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Application of airless shotcrete system to tunnel construction

Tatsuya Noma, Yuichi Suzuki
Toshiro Tsuchiya*1, Nagayasu Mitsugochi*2

Abstract

This paper describes the results of field tests of a new shotcrete system that does not use compressed air. The field tests compared the new shotcreting system with a conventional wet-mix shotcreating method by measuring relative dust concentrations, rebound ratios, and compressive strengths. Consequently, it became clear that total dust created by the new system could be one half to one fifth of that of the conventional wet-mix shotcreating — regardless of the inner section of the tunnel.

§1. Introduction

Since the NATM was introduced, shotcrete has usually been used for rock support in tunnel construction In Japan, where rock conditions can be very poor, shotcrete that attains high compressive strength quickly is increasingly indispensable. However, a high dust concentration in tunnels can cause stoneperson's disease in workers and has led to both social and legal problems, such as lawsuits for pneumoconiosis. Taking into account these social conditions, the Japanese Ministry of Health, Labor and Welfare established guidelines for dust concentration in tunneling work in December 2000. In the guidelines, they set ~~up~~ a target value (dust concentration of 3 mg/m^3 or less at a distance of 50m from the tunneling face). The majority of shotcrete in Japan is applied using the wet-mixed method, which generates a comparatively small amount of dust. In recent years, the amount of dust generated has been decreasing due to the development of high viscosity and a high quality concrete and the introduction of a liquid accelerator. Nevertheless, even using these technologies, dust concentrations remain above the government's target. Clearly, novel technologies will be needed to meet the current government target (and any lowered targets which may be set in the future).

As a result of the new legal demands a number of methods for spraying concrete without using compressed air have been developed and are approaching commercialization. In particular, the "Airless Shotcrete System" developed by Ishikawajima-Harima Heavy Industries CO., Ltd. and Livecon Engineering CO., Ltd. shows great promise as a new-generation shotcrete method.

The object of these field tests was to test the applicability of this airless shotcrete system to a real construction environment and to make performance comparisons with the conventional wet-mixed shotcrete.

Keywords : tunnel dust airless accelerator

*1 Hiroshima Regional Office
*2 Tokyo Civil Engineering Regional Office

§2. Outline of airless shotcrete system

2.1 Features of airless shotcrete system

The new, airless shotcrete system (hereafter referred to as the “Airless Process”) differs from the conventional wet-mixed shotcrete system (hereafter referred to as the “Air Process”) by not using compressed air and using a liquid accelerator instead of a powder accelerator. The key components required in the airless process (the impeller head, hydraulic unit, and the unit for adding liquid accelerator) can all be installed on standard shotcreting vehicles, so no great change in equipment or working methods is required. In addition, the Airless process has a lower rebound ratio and a higher shotcreting rate per hour than a conventional system. As a result, higher levels of efficiency can be anticipated[1].

Fig.1 Airless shotcrete system

2.2 Mechanism of airless shotcrete system

An Airless shotcrete machine mounts an impeller head on the tip of a manipulator instead of a nozzle. The impeller head has four blades, which are rotated at a maximum of 2,800 rpm by a hydraulic motor. Wet-mixed concrete is used for shotcreting. A liquid accelerator is added from an injection nozzle provided on the external surface of a projection port.

Airless shotcreting is performed as follows:

1. Concrete is pumped to the impeller head via transport pipes and flexible hoses.
2. The concrete is then pumped into the rapidly-rotating impeller head.
3. The concrete is driven by the blades and projected from the injection port at high speed.
4. The liquid accelerator is sprayed onto the concrete from the liquid accelerator injection nozzle on the external surface of the projection port.
5. The concrete to which the liquid accelerator was added is sprayed on the tunnel wall surface.

Fig.2 Impeller Head

Fig.3 Adding a liquid accelerator

§ 3. Test method

3.1 Specification for field test

Table 1 shows the sites at which the field tests were carried out. All three sites were part of the same large tunneling project, although each site differed in inner section profile and design thickness of sprayed concrete. A total of 17 timed, test shotcretings were carried out. For each test shotcreting, both the new Airless Process and the traditional Air process were used on the same face

Table 1 Specification for Field Test

test work No.	No.1	No.2	No.3
name of tunnel	A tunnel	B tunnel	B tunnel
type of tunnel	double-track highway tunnel	double-track vehicular tunnel	double-track vehicular tunnel
inner section(m^2)	71.4	46.7 upper half section	62.9
support	sprayed concrete full grouted rock bolt	sprayed concrete full grouted rock bolt steel arch	sprayed concrete full grouted rock bolt steel arch
design thickness of shotcrete (cm)	10	15	10
ventilation (m^3/min)	1,200	1,200	1,200

in order to compare the systems under the same ventilation and rock conditions. The volume of concrete sprayed by each shotcrete method was 3 to 5 m^3.

