

## **Enhancement of Slurry Treatment Efficiency in Slurry Shield TBM Tunneling by Optimal Application of Coagulant Agent**

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### **ABSTRACT**

For slurry shield TBM tunneling, the slurry treatment efficiency in the slurry circuit is one of the most important factors affecting advance rate. The slurry treatment efficiency is significantly influenced by amount of fine content in the discharged slurry from the excavation chamber which is dependent of the ground conditions ahead of the tunnel face. In order to enhance the slurry treatment efficiency, it is required to reduce fine content in the slurry which inflows into the treatment plant. This paper presents a case study of enhancing slurry treatment efficiency for slurry TBM tunneling in mixed face condition by adding PAC (Poly Aluminum Chloride) as a coagulant. Optimal dosage of PAC was decided from the results of laboratory test. It was applied to actual slurry treatment work, and significant increase of slurry treatment rate could be found from the field operation data.

### **1. INTRODUCTION**

The slurry shield TBM is a tunneling machine that is able to support the tunnel face with pressurized bentonite slurry pumped into the excavation chamber. The slurry also functions as transport medium for mucking out the excavated material. After the slurry has been pumped into a treatment plant for the removal of suspended solids, and when the regulation of its density is completed, it is pumped back to the shield machine. In the slurry shield tunneling the quality of bentonite slurry plays an important role in the slurry shield TBM operation and the advance rate (Longchamp 2005). Hence, the rheological properties of shear strength and viscosity and the suspension density of the slurry, which are generally adapted to suit the ground properties, needs to be monitored continuously and carefully during the TBM drive.

Because the slurry applied for tunnel face support is getting mixed with the excavated material in the excavation chamber, the density of the discharged slurry from the excavation chamber increases and it causes surplus slurry, the rest of slurry for quality regulation before pumping back to shield machine. The amount of surplus slurry

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depends on the fine content in the excavated material. If the accumulated surplus slurry in the storage tank exceeds the capacity of the storage tank due to delay of dehydration process of filter press or cyclone, TBM drive has to be ceased and consequently it will increase of the construction period. To this matter, increasing capacity of storage tank and relevant mechanical suspension separation equipments is not a reasonable approach due to cost and land-use restrictions in TBM tunneling. Instead, physio-chemical pre-treatment of the slurry using coagulat agent could be a better way for enhancing treatment efficiency.

This paper presents a case study of applying PAC (Poly Aluminum Chloride) as coagulant agent for improvement of the slurry treatment efficiency in slurry shield tunneling within the mixed face condition. A series of laboratory tests were carried out for optimization of dosage amount of the agent for reliable quality management of the slurry on the basis of its key performance indicators.

