM and reduces the friction on the surface of the temporary materials to facilitate the pulling-out. On the other hand, in the above method, the amphoteric WSFRM is less effective for pulling-out the core material because it starts and completes swelling when placed in the stabilizing fluid and so is likely to be detached during the process in which soil cement or cement fluid is filled.

4. THE SWELLING TEST AND PULLING-OUT TEST OF THE WSFRMS

4.1 The Swelling Test

4.1.1 Test method

The swelling characteristics of the amphoteric and alkaline WSFRMs are an important factor during the pulling-out of the temporary materials. Therefore, to verify the swelling characteristics of the amphoteric and alkaline WSFRMs, the swelling test was implemented by the following method.

(1) A certain amount of amphoteric and alkaline WSFRMs was dried and test specimens of 20×20mm were prepared.
(2) The initial weights of the test specimens were measured and immersed in water tanks with various qualities and temperatures according to the application.
(3) The test specimen was taken out whenever each immersion time had passed and the weight was measured after the immersion.
(4) The weight-swelling ratio (= the weight after the immersion / the initial weight) was calculated.
(5) As required, steps (3) and (4) were repeated until the predetermined time had passed.

4.1.2 Results and discussion

Fig. 4 shows the relationship between the pH of the immersion water and the swelling ratio after 24 hours of immersion regarding the amphoteric and alkaline WSFRMs. It shows that the alkaline WSFRM hardly swells when the pH of the immersion water is kept between neutral and acid, while the material swells 15-20 times (ratio by weight) in the alkaline immersion water. Also, it was found that at least pH 10 is required for the immersion water so that the alkaline WSFRM will acquire a high swelling ratio. On the other hand, although the swelling ratio of the amphoteric WSFRM dropped in the strong acid and alkaline immersion water, it swelled 15-20 times in the moderate acid or alkaline immersion water.

Fig. 5 shows the relationship between the water temperature and the swelling ratio, comparing the amphoteric and alkaline WSFRMs after being immersed for 24 hours in the fresh water (pH7) and the synthetic seawater (pH8) (consisting of the contents shown in Table 1). It indicates that the amphoteric WSFRM is subject to the temperature of both the fresh and synthetic seawater for immersion and increases its swelling ratio as the water temperature rises. The reason why the swelling ratio under the synthetic seawater environment is lower than under the fresh water environment is that the swelling of the super-absorbent polymer contained in the amphoteric WSFRM is inhibited by the salts contained in the synthetic seawater. On the other hand, the alkaline WSFRM hardly swells in pH neutral immersion environments such as fresh water and synthetic seawater.

Fig. 6 shows the relationship between the immersion time and the swelling ratio of the amphoteric WSFRM immersed in fresh water (pH7) at the temperatures of 10°C and 20°C. It is found that the material swells faster and larger at a

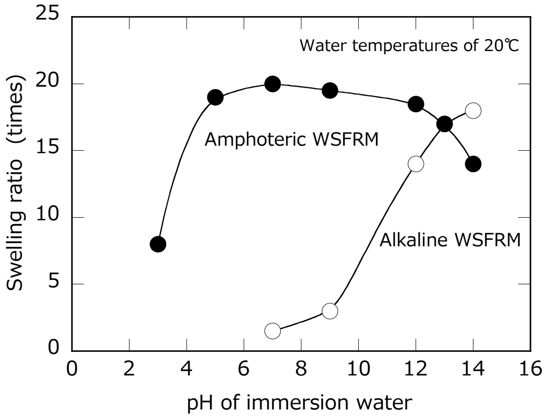


Fig. 4 Relationship between pH of immersion water and swelling ratio after 24 hours of immersion

