Quick-Setting Sprayed Mortar for Rock Support in Tunnel Boring Machine Excavation

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ABSTRACT

When a tunnel boring machine (TBM) is used to excavate a tunnel, a lining layer of quick-setting sprayed mortar can be applied to prevent instability of the rock immediately after excavation. In this report, the performance of quick-setting sprayed mortar and its application to TBM excavation are summarized. The strength of quick-setting sprayed mortar 1 h after spraying is more than 1 N/mm^2 even at low temperatures, and the strength at 28 days is more than 35 N/mm^2 at temperatures between 5–30 °C. Blending with synthetic fiber gives the hardened quick-setting sprayed mortar higher flexural toughness than that produced without synthetic fiber. The resistance of the mortar layer to water inflow is evaluated experimentally, and the mortar is found to adhere stably at a water inflow rate of 7 L/min. A TBM can be easily equipped with the system for mortar spraying, and the system is compact and takes up little space. In addition, spraying work with this system can be performed by only a few workers and in a low-dust environment.

1 INTRODUCTION

A TBM can be used to excavate a tunnel several times faster than the New Austrian Tunneling Method (NATM), which is the standard method for excavation of mountain tunnels. TBM excavation is effective for long-distance tunnels and can be applied to soft and hard ground. However, during tunnel excavation, some instability can occur because of cracked, crushed, and water inflow zones, and very soft ground. In these situations, quick-setting sprayed mortar is applied to form a thin lining layer on the excavated area to prevent rock instability.

Pre-mixed (PM) mortar contains Portland cement, size-controlled sand, synthetic fiber, and various cement admixtures. For TBM applications, the PM mortar is mixed continuously with water, and then pumped through a delivery hose. In the nozzle of the hose, an acidic liquid accelerator (LA) is introduced together with compressed air. Mortar sprayed in this manner has excellent quick-setting characteristics and strength development, and can be applied in a low dust environment with a low rebound ratio.

In this report, the performance of the quick-setting sprayed mortar and its application to TBM excavation are summarized.

Table 1 Composition and physical properties of quick-setting sprayed mortar

Material	Main component	Density	pH	Appearance
PM mortar	Cement, Sand, Fiber, Admixtures	2.70–2.90	—	Gray powder
Liquid accelerator	Aluminum sulfate	1.25–1.5	2.0–3.0	Light brown liquid

Table 2 Mixing proportions of for quick-setting sprayed mortar

W/PM	Mixing proportion (kg/m^3)		
	PM	Water	LA
0.20	1770	357	88.5

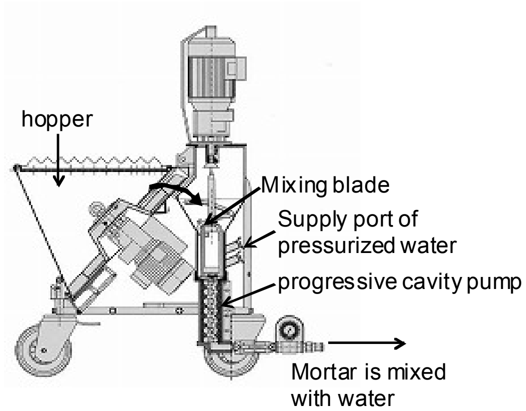


Figure 1 Architecture of CM-Pump

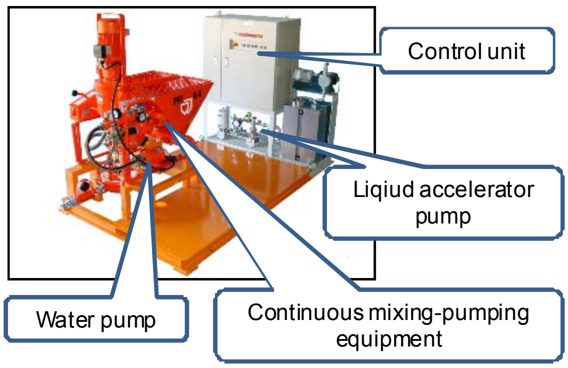


Figure 2 Built-in system equipped with CM-Pump, LA-Pump, and control unit

2 MATERIALS and SYSTEM

2.1Materials and mixing proportions

Table 1 shows the composition and physical properties of the PM mortar and LA. PM mortar contains Portland cement, size-controlled sand, synthetic fiber, and various cement admixtures. Synthetic fiber is included in the mixture because it gives the hardened mortar higher flexural toughness than that produced without synthetic fiber, and this prevents flaking of the mortar. The various cement admixtures are included to adjust the flow, setting, and early strength properties of the mortar. The main component of the LA is aluminum sulfate, and it is a light brown acidic liquid. Table 2 shows the mixing proportions for quick-setting sprayed mortar.