## 2. SLURRY TREATMENT TECHNOLOGY

### 2.1 Slurry treatment cycle

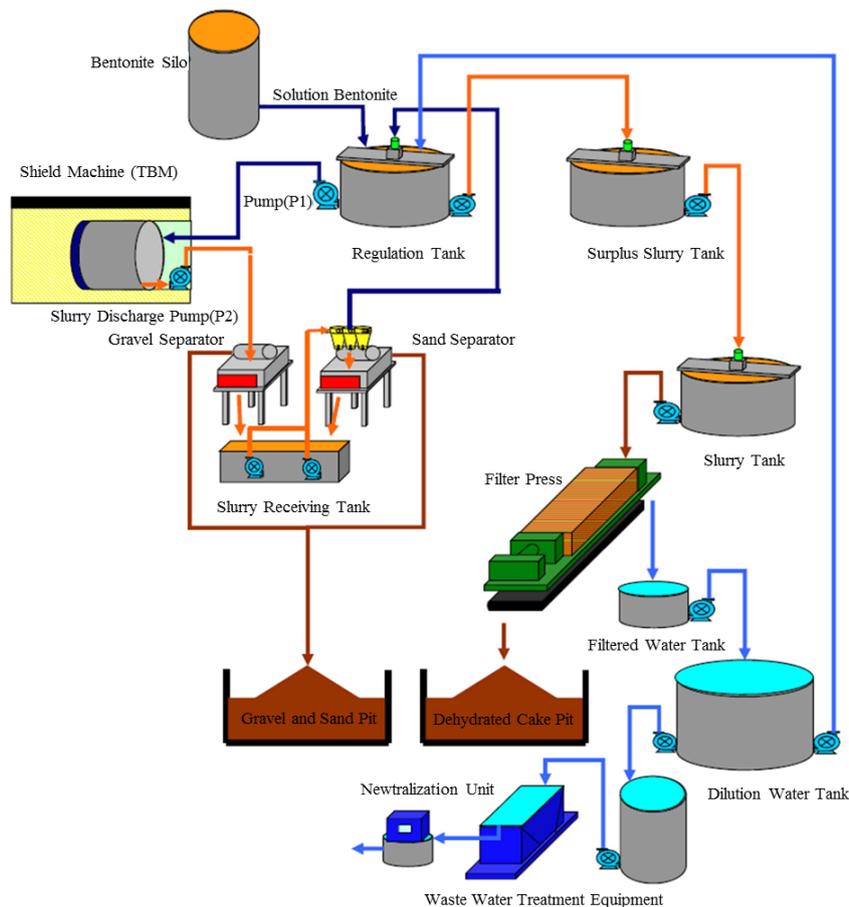


Figure 1. Schematic description of slurry treatment cycle (Dehydration by filter press)

Figure 1 illustrates the schematic description of slurry treatment cycle with dehydration by filter press. First, the slurry mixed with excavated material discharged from the excavation chamber is transported to the treatment plant. As the separation process for the removal of coarse grains from the slurry is completed, the slurry is pumped into regulation tank, where its properties are regulated by adding bentonite solution or water. The quality management is usually carried out based on the KPIs (Key Performance Indicators, Marotta 2010). If the properties of slurry meet the KPI, slurry is fed into the shield machine. Otherwise, its regulation will be continued until satisfying the KPIs. If the density of slurry is too high to regulate, the surplus of slurry develops. It is transported to the surplus slurry tank and then is dehydrated by filter press or cyclone.

### 2.2 Challenges of TBM driving through mixed face

As aforementioned in 2.1, the developed surplus slurry is dehydrated for disposal. As the higher density of slurry is, the more surplus slurry develops. Besides, because the slurry density depends on the amount of fine contents in the slurry pumped into the treatment plant, the slurry treatment efficiency for dehydration process can be degraded when drives through silty and clayey ground. Hence, when TBM drives through the mixed face, the slurry treatment efficiency can be one of the possible risks related to the TBM advance rate. The high density of slurry requires more time for the dehydration, and due to the delay of dehydration, the more surplus slurry will be accumulated in the tank. If the amount of the accumulated surplus slurry exceeds the storage capacity of the tank, TBM advance is broken and, as a result, the construction period will be also delayed. To prevent the TBM advance breakage, it is necessary to enhance the slurry treatment efficiency. For this purpose, the agent for coagulation and flocculation is added to the surplus slurry before dehydration to settle the fine particles in the slurry (Jeon 1993, Stechemesser and Dobias 2005). Figure 2 shows the principle of floc formation through coagulation and flocculation process.