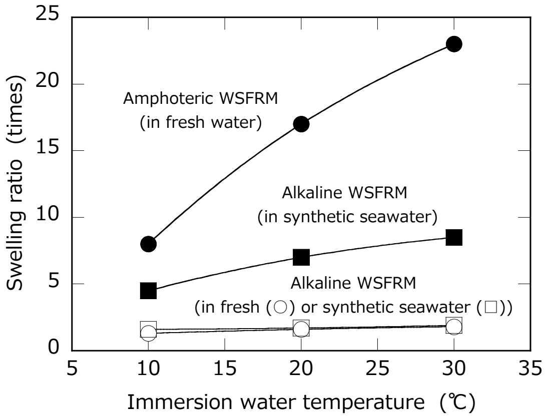


Fig. 5 Relationship between water temperature and swelling ratio

Table 1 Sea water contents in 1kg of water

NaCl	$MgSO_4$	$MgCl_2$	$CaCl_2$	KCl
28.5g	6.8g	5.2g	1.5g	0.7g

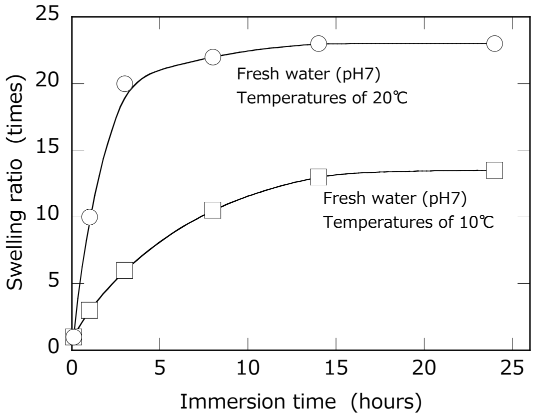


Fig. 6 Relationship between immersion time and swelling ratio of amphoteric WSFRM immersed in fresh water (pH7)

temperature of 20°C compared to 10°C. The authors assume that this is because the swelling speed of the super-absorbent polymer contained in the material increases as the temperature rises. Furthermore, Fig. 7 shows the relationship between the immersion time and the swelling ratio of the alkaline WSFRM immersed in the alkaline water (set as pH13 with NaOH) at 10°C and 20°C. Like the amphoteric WSFRM (*see* Fig. 6), the swelling characteristics of the alkaline WSFRM subject to the temperature of the immersion water and the swelling ratio increases as the water temperature rises. Moreover, the longer immersion time also increases the swelling ratio.

Fig. 8 shows the comparison of the swelling ratios of the amphoteric and alkaline WSFRMs in the alkaline water (set as pH13 with NaOH). Compared to the alkaline WSFRM, the amphoteric WSFRM starts swelling and reaches the plateau (saturation point) faster in the alkaline water.

A similar swelling test was undertaken using the supernatant liquid (alkaline water with pH13) gained after Portland cement was suspended in pure water. As shown in Fig. 9, the result was similar to that of Fig. 8. Although the supernatant liquid of Portland cement suspension contains a lot of Ca ions, it is thought that these metallic ions do not largely affect the swelling characteristics of the amphoteric and alkaline WSFRMs. However, depending on the conditions of the immersion water, the swelling of the WSFRM may be inhibited and less effective as WSFRM. Therefore, the authors tested and reviewed the influence on the swelling using the amphoteric WSFRM and the immersion water containing various metallic ions. As for the metallic ions, the authors assumed applications in waste landfills and so on, and selected certain chemicals (metallic ions) randomly as shown in Table 2 with the concentration of 2,000ppm for the immersion water. As shown in Table 2, approximately the same swelling ratios are gained in the immersion water containing metallic ions as that in water for comparison (fresh water for immersion), and so it can be said these metallic ions do not affect the swelling characteristics so much.

Photos. 1 and 2 show each swelling status when the amphoteric and alkaline WSFRMs are immersed in the fresh water (pH7) and alkaline water (set as pH13 with NaOH). It is found that although the amphoteric WSFRM swells in both types of immersion water, the alkaline WSFRM does not swell in the fresh water.