2.2 Method for producing quick-setting sprayed mortar

Mixing and pumping of the mortar is carried out using continuous mixing-pumping equipment (CM-pump) (Figure 1). This equipment consists of a hopper, mixer, and pump. The PM mortar is added to the hopper and pressurized water is supplied continuously from each supply port. The

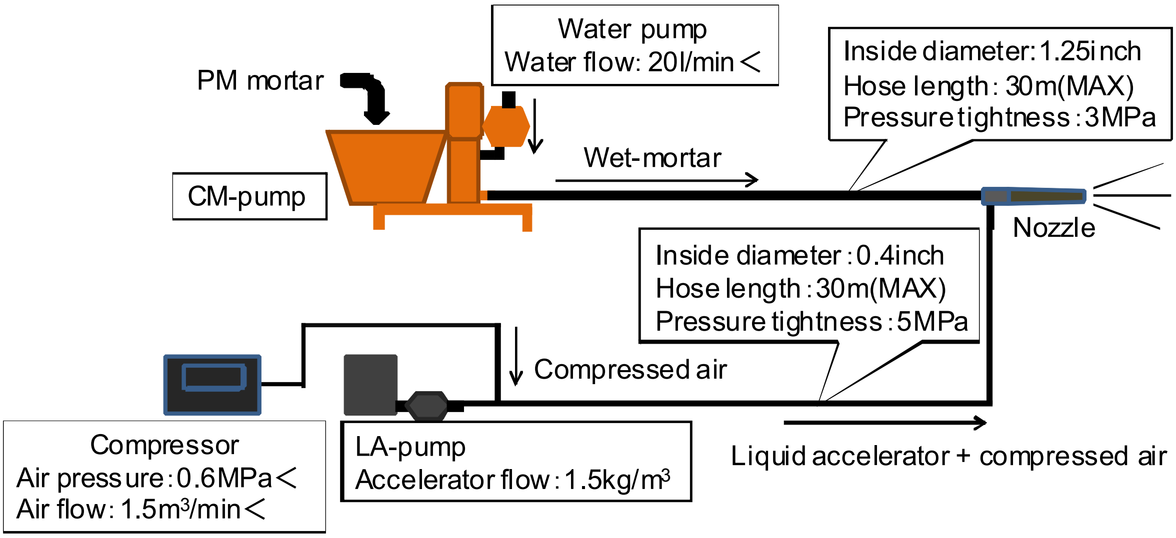


Figure 3 spraying system for quick-setting sprayed mortar

water and mortar are mixed instantly by the mixing blade. The water-mortar mixture is immediately moved through the system by the connected progressive cavity pump.

The system (Figure 2) built onto the TBM will include the CM-pump, a LA pump, and a control unit for these pumps. The water supply is adjusted by a flow meter after determining the supply velocity of the PM mortar. The LA supply is adjusted by the flow meter after determining the pumping velocity of the mixed mortar. The volume of LA to be added to the mortar is calculated from the weight of the PM mortar using the mixing proportions in Table 2.

2.3 Spraying system

Figure 3 shows the spraying system for the quick-setting sprayed mortar. The mixed mortar is pumped through a delivery hose. In the nozzle of the delivery hose, the acidic LA is introduced together with compressed air.

3 PERFORMANCE OF QUICK-SETTING SPRAYED MORTAR

The performance of quick-setting sprayed mortar was evaluated by using spraying system (Figure 3) in the laboratory.

3.1 Mixed mortar flow and estimation of mixing proportions

Figure 4 shows the flow of mortar with continuous mixing. The mortar flow is controlled between 190–220 mm. Table 3 shows the estimated mixing proportions of the mixed mortar that is obtained from the CM-pump. The estimated mixing proportions of the obtained mortar are almost the same as the required mixing proportions given in Table 2.