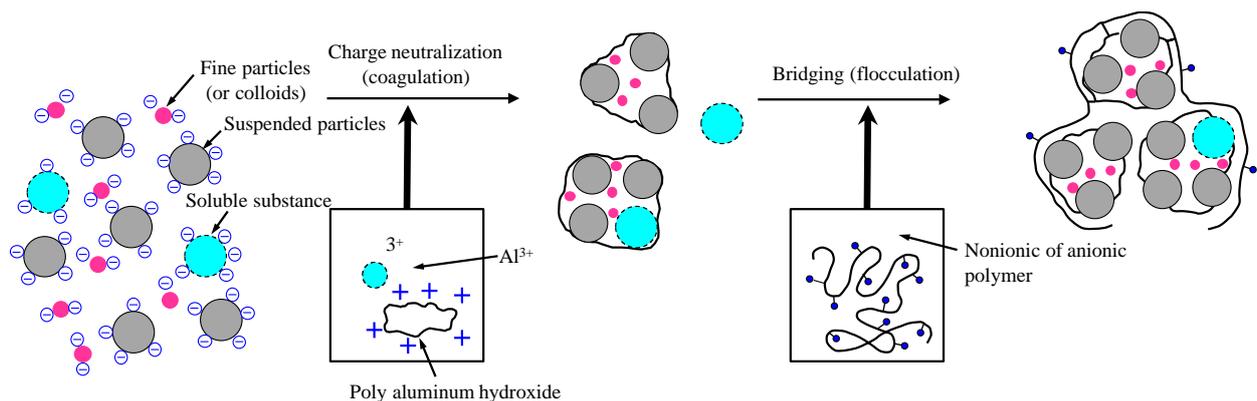


Figure 2 Principle of coagulation and flocculation (Jeon 1993)

PAC (Poly Aluminum Chloride,  $Al_2(OH)_nCl_{6-n}$ ) is a kind of inorganic polymer coagulant / flocculent. In general, PAC is used as an agent, since its features are not

influenced by the temperature. In addition to its insensitivity to the temperature, dosage of PAC induces small change of pH and accordingly it has wide application range.

For using PAC it needs to consider the optimal dosage amount depending on the ground type. In case of the tunneling in homogeneous ground the optimal dosage of PAC can be simply determined. However, the tunneling in mixed ground conditions requires the variation of the optimal dosage depending on the geological conditions at tunnel face along the tunnel alignment.

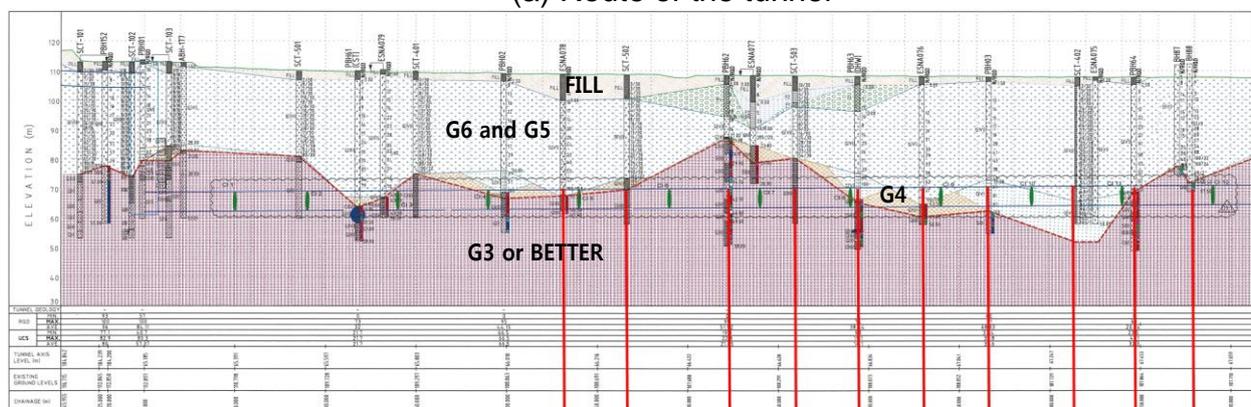
### 3. CASE STUDY OF PAC DOSAGE OPTIMIZATION

#### 3.1 Site description and issues

The tunnel is northern part of the three sections in the North-South Transmission cable tunnel in Singapore. It is 5.87km long tunnel with an internal diameter of 6m. Three construction shafts were built for launching and retrieval of TBM machines. Two TBMs were applied for the works launching from two shafts (Gambas and Mandai shafts), located at each end, driving toward a central receiving shaft (Sembawang shaft). The plan alignment of tunnel is shown in Figure 3(a).