3.2 Equipment

For the field tests, the Airless system was tested against a standard shotcreter already on-site (i.e. a shotcreting manipulator equipped with a compressor).

3.3 Materials

The cement, aggregate, and water used in the field trials were the same as those employed by the contractor in the wider tunneling project. The maximum diameter of coarse aggregate was 15 mm. In the Airless process, superplasticizers were used to reduce the quantity of the mixing water and to improve the pumpability of the concrete. An alkali-free liquid accelerator was used for the Airless process and cement based powder accelerator was used for the Air process. Additionally, a percentage of high-early-strength portland cement was used in the shotcreting mix for the Airless process due to its compatibility with the liquid accelerator.

3.4 Mix proportion

The final mix used for the Airless shotcrete process was determined by a trial mix. The water-cement ratio of base concrete to be used for the Airless shotcrete process was set to up to 50% and the cement content was set to 440 to 450 kg per m^3, taking into account the particular mix requirements for using alkali-free liquid accelerator. The mix for the Air shotcrete process was the same used in the rest of the tunneling works (see Table 2). The concrete used for test shotcreting was supplied from a concrete batching plant installed in the works.

3.5 Test methods

Table 3 shows test methods carried out the field test. Strength tests were performed at the usual intervals of 3 and 24 hours. Additionally, ultra short-term strength tests were conducted at 5, 30, and 60 minutes using the penetration needle method.

§4. Test results and evaluation

4.1 Test implementation

The test shotcreting using the Airless shotcrete process were basically able to be carried out in the tunnel excavation cycle. However, several shotcretings were not able to be carried out due to problems on site. Most of these related to problems with the base machine, such as closure of

Table 2　Mix design

	Airless shotcrete process	Air shotcrete process
type of cement	ordinary portland cement high-early-strength portland cement	ordinary portland cement
w/c (%)	45.0-47.7	60.0-61.1
s/a (%)	60.0-70.0	61.0-62.0
<materials per cubic meter>		
cement (kg per m^3)	440-450	360
water (kg per m^3)	198-203	216-220
gravel (kg per m^3)	475-686	686-721
sand (kg per m^3)	948-1,183	1,056-1,147
<admixture>		
superplasticizer (% per cement)	0.5-1.0	-
set accelerating agent	alkali-free liquid accelerator	cement based powder accelerator
dosage (% per cement)	5-12	7
slump (cm)	18	10

Table 3　Test method

test	method
slump	JIS A 1101
early strength (3 and 24 hour strength)	JSCE－G 561(pull-out method)
early strength (5 and 30 and 60 minute strength)	penetration needle method
long term strength (base concrete)	JIS A 1108
long term strength (core)	JSCE－F 561JIS A 1107
dust measurement	*1
rebound rate	*2

*1.　Dust concentration measurement

Dust concentrations were determined by measuring dust particle counts using optical digital aerosol monitors. Measurements were carried out in three key locations (see Figure 4): A. 50m from the face (standard measurement location for legislative compliance) a total of three points, B. 5m from the face and C (the postion in which a nozzleperson would usually stand).

*2.　Rebound ratio measurement

In measurement of rebound ratio, 0.5 m^3 of concrete was shotcreated on the shoulder of the face, and weight was measured.

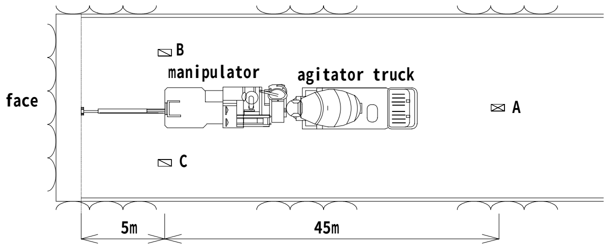

Fig.4 Measurement points of dust concentration

piping and a concrete pump fault; few problems resulted from the mechanism of the Airless shotcrete system itself. Minor problems on site also led to some interruptions in the shotcreting process itself. Although the Airless process performed acceptably under the conditions, some design improvements would ensure it could be used process itself. Although the Airless process performed acceptably under the conditions, some design improvements would ensure it could be used continuously. However, performance was sufficient to confirm the feasibility of the method for commercial application.