Figure 4 Flow of the mortar mixed by CM-pump

Table 3 Estimated mixing proportions

Flow rate of mixed mortar (m^3/hr)	Density (kg/m^3)	Estimated mixing proportions (kg/m^3)		
		W/PM	PM mortar	Water
2.15	2119	0.202 (0.20)	1763 (1770)	356 (354)

(　)：Required mix proportion

Table 4 Dust concentration and rebound ratio

Dust concentration during spraying						Rebound ratio		
Time elapsed					Average (mg/m^3)	Weight of sprayed mortar (kg)	Rebounded material (kg)	Rebound ratio (%)
1 min	2 min	3 min	4 min	5 min				
0.6	1.1	1.4	1.7	1.9	1.4	389.4	4.8	1.2

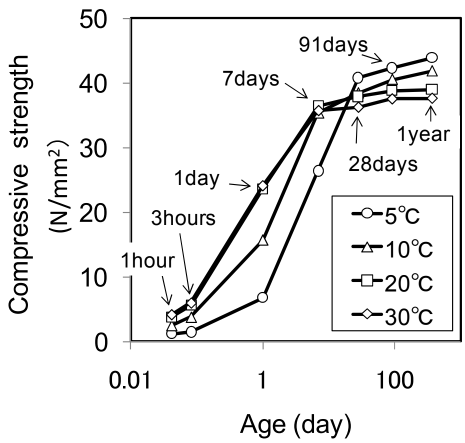


Figure 5 Compressive strength of quick-setting sprayed mortar

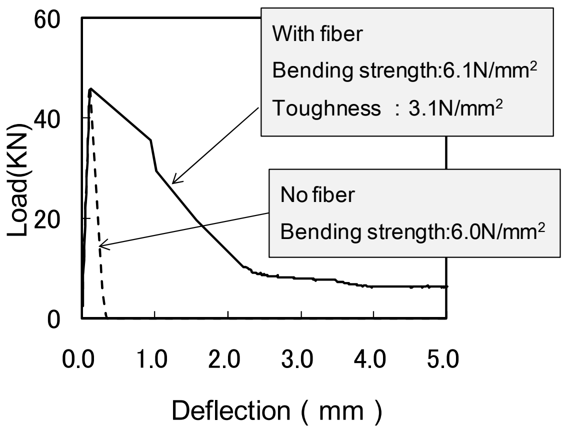


Figure 6 Load-Deflection curve of quick-setting sprayed mortar

3.2 Dust concentration and rebound ratio

Table 4 shows the dust concentration and rebound ratio of the quick-setting sprayed mortar. The dust concentration is measured by a dust counter for 5 min in a simulated tunnel (3.8 m high, 4 m wide, 4.2

＜Spraying under water inflow＞ ＜After spraying＞

Figure 7 Test on resistance to water inflow

m long). The dust concentration of the quick-setting sprayed mortar is very low concentration when acidic LA is used. The rebound ratio of the quick-setting sprayed mortar is also very low compared to general sprayed concrete.

3.3 Strength properties

Figure 5 shows the relationship between age and compressive strength of the mortar. The compressive strength up to 1 day is measured by the pullout method. The strength after 7 days is measured using a cylindrical mortar specimen. The strength of the quick-setting sprayed mortar 1 h after spraying is more than 1 N/mm^2 even at low temperatures. The strength 28 days after spraying is more than 35 N/mm^2 at temperatures between 5–30 °C. The compressive strength after 1 year is similar to that after 28 days. The strength development depended on the curing temperature. Up to 7 days the strength increased with increases in the temperatures, while after 7 days the strength decreased with increases in the temperature. This is because formation of cement hydrate increases when the temperature is higher in the early stages of strength development, and this reduces the strength development later on. Figure 6 shows the load-deflection curve of quick-setting sprayed mortar. Because the PM mortar contains synthetic fiber, the hardened quick-setting sprayed mortar has higher flexural toughness than that produced without synthetic fiber. This prevents flaking of the mortar once it is set, which can occur through cracking in response to rock displacement.

3.4 Resistance to water inflow

The resistance to water inflow is evaluated experimentally, and the results are shown in Figure 7. A water inflow area is simulated by spraying water at 7 L/min onto a wooden board. The quick-setting sprayed mortar is then sprayed onto the inflow area. The mortar adhered stably on the inflow area with a mortar thickness of 5–8 cm. This indicates that a lining layer can be formed using the mortar except on water inflow areas with inflow rates of less than 7 L/min.

4 TBM APPLICATION

The quick-setting sprayed mortar can be applied to TBM excavation because it hardens quickly and will not affect the excavation process. In Japan, this mortar has been used in many TBM projects. For example, the TBM had been applied to excavation of a road tunnel with a large cross section (200 m^2) and used the shield type for purposes of the safety under excavation.