(a) Route of the tunnel



(b) Geological profile

Figure 3. Tunnel route and geological profile

The soil strata encountered at the tunnel excavation are mostly Bukit Timah Granite rock with weathering grade II to III with fill layer at the top and sometimes alluvial sand (F1) or clay (F2) from Kallang Formation underlain the fill layer (Figure 3(b)).

The mixed ground condition and large amount of fine content in excavated material were found during driving of TBM Tunnel 2 and they resulted in degradation of slurry treatment efficiency. The extremely high fine content in the slurry pumped into the treatment plant induced reduction of the dehydration efficiency of the filter press and also to the excess of the surplus slurry over the capacity of the surplus slurry tank. As a result, the breakage of TBM advance occurred. To cope with the problem, the amount of surplus slurry was regulated by using PAC and, for maximization of the slurry treatment efficiency of the filter press, optimal dosage amount of PAC was investigated.

### 3.2 Optimization of dosage amount of PAC content

Increased dosage amount of PAC helps the formation of floc (Coagulation) and the formation of floc structure (Flocculation). But the excessive dosage of PAC over the arbitrary critical value leads to the reduction of coagulation and flocculation of slurry suspension and the waste material cost. Hence, it is necessary to determine the optimal dosage amount of PAC considering the fine content in the discharged slurry, that is, the ground conditions in front of the tunnel face.

To determine the optimal dosage amount of PAC, filtration test and Marsh Funnel test were applied (Figure 4). Samples for tests were taken from the surplus tank (Figure 5(a)). After sampling their densities were measured to determine of the dosage amount of PAC, since the dosage amount of the agent is evaluated based on the ratio of its weight to the solid weight in the slurry (Figure 5(b)).



(a) Filtrate test



(b) Marsh Funnel test

Figure 4. Fluid loss test and marsh funnel test



(a) Sampling



(b) Measurement of density

Figure 5. Sampling from surplus slurry tank and measurement of sample density

The dewatering time of the filter press depends on the permeability of the mud cake in the press. When the clay particles in the slurry suspension are coagulated by the aluminum ions ( $Al^{3+}$ ) in the PAC, the apparent surface of particles get larger and it leads to the increase of permeability of the mud cake. Hence, the optimal value of the PAC dosage amount can be determined as when the filtrate is the highest in the filtration test. Figure 6 shows the results of filtrate for various PAC dosage amount. With the increase of the PAC dosage amount the filtrate also increase. At the about 40 kgf/tf the filtrate shows the maximum value of filtrate, which was considered as the optimal dosage of PAC.