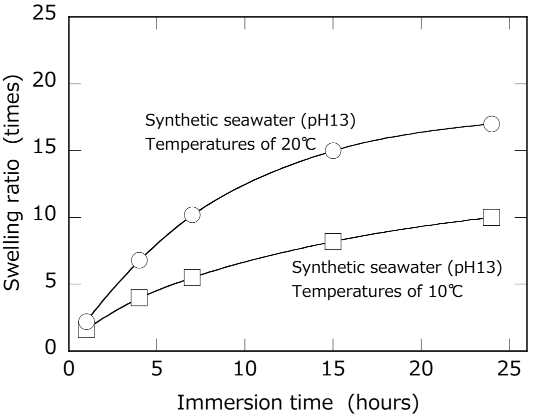


Fig. 7 Relationship between immersion time and swelling ratio of alkaline WSFRM immersed in alkaline water (set as pH13 with NaOH)

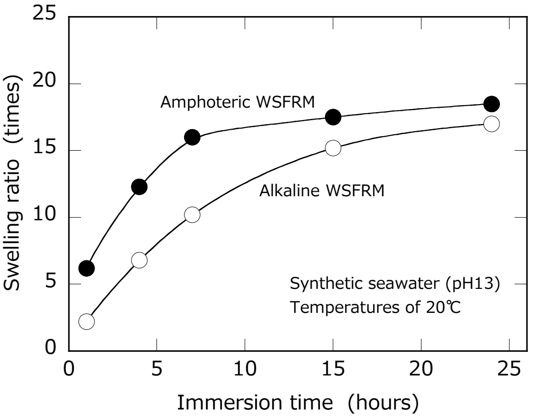


Fig. 8 Comparison of swelling ratios of amphoteric and alkaline WSFRMs in alkaline water (set as pH13 with NaOH)

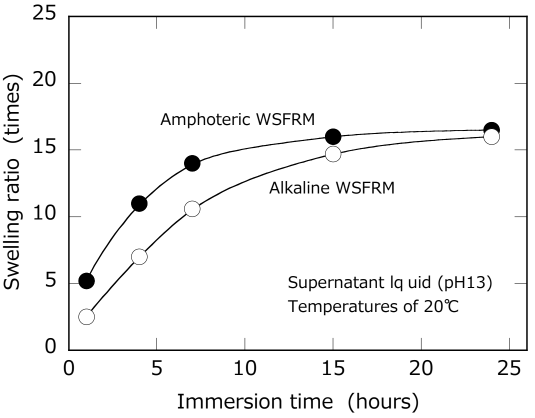


Fig. 9 Comparison of swelling ratios of amphoteric and alkaline WSFRMs in supernatant liquid (alkaline water with pH13) gained after Portland cement was suspended in pure water

4.2 The Pulling-out Test

4.2.1 Test method

It is thought that the pulling-out characteristics of the steel sheet-piles and H-steels on which the amphoteric and alkaline WSFRMs is coated in advance, largely depend on the applied amount of

Table 2 Swelling ratio of WSFRM obtained in immersion water containing chemical substances

Chemicals (2,000ppm)	The swelling ratio (Times) (The water temperature: 20°C)
Arsenic trioxide	21.0
Selenious acid	19.5
Chromium oxide (4)	20.0
Cadmium sulphate	19.3
Lead chloride	21.5
Mercury nitrates	19.0
Potassium ferrocyanide	20.0
Comparison (fresh water)	21.0

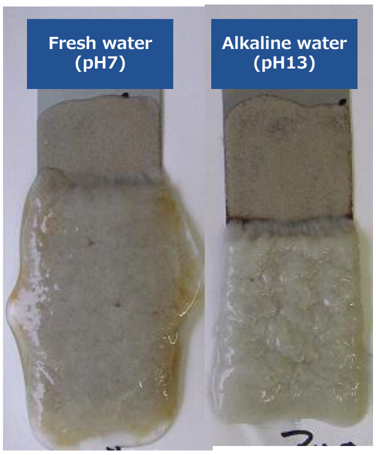


Photo. 1 Swelling status when amphoteric WSFRM is immersed in fresh water (pH8) and alkaline water (set as pH13 with NaOH)