In this tunnel, the excavation was conducted in two steps. In the first step, TBM excavation was used to form a tunnel 5 m in diameter and the mortar was applied for temporary rock support. In the second step, the 5 m diameter tunnel was enlarged by NATM. Because the supporting by NATM can design suitably by catching the detailed geological conditions, the top heading pile drift technique by TBM was applied to this tunneling method. The geological feature of rock in this tunnel is the alternation of sand and mud. The velocity of elastic wave is 3.4-3.5 km/s and the uniaxial compressive strengths of the rock are 600-700kgf/cm^2. Although the rock is hard, the rock has many cracks by the effect of earth fault (Itoigawa-Shizuoka Tectonic Line). Figure 8 shows how to equip a TBM with the mortar spraying system. For application to TBM excavation the following equipment are required:

1) A delivery system for moving the PM mortar from the stock yard to the excavation site.
2) A hopper for storage of the PM mortar and supply it to the small hopper of the CM-pump.
3) A system for spraying the quick-setting mortar, which includes the CM-pump, compressor, LA-pump, water pump, delivery hose, and nozzle.
4) A dust catcher.
5) A unit for controlling steps (2)–(4).

The delivery system uses a pressure tank (lift tank, Figure 10) to transfer the PM mortar using dry compressed air. This tank is connected to a rail so that it can transport the PM mortar from the stock yard (Figure 9) to the excavation site. Dry compressed air is used to transfer the PM mortar from the pressure tank to the mortar hopper. Figure 11 shows the mortar hopper and the CM-pump, which will be attached to the TBM. The PM mortar is moved from the mortar hopper to the small hopper on the CM-pump by a screw feeder. This supply is continuous so that the small hopper is never empty. The LA-pump and tank are placed in the space under the mortar hopper (Figure 12).

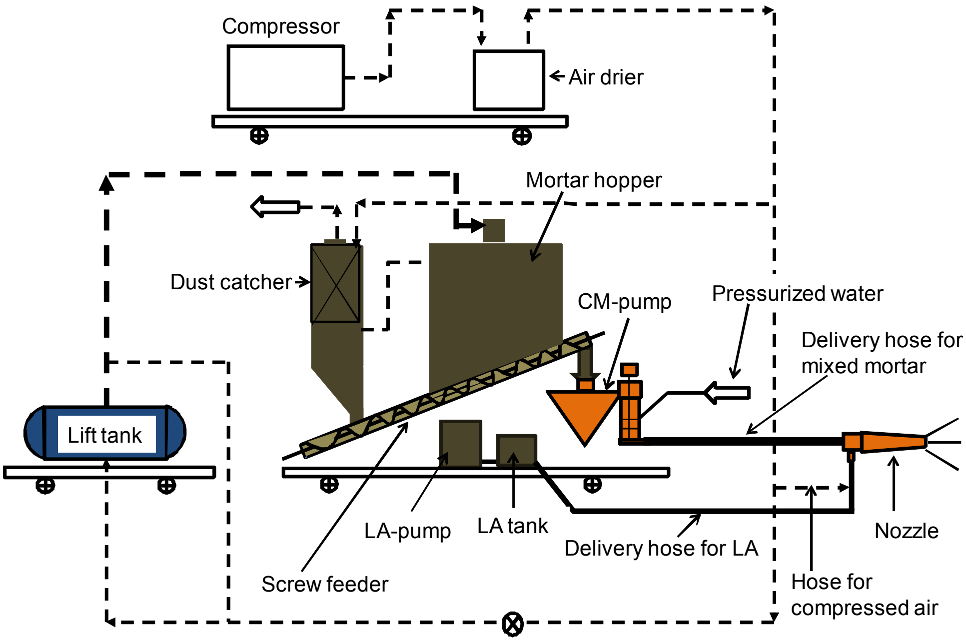


Figure 8 System flowchart for equipping to TBM

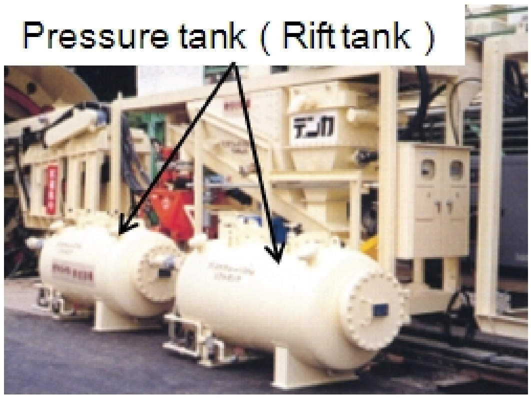
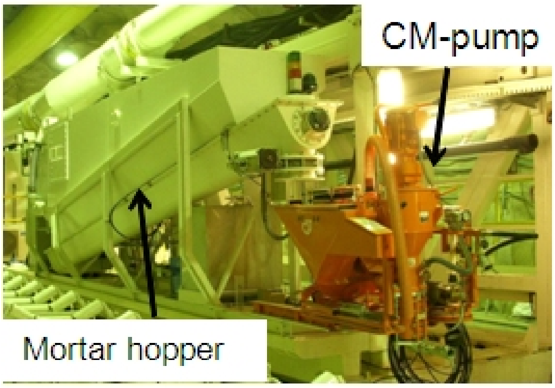