4.2 Dust concentration

Results of dust concentration measurement in the B tunnel are shown in Figs. 5 and 6. Comparing the results with those for point A (50 m away from the face) it can be seen that dust concentrations from the Airless process were consistently less than 2.2 mg/m^3, whereas the dust concentration attained a maximum value as high as

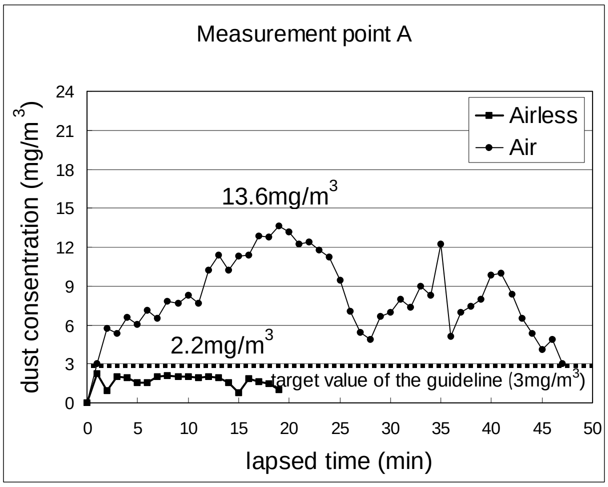

Fig. 5 Dust measurement at Point A

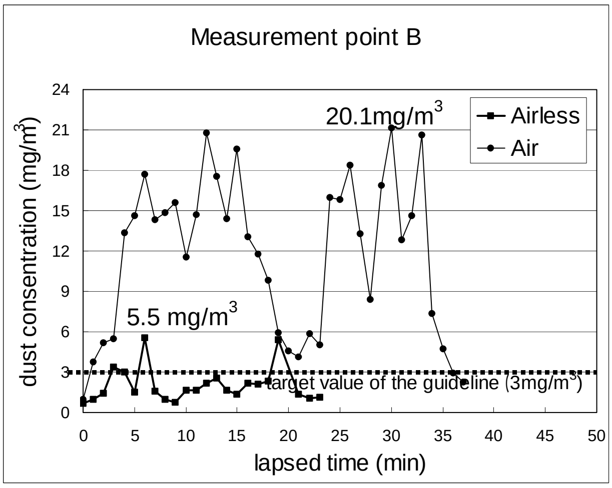

Fig.6 Dust measurement at Point B

Fig. 7 Condition in the tunnel

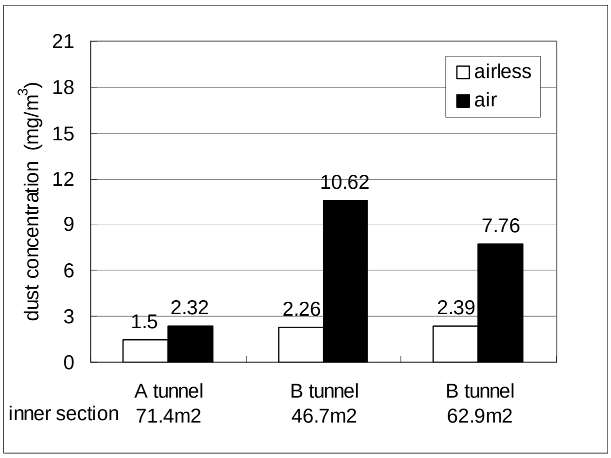

Fig.8 Average of dust measurement

13.6 mg/m^3 in the Air process. A more remarkable result was obtained close to the face. Whereas extremely high dust concentrations were measured in the Air process, in the Airless Process, the dust concentration was 2.0 mg/m^3 on average and exceeded 3.0 mg/m^3 only briefly.

