Development of a Centrifugal Sprayed System for Shotcrete Application

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A new Japanese Ministry of Health document provides regulations and guidelines for the allowable dust concentration in tunnel works. The recommended maximum concentration should be less than 3.0 mg/m^3 (2.3 mg/y^3) at 50 m (164 ft) from the tunnel face. To observe this guideline, it is a serious problem as to how to reduce the generation of mineral particles of dust during shotcreting operations. In general, shotcrete is placed using pneumatic energy. This is a main factor causing dust generation during shotcrete operations. It may be easily imagined that if shotcrete application can be conducted by centrifugal force, dust concentration would be dramatically reduced. In this paper, we describe the development of a centrifugally sprayed shotcrete system named Dustless Shotcrete and also provide the results of a practical application of this technology at the Hishino Tunnel.

Introduction

New regulations in Japan require that the dust concentration in tunnelling should be controlled at less than 3.0 mg/m^3 (2.3 mg/y^3) at 50 m (164 ft) distance from the tunnel face. Shotcrete application is one of the biggest causes of dust occurrence. Therefore, various concrete mix designs for low dust generation were proposed and submitted for trials. The occurrence of dust, however, depends not only on the shotcrete mixture but is also greatly influenced by the mechanism used for shotcrete application.

Compressed air is generally used to spray concrete. This same air, by spraying and separating the material out of the nozzle, however, causes some of the fine particles to scatter as dust in the air. Therefore, occurrences of dust will decrease greatly if compressed air is not used for spraying. It is thus desirable to spray concrete using the centrifugal force method. Some problems need to be solved to use this system in practical applications, however. In the following, an outline of the centrifugal sprayed machine we developed is provided and a proving test, which was conducted to examine the effect on dust generation, is also shown.

Mechanism of Centrifugal Sprayed System (Dustless Shotcrete)

It is not difficult to spray concrete by centrifugal force. Several problems need to be solved to spray concrete in place and produce high quality, however. These problems can be classified into two main categories. The first is how to release concrete in a controlled direction. The second is how to properly mix the concrete and accelerator. In the following, we describe the process of concrete spraying by centrifugal force and explain the ideas behind directed spraying and accelerator addition.

The appearance of the centrifugal sprayed machine is shown in Fig. 1. This machine is comprised of a self-propelled vehicle, a boom with multiple degrees of freedom, and a centrifugal head at the tip of the boom. As shown in Fig. 2, the centrifugal head has both a mixing and spraying

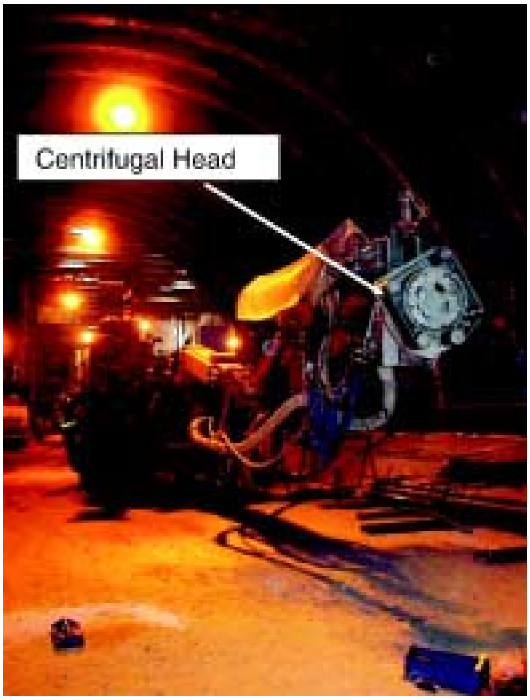

Figure 1: Photo of centrifugal head mounted on spraying machine

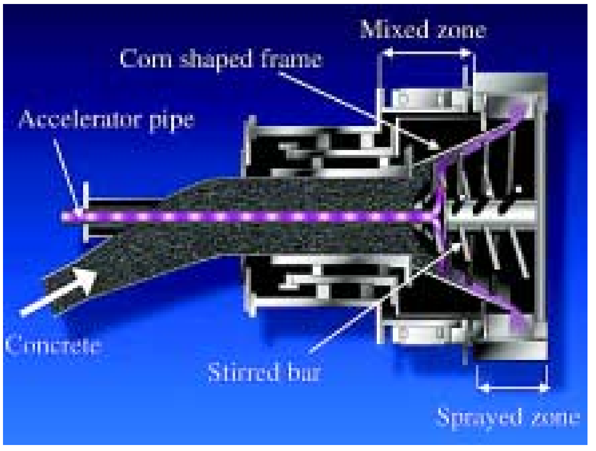

Figure 2: Side view of centrifugal head

Figure 3: Appearance of centrifugal head with impeller wing and stirring bars removed.