Figure 9 Stock yard

Figure 10 Pressure tank (Rift tank)



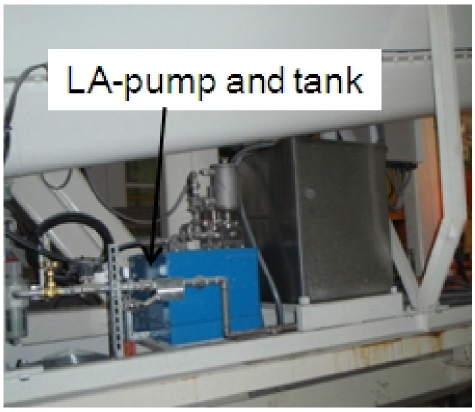


Figure 11 Mortar hopper and CM-pump

Figure 12 LA-pump and the tank

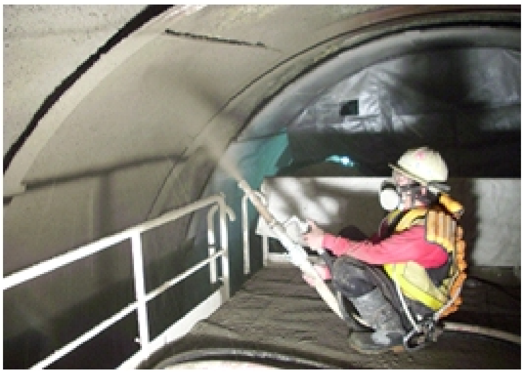


Figure 13 Spraying work

Supply of PM mortar to the small hopper from the mortar hopper, mixing and pumping of the mortar by the CM-pump, and supply is the LA are operated by the control unit. Compared to batch mixing, continuous mixing of the mortar means that spraying work can be performed by fewer workers because the mixing process does not require measurement of materials for individual batches. The PM mortar supply system is a closed system and does not generate cement dust. The spraying velocity is 2.0–2.2 m^3/h. Spraying can be carried out easily by hand (Figure 13) because the hose and nozzle are light.

In summary, TBM can be equipped with this system in a limited space, spraying can be performed by only a few workers, and during spraying there is little cement dust present.

5 CONCLUSIONS

1) Mixed mortar flow and estimation of mixing proportions
The mixing proportions of the mortar obtained using the CM-pump were almost the same as the required mixing proportions. This mortar showed suitable mortar flow for pumping.

2) Dust concentration and rebound ratio
Spraying of the quick-setting sprayed mortar gave a very low dust concentration and very low rebound ratio.

3) Strength properties
The strength of quick-setting sprayed mortar 1 h after spraying was more than 1 N/mm^2 even at low temperatures. The strength after 28 days was more than 35 N/mm^2 at temperatures between 5–30 °C. The compressive strength after 1 year was similar to that at 28 days. After setting, the quick-setting sprayed mortar was sufficiently hard to resist flaking in response to rock displacement.

4) Resistance to water inflow
The quick-setting sprayed mortar sprayed on a water inflow area adhered stably with a mortar thickness of 5–8 cm. This indicates that a lining layer can be formed using this mortar, except for when the water inflow rate is very high.

5) TBM application
It is easy to equip a TBM with the system for mortar spraying. The system is compact, spraying work can be performed by only a few workers, and during spraying there is little cement dust present.

ACKNOWLEDGMENT

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REFERENCES

Catalogue of mixing pump “PFT G4”, knauf PFT GmbH & Co. KG., Germany.

Catalogue of spraying system (M-PAC), MCM Co. Ltd., Japan.

H.Tanaka:TBM Drift Breakthrough in Shimizu No.3 Tunnel-Shimizu No.3 Tunnel on Tomei No.2 Expressway, Tonneru and Chika, Vol.28, No.6, p.15-22, 1997.

K.Otomo.et.al：Rapid Excavation of 6 km Evacuation Tunnel using TBM-Evacuation Tunnel of Atsumi Tunnel Nihonkai-Engan Tohoku Expressway, Tonneru and Chika, Vol.39, No.3, p.15-26, 2008.