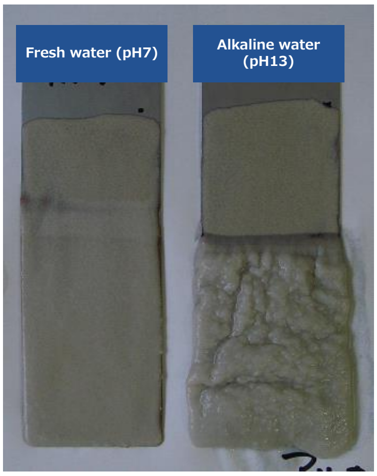


Photo. 2 Swelling status when alkaline WSFRM is immersed in fresh water (pH8) and alkaline water (set as pH13 with NaOH)

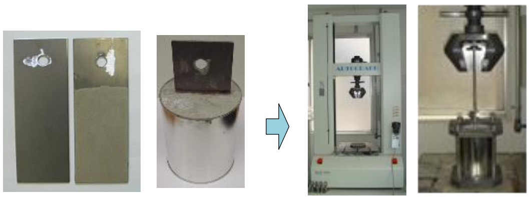
coating. Therefore, to verify the relationship between the applied amount of coating and the pulling-out characteristics, the authors implemented pulling-out tests with an iron flat-bar on which such WSFRM was coated in advance.

The procedure of the pulling-out test is as follows:

(1) Apply a certain amount of the amphoteric and alkaline WSFRMs on both surfaces (each application area is 75×130mm) of an iron flat-bar (75×200×3mm) (*see* Photo. 3).

(2) Pour a certain amount of cement fluid into an iron container (1L volume) before inserting the iron flat-bar mentioned in (1).

(3) After the insertion, implement the dry curing for a month.



<Iron flat-bar and test specimen> <Pulling-out test apparatus>

Photo. 3 Simple overview for pulling-out test using amphoteric and alkaline WSFRMs

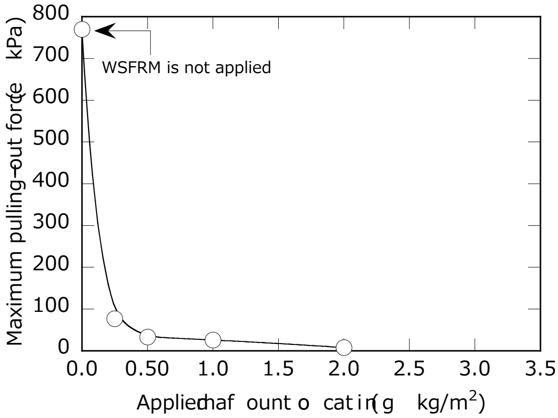


Fig. 10 Relationship between applied amount of coating and maximum required pulling-out force regarding amphoteric WSFRM applied on the iron flat-bar

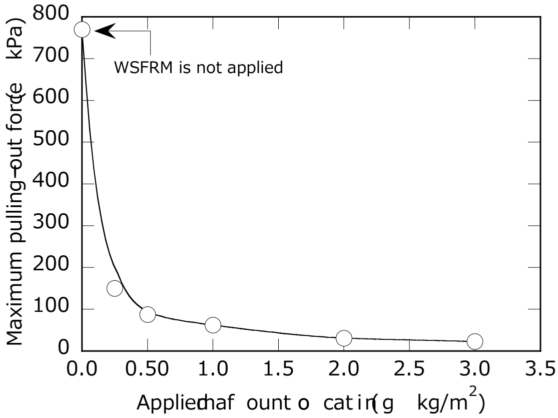


Fig. 11 Relationship between applied amount of coating and maximum required pulling-out force regarding alkaline WSFRM applied on the iron flat-bar

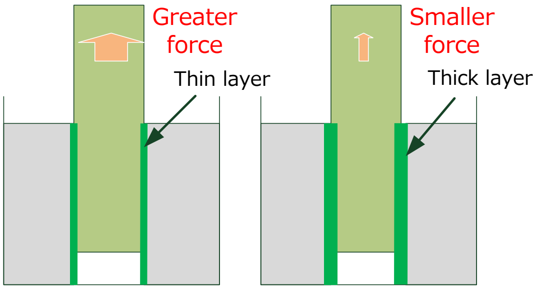


Fig. 12 Relationship between the thickness of the swelling membrane and the force required to pull out

(4) Using the machine for the pulling-out test (Autograph 50kN equipment made by Shimadzu), measure the pulling-out force required when the iron flat-bar is pulled out from the iron container (*see* Photo. 3).