Figure 4: Impeller wing and stirring bars

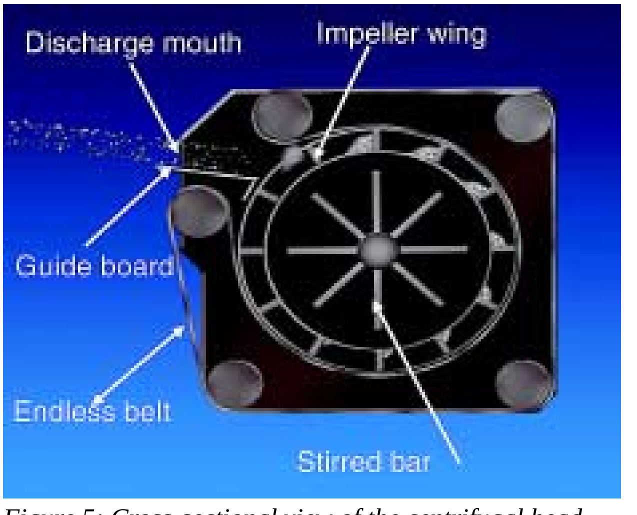

Figure 5: Cross-sectional view of the centrifugal head

function. Supplied concrete is carried to the mixing zone by a pump. The pumping rate of concrete is controlled by the actuator speed. This pump can also transport high-viscosity concrete, such as high-strength shotcrete. The accelerator is supplied by a pipe to the mixing zone.

The mixing zone is comprised of a cone-shaped frame and stirring bars as shown in Fig. 3 and 4. This cone-shaped frame rotates at about 140 rpm in low speed and the stirring bars rotate at 900 to 1600 rpm at high speed at the time of introduction of the concrete and accelerator mixture. The two materials are stirred homogeneously by the difference in this rotation speed. And, because the frame has a cone-shape, the material is carried to the sprayed zone by the centrifugal force of the rotation. Figure 3 shows a head section as seen from the front. It can be seen that the inside frame is cone-shaped (the accelerator supply pipe, impeller wing, and stirring bars are removed in this sketch).

The materials carried to the spraying zone are flung off by the centrifugal force of the wings, which are called impeller wings. The ejected shotcrete speed at this time is controlled by the rotation speed of the impeller wings (900 to 1600 rpm), and directional control is provided by the following mechanism. Figure 5 shows a plan view of this spraying zone. The supplied concrete rotates with the impeller wing at high speed, and a discharge mouth is set up at only one place, where it covers the circumference of the impeller wing with an endless belt to spray concrete in a fixed direction. In other words, concrete is sprayed from the discharge mouth into the air by rotating along the endless belt around the circumference of the centrifugal head.

The base frame in the spraying zone is installed in a structure that can rotate 360 degrees. Therefore, concrete can be sprayed in any direction, at different ranges using the rotation of the discharge mouth and the up and down movement of the machine boom. Moreover, a guide board is set up on the discharge mouth to improve the precision of the spray direction. A list of the main specifications for this centrifugal system is shown in Table 1.

Table 1: Main specifications of centrifugal sprayed machine (Dustless Shotcrete)

Principal of sprayed system	Centrifugal sprayed system
Capacity	15 to 16 m^3/h (11 to 12 yd^3/h)
Accelerator mixing system	Forced mixing type
Recommended accelerator	Powdered accelerator (Liquid accelerator also available)
Concrete supply system	Piston pump (pumping rate 20 m^3/h [15 y^3/h])
Base machine	Self-propelled by tires (self weight 17 t)
Electrical consumption	110 kVa

A Field Trial for Verifying Low Dust-Generating Performance

A field trial was conducted at the Hishino Tunnel construction site with the purpose of verifying the low dust-generating performance of this machine. An outline of the field test and test results are described as follows.

The Hishino Tunnel consists of two tunnels, one on the ascent line and one on the down line. The two tunnels adjoin each other and have the shape of glasses as shown in Fig. 6. The tunnels are about 325 m (1065 ft) long and up to 80 m^2 (860 ft^2) in cross-sectional area. The tunnel construction site is in a city area and private houses stand close together on the ground surface. Moreover, there is only a maximum of 20 m (65 ft) and a minimum of 3 m (10 ft) in the distance from the surface of the earth to the tunnel crown. Therefore, ground settlement and/or collapse of tunnel had to be prevented.