Due to the low dust concentrations, the inside of the tunnel was bright and the visibility was barely affected (see Figure 7). Figure 8 shows the average dust concentration ~~that~~ measured at each tunnel. In the Air Process, the smaller an inner section of a tunnel is, the higher the dust concentration ~~is~~. In contrast, in the Airless Process, the dust concentration is less than 3.0 mg/m^3 regardless of the inner section. Consequently, shotcreting using the Airless Shotcrete System may be particularly suited to minimizing dust concentrations in small or medium section tunnels.

4.3 Adhesive properties

Table 4 shows the relation between dosages of liquid accelerator and the adhesion of the shotcrete in the Airless Process. In the field tests, the most favorable adhesive conditions were obtained at a dosage of 11.3%. According to technical data of the manufacturer of liquid accelerator, optimum dosages of liquid accelerator are 3 to 10 %[2]. However, even in the additive rate of 11.3%, adhesion was worse than in shotcreting with the air process. Therefore in the Airless Process, the optimum dosage of liquid accelerator seems to be more than 12 %. The reason for this problem might

Table 4 Adhesive properties

name of tunnel	dosage(%)	adhesion			
		thinner than 15cm		thicker than 15cm	
		side wall	crown	side wall	crown
A tunnel	9.0	good	good	-	-
B tunnel	4.4	fair	fair	poor	poor
	4.9	fair	fair	poor	poor
	7.1	good	fair	poor	poor
	8.7	excellent	good	fair	poor
	9.5	excellent	good	good	fair
	11.3	excellent	excellent	good	good

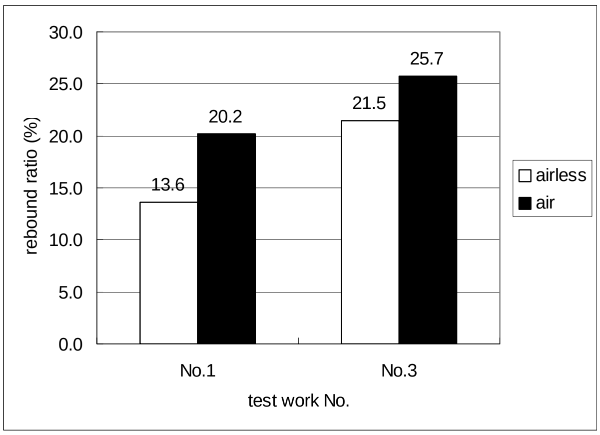

Fig.9 Rebound ratios

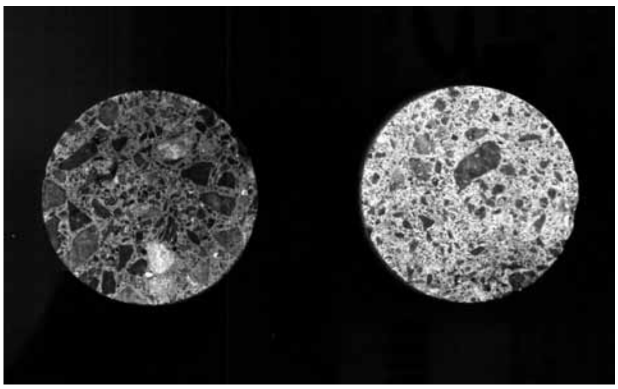

Fig.10 Core Sample

be that the mixture of liquid accelerator and concrete is insufficient because the liquid accelerator is added from the outside. It is necessary to improve the way of adding liquid accelerator to solve this problem.

4.4 Rebound Ratio

The rebound ratio of the Airless Process is reduced 5 to 10% compared with the Air Process. In general, it is known that much of the rebound of shotcrete is coarse aggregate[3]. However in the Airless Process, the ratio of coarse aggregate in rebound is even higher. Upon comparing the coarse aggregate sectional area of the core sampled from a specimen, the area was 49 % for the Air Process and 28 % for the Airless Process. This also might be due to the way of adding liquid accelerator.

§5. Conclusion

The following findings were made in field trials of the Airless shotcrete system.

1) The dust concentration can kept at less than 3 mg/m^3 regardless of the size of the inner section.
2) It is necessary to raise the dosage of liquid accelerator to secure the adhesion of concrete. It is necessary to improve the way of adding liquid accelerator to solve this problem.
3) A rebound ratio can be reduced 5 to 10% from the Air Process. However, the ratio of coarse aggregate in rebound is higher.

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Tatsuya Noma

short comment It has been clearly shown that this method can significantly reduce dust from shotcrete in tunnels. I want to apply this technology to many sites with further improvements in the future.