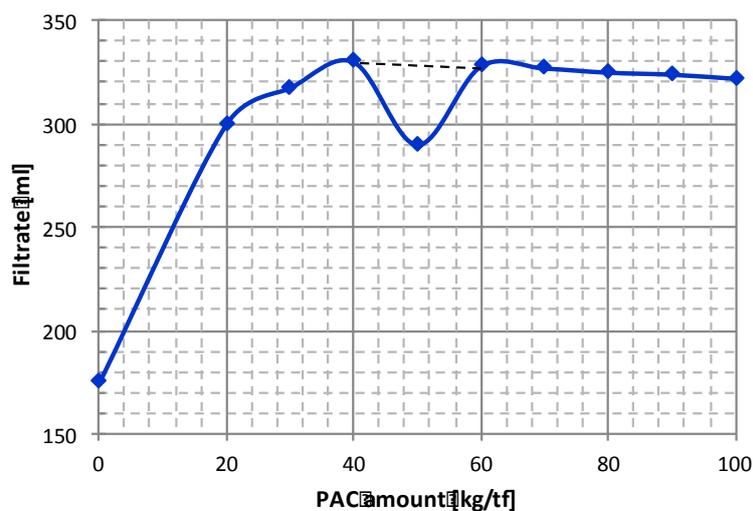


Figure 6. Change of filtrate with increase of the PAC dosage amount

The filtration test needs time for the water filtration, i.e. for the determination of the optimal value of dosage the time for testing is required. Hence, in this study, Marsh Funnel test was employed to checked, if it is possible to determine the optimal value with the viscosity. The clay particle is neutralized by the aluminum ions ( $Al^{3+}$ ). This causes not only the reduction of the repulsive force but also the enhancement of the attractive forces between particles. However, if the PAC is added to the slurry suspension excessively, the clay particles will be charged positively and dispersed in the suspension. Therefore, the Funnel viscosity can be the highest when the dosage amount of PAC is near its optimal value. In the diagram in Figure 7 the maximum value of the funnel viscosity is shown at the value of about 40kgf/ft. This value can be the optimal value for PAC dosage amount and is equal to the value from the fluid loss test.

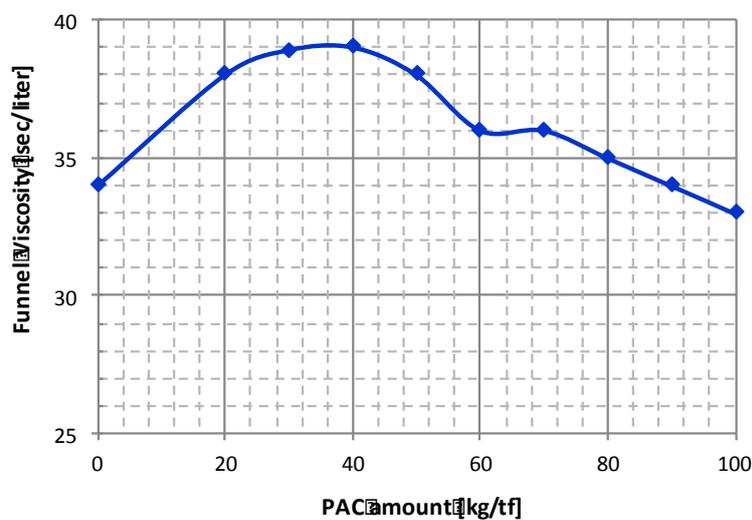


Figure 7. Change of funnel viscosity with increase of PAC dosage amount

When the TBM advance was broken, the dosage amount of PAC was 7.5kgf/ft. This value is much lower than the optimal value (40kgf/ft) estimated from the laboratory tests. It could be concluded that the lower amount of dosage reduced the slurry treatment efficiency of the filter press and consequently led to the TBM advance breakage. Therefore, the PAC dosage amount was adjusted to the optimal value. As a

Table 1. Change of the PAC dosage, treatment efficiency of filter press, and TBM advance rate

	Avg. PAC Dosage per ring (Liter)	Avg. treated slurry/ filter pressing time (Liter/min)	TBM advance rate (rings/day)
Before Optimization	233	170	5.07
After Optimization	399	210	4.58

result, the slurry treatment capacity per minute increased (Table 1) and there was no TBM advance breakage due to delayed slurry treatment. However, it can be seen from Table 1, that the TBM advance rate after PAC dosage optimization was found to be slower than before due to other factors in TBM driving such as maintenance, segment damage etc.

#### **4. CONCLUSIONS**

In this paper, a case study of using PAC as coagulant to improve the slurry treatment for slurry shield tunneling in the mixed face condition was presented. When the slurry shield TBM drives through the ground having excessive amount of fine particles, the risk related to the slurry treatment efficiency should be considered. In such a case, the addition of PAC is very helpful to enhance the slurry treatment efficiency and the optimization of its dosage amount plays a great role to maximize its function. The optimization of PAC dosage amount is possible with the simple tests such as filtration tests and Marsh Funnel tests. Currently the slurry shield tunneling method is popular for the tunneling in the mixed face because this method has is very advantageous in terms of supporting the excavation face. Hence, before the execution of projects it can be essential to establish the strategy for optimization depending to the section of the ground and to correct this strategy with observation of the trend of the slurry treatment efficiency.

#### **ACKNOWLEDGEMENT**

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