4.2.2 Results and discussion

Figs. 10 and 11 show the relationship between the applied amount of coating and the maximum required pulling-out force for the amphoteric and alkaline WSFRMs coated on the iron flat-bar. These indicate that the prior application of the amphoteric and alkaline WSFRMs on the iron flat-bar is effective for reducing the force required to pull out the iron flat-bar and the effect depends on the applied amount of coating. Specifically, the force required to pull out the iron flat-bar on which the amphoteric WSFRM was coated was 77kPa and 1/10 when the applied amount of coating was 0.25kg/m^2, and 26kPa and 1/30 when the applied amount of coating was 1.0kg/m^2, compared to 770kPa, which was the required pulling-out force when no such material was applied. On the other hand, the required force to pull out the iron flat-bar on which the alkaline WSFRM was coated in advance was 150kPa and 1/5 when the applied amount of coating was 0.25kg/m^2, and 62kPa and less than 1/10 when the applied amount of coating was 1.0kg/m^2, compared to 770kPa, which was the required pulling-out force when no such material was coated. Although the required force to pull out the iron flat-bar on which the alkaline WSFRM was coated was slightly larger than when the amphoteric WSFRM was coated, it was still very good compared to when no such material was coated.

By forming the lubricant layer (swelling membrane) as mentioned above, the amphoteric and alkaline WSFRMs become effective for reducing the required force to pull out the iron flat-bar representing the temporary materials. Here, the coated amount of the amphoteric and alkaline WSFRMs affects the pulling-out characteristics of the iron flat-bar significantly. It is thought that the pulling-out characteristics depend on the thickness of the lubricant layer (thickness of the swelling membrane). That is, the more the amount of coating of the amphoteric and alkaline WSFRMs is coated, the thicker the lubricant layer (the swelling membrane) becomes, and the less the friction on the contact surface against the surrounding ground, concrete, or mortar becomes; and, therefore, they can be pulled out with less force (*see* Fig. 12).

Photo. 4 Working scenery of applying WSFRM to a steel sheet-pile

Photo. 5 Working scenery in which WSFRM was used in the pulling-out of a steel sheet-pile

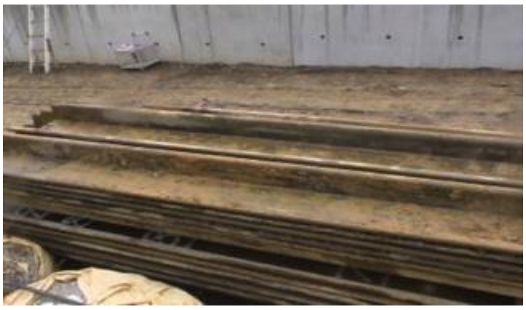


Photo. 6 A steel sheet pile after pulling-out

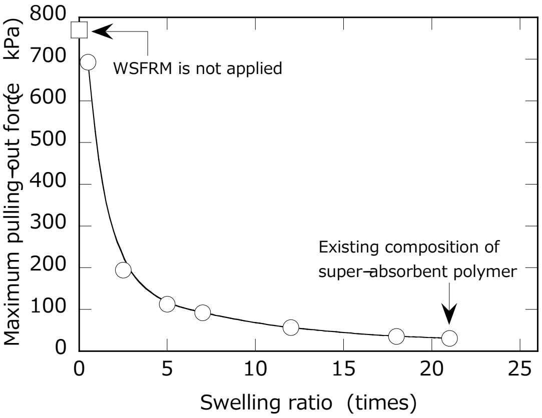


Fig. 13 Relationship between the swelling ratio of amphoteric WSFRM and the maximum force required for pulling out the iron flat bar

4.2.3 Pulling-out steel sheet-piles (countermeasure to prevent soil adhesion during the pulling-out)

Construction work was undertaken in Kochi City to prevent soil adhesion while pulling out steel sheet-piles (*see* Photos. 4, 5 and 6). In this construction work, the amphoteric WSFRM was coated on 7m lengths on both sides (the concave and convex surfaces) of 10m length, type III steel sheet-piles before being installed into the soil retaining wall on the street. When the steel sheet-piles were pulled out after the construction work (a month later), the soil did not adhere to the surface of the steel sheet-piles during the pulling-out, and so the method was found to be effective for preventing soil adhesion (*see* Photo. 6).