At the same time, the contractor was required to keep the influence of construction on the surrounding environment to a minimum. The influence of construction noise and vibration had to be kept to a minimum, as well as the amount of dust being released into the surrounding environment. It was important to limit the disturbance to daily life and to protect the health of the local population. Therefore, the portal on the excavation end of the tunnel was covered in a soundproof house. Thus, noise and dust were prevented from being released into the surrounding neighborhood at this location.

After tunnel penetration at the other end of the tunnel, however, another countermeasure was looked for because dust caused by shotcrete application flowed out from the portal. It was deemed necessary to reduce the amount of dust being generated by shotcreting. Thus, a centrifugal spraying machine was tried.

A field evaluation was conducted from February to March 2001. Shotcrete application was carried out after the tunnel was excavated. Steel support using H-200 or H-150 segments was built with an interval of 1 m (3.3 ft) and a 150 mm (6 in.) wire mesh. Shotcrete was supplied from a plant setup at the construction site. The mix proportions are shown in Table 2. This mix design is a standard in Japan and satisfies the minimum strength of 18 MPa (2600 psi) at 28 days. It also satisfies the strength of 5 MPa (725 psi) at one day. The thickness of the shotcrete was 150 mm (6 in.).

Usually, visually comparing the difference in the working environment is a suitable method for evaluating the effect of a change in the shotcreting system in decreasing the amount of dust production. Figure 7 shows the dust environment at the work site for the two types of machines. The working environment when a conventional pneumatic machine is used is shown in the left photograph; and the new centrifugal machine, in the right photograph. When a centrifugal machine is used, the working environment improves dramatically, as is clearly evident from these photographs. Because the various test conditions are controlled, this difference is attributable to the difference in the performance of the machines only.

The dust concentration measurement results are shown in Table 3. Measurements were conducted with a measuring device and a measuring method prescribed by the Japanese Ministry of Health guideline.

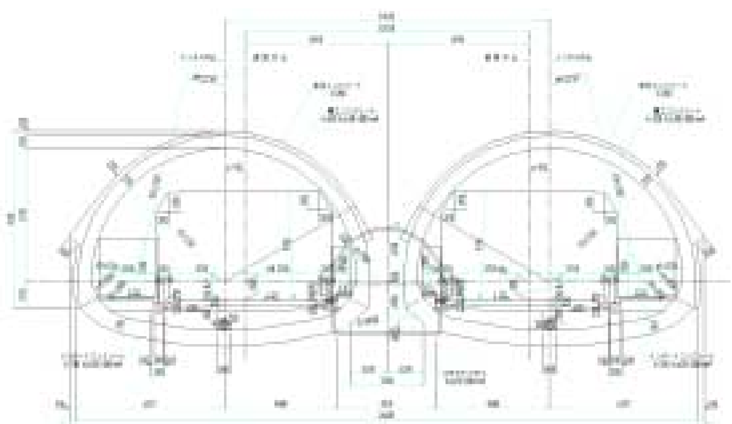

Figure 6: Cross section of the Hishino Tunnel

Table 2: Shotcrete mix proportions

w/c,* %	*S/A*,† %	Weight of unit volume				
		Water, W	Cement, C	Sand, S	Aggregate, A	Accelerator (Powder)
58	57	209	360	984	754	C x 0.07

*Water-cement ratio †Sand-course aggregate ratio

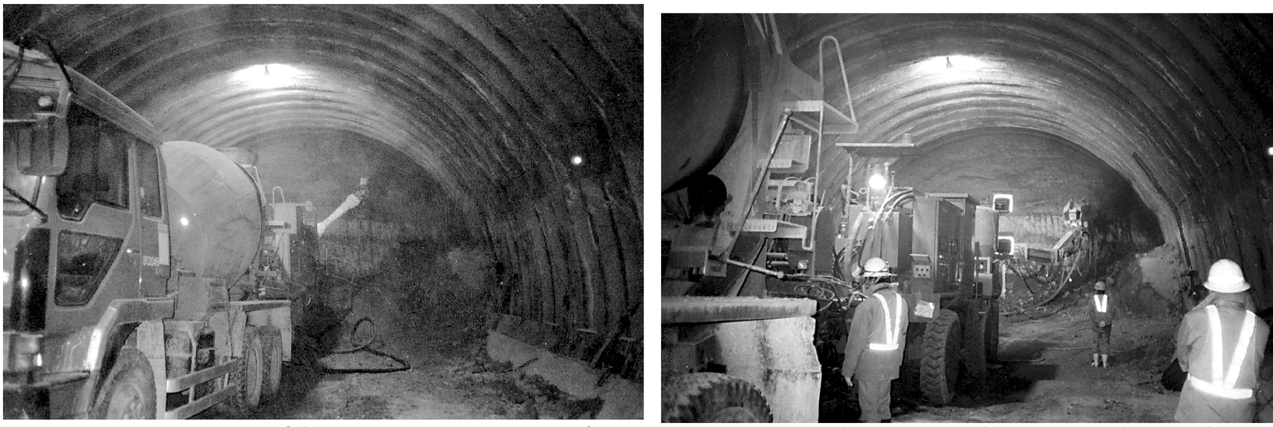

Figure 7: A comparison of the working environment after using a conventional pneumatic shotcrete machine and a centrifugal spraying machine