4.3 The Relationship Between The Swelling Ratio and The Effect of Reducing for the Required Pulling-Out Force

The pulling-out characteristics of the iron flat-bar on which the amphoteric and alkaline WSFRMs is coated significantly depend on the coated amount of such WSFRM (*see* Figs. 10 and 11). Here, the more the amphoteric and alkaline WSFRMs are coated, the more the super-absorbent polymer will be applied. As a result, it is thought that the coated amount of the amphoteric and alkaline WSFRMs affect the swelling characteristics and such characteristics dramatically affect the pulling-out characteristics of the iron flat-bar on which such WSFRM is coated.

Therefore, targeting the amphoteric WSFRM, the relationship between the swelling ratio of such WSFRM and the pulling-out characteristics was reviewed. Specifically, following Section 4.1.1, the swelling ratio of the amphoteric WSFRM was calculated for which the contained amount of coating of the super-absorbent polymer was changed several times [8]. Furthermore, using the iron flat-bars on which the WSFRMs containing different amounts of coating of the super-absorbent polymer were coated in advance, the pulling-out tests were implemented following Section 4.2.1.

Fig. 13 shows the relationship between the swelling ratio of the amphoteric WSFRM and the maximum force required to pull out the iron flat-bar on which such WSFRM was coated in advance. This indicates that the more the swelling ratio of the amphoteric WSFRM is increased, the less force is required to pull out the iron flat-bar on which such WSFRM has been coated in advance. That is, an increase of the swelling ratio in the amphoteric WSFRM contributes to thicken the formed swelling layer, and as a result, the friction on the contact surface between the steel sheet-pile and the cement fluid or ground will be reduced. It is thought the alkaline WSFRM has the same tendency.

5. CONCLUSIONS

In this paper, given that the amphoteric and alkaline WSFRM is coated to temporary materials, to facilitate the pulling-out, the authors undertook some experiments to review the fundamental characteristics such as the swelling ratios of the amphoteric and alkaline WSFRMs and the forces to pull out the iron flat-bars on which such WSFRMs were coated in advance.

The findings are as follows:

1. The amphoteric WSFRM can swell under an immersion environment such as fresh, saline, or alkaline water.
2. Also, the desired swelling characteristics are achieved under the immersion environment containing metallic ions. On the other hand, it was demonstrated that the alkaline WSFRM could swell and have the desired swelling characteristics under the immersion environment of the alkaline immersion water with pH10 or higher.
3. The amphoteric and alkaline WSFRMs coated in advance reduce the friction on the contact surface between the flat-bar and the mortar and enables the pulling-out with less force.
4. The required force to pull out the iron flat-bar on which the amphoteric and alkaline WSFRMs are coated in advance is subject to the swelling ratio and the coated amount of such WSFRM significantly.

The amphoteric and alkaline WSFRMs swell under the immersion environment of fresh, saline, or alkaline water to form the lubricant layer (swelling membrane). However, in the future, further studies would be required to verify how the effect to reduce the required pulling-out force changes with the swelling ratio of the amphoteric and alkaline WSFRMs when the immersion water such as fresh, saline, and alkaline water is little, and how the surrounding soil pressure, and so on, affect the pulling-out of temporary materials, on which the WSFRM is coated in advance.

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Int. J. of GEOMATE, June, 2014, Vol. 6, No. 2 (Sl. No. 12), pp. 910-918.

MS No. 131209 received on Dec. 9, 2013 and reviewed under GEOMATE publication policies.

Pertinent discussion including authors' closure, if any, will be published in the June. 2015 if the discussion is received by Dec. 2014.

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