The dust concentration is measured at 3 points inside a section, which is 50 m (164 ft) from the tunnel face. The average measured value in three places is defined as the dust concentration in the tunnel. From this table it is clear that when the centrifugal spraying machine is used, the dust concentration reduces by about 1/3 to 1/4 in comparison to a conventional pneumatic spraying machine. But the sprayed shotcrete quantity increases a little as shown in Table 3. This is because the concrete rebound increases. It is thus necessary to increase the spraying speed to decrease the amount of rebound.

Most of the dust, which developed in this centrifugal spraying machine, was judged to be due to an outflow

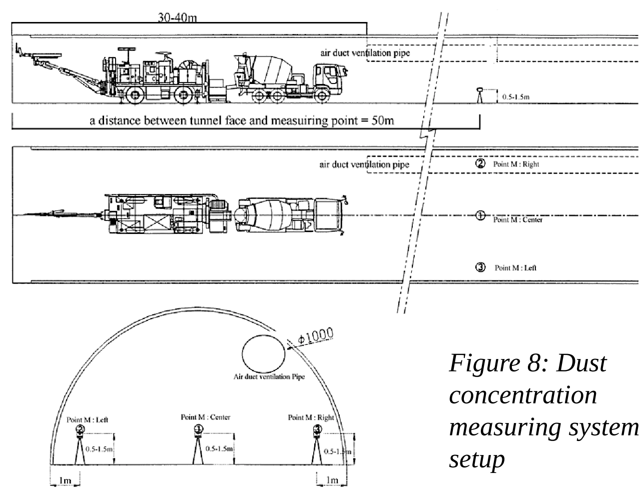

Figure 8: Dust concentration measuring system setup

Table 3: A list of dust concentration

Spraying machine	Method	By pneumatic energy		By centrifugal force	
	Model	AL-285		Dustless shotcrete	
Measuring device	Type	Digital dust concentration meter			
	Model	P-5L_2 (Lion Co., Ltd.)			
Measuring method		Carrying out in accordance with the guideline			
Measuring position		Specified on the guideline (as shown in Fig. 3)			
Date of shotcrete application		02/19/02	02/20/02	02/19/02	02/20/02
Distance from tunnel portal to test section		308 m (1000 ft)			
Temperature at test section (ºC, ºF)		21 (70)	20 (69)	20 (69)	21 (70)
Wind velocity at test section (m/s, ft/s)		0.28 (0.91)			
Amount of ventilation air (m^3/min, cfm)		941 (33,000)			
Rate of sprayed shotcrete (m^3/h, yd^3/h)		12.0 (9.1)	11.0 (8.4)	12.0 (9.1)	10.2 (7.8)
Measured dust concentration (mg/m^3)	Left	2.90	1.30	0.73	0.69
	Center	2.22	2.44	0.62	0.49
	Right	2.73	2.27	0.68	1.04
	Average	2.62	2.0	0.68	0.74

of unmixed powdered accelerator. The shotcrete transport by pump is intermittent; on the other hand, the supply of accelerator is continuous. Therefore, there are times when the accelerator does not mix with the shotcrete and is spouted in the air. This spouted accelerator becomes powdered dust in the air. If shotcrete transport can be made continuous, then dust occurrences can be reduced even more.

The dust concentration permitted in the Japanese guideline is less than 3 mg/m^3 (2.3 mg/yd^3) at a point of 50 m (164 ft) from the tunnel face, and it satisfies this standard even with a conventional pneumatic machine. But it is not necessarily a guarantee of workers' health. The present standard value is only a goal and we have a duty to workers' health to produce a better working environment. If the standard is changed to even more stringent limits, then shotcrete application by a centrifugal spraying machine will be judged to be very effective.

The quality of the applied shotcrete by this machine was almost equal to the quality produced by a conventional pneumatic machine. The uniaxial compressive strength at 28 days was about the same.

Conclusions

The occurrence of dust is decreased dramatically by using centrifugal force instead of pneumatic means to apply shotcrete. A centrifugal spraying machine was developed based on this concept, and field trials at a tunnel construction site were conducted. It was demonstrated that the centrifugal spraying machine resulted in a quality shotcrete product with a dramatic reduction in the amount of dust generated.

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