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CONSTRUCTION PLACEMENT, HARDENED PROPERTIES AND DURABILITY OF SHOTCRETE WITH HIGHLY FUNCTIONAL FLY ASH

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Construction placement, hardened properties and durability of shotcrete with highly functional fly ash

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ABSTRACT

Shikoku Electric Power Co., Inc. which is one of the famous Japanese electric power companies has developed the technology to manufacture the highly functional fly ash (HFA) which is a brand name "Finash" produced by sorting and classifying coal ash generated in coal fired power plants. When HFA is used as substitute for fine aggregate of 100kg/m^3, the shotcrete has the advantages of decreasing the amount of dust and rebound during spraying operation, improving the hardened properties of concrete, etc. This paper discusses about the various characteristics such as construction placement, hardened properties and durability of shotcrete with highly functional fly ash (HFA), by means of the results obtained from the spray tests at the model tunnel and actual road tunnel.

INTRODUCTION

In power plants using pulverized coal, the particular waste material that is collected from the flue gases is called fly ash. Fly ash acts as a pozzolana by reacting with lime in the presence of moisture as ambient temperatures to from cementitious compounds. At collaboration of Shikoku Electric Power Group, that has Yonden Business Company and Shikoku Research Institute, and the University of Tokushima, many papers (Kawaguchi *at el* (1), Kohno *at el* (2), Kohno *at el* (3), Bakoshi *at e*l (4), Kohno *at el* (5), Yamaji *at el* (6), Mitsuiwa *et al* (7), Hashimoto *at el* (8), Heng *at el* (9), Hashimoto *at el* (10) and Heng *at el* (11)) on fly ash concrete has been published for about the last dozen years.

On the other hand, due to the improvement of work environment for workers in tunnel construction site in Japan, the Ministry of Welfare, Health and Labor had tightened dust regulations on spraying shotcrete, which gave a boost to development of many dust reducing materials.

In such circumstances, the Shikoku Electric Power Group has developed the technology to manufacture a brand name “Finash” about 12 years ago. This technology has been accomplished by advanced wind-power-utilizing classification technology of sorting and extracting from raw particles of coal ash, the investigation of HFA’s characteristics of sphere-shape and fine particle and through the use of HFA in shotcrete. “Finash” is highly functional fly ash ((hereafter HFA) produced by removing irregular coarse particles.

It is important for the production of HFA to minimize the variation in quality of coal ash with sophisticated classification technique and extracting good-quality spherical fine particles. The specific surface of HFA is more than 5000 cm^2/g. It is realized that improving the construction placement (namely less dust concentration and less rebound rate), increasing the strength and enhancing the neutralization and dry shrinkage of the hardened concrete, Sasaki *et al* (12).

When HFA is used as shotcrete admixture to substitute for fine aggregate of $100kg/m^3$, the shotcrete has the advantages of decreasing the amount of dust and rebound during spraying operation, improving the hardened properties and durability of concrete, etc. Therefore, it has been applied in many tunnels by NATM. It is now widely utilized as concrete admixture for general civil engineering structures and buildings in Japan.

In order to verify the high performance of shotcrete with HFA, firstly it was carried out the spray tests at the model tunnel using the shotcrete with HFA having the specific surface of $5530cm^2/g$ compared with normal shotcrete without fly ash and shotcrete with the lower fly ash (class 4th-FA) having the specific surface of $1770cm^2/g$. Secondly it was carried out the spray tests at an actual road tunnel using the shotcrete with HFA having the specific surface of $5450cm^2/g$ compared with normal shotcrete without fly ash and shotcrete with the conventional dust reducing agent of 0.1% mass of the cement. This paper discusses about the various characteristics such as dust concentration, rebound rate, strength, dry shrinkage, accelerating neutralization, water permeability and resistance for freezing and thawing on theses several sorts of shotcrete.

CHARACTERISTICS OF HFA

Figure 1 shows the micrograph of HFA. Comparison with characteristics of one example of HFA and Class 1st of JIS A 6201 is shown in Table 1. One of the main factors to change quality of fly ash is the amount of poor shaped particles due to the mixture of coals from different foreign countries or the change in combustion conditions resulted from countermeasures for environmental preservation, Kanatsu *et al* (13). By removal of these irregular coarse particles, the quality of fly ash becomes good. HFA is obtained by means of the wind-power-utilized sophisticated classification technique to sort and extract high-quality round and fine particles less than 20μm. HFA has much higher quality and function than original fly ash, Ukita *et al* (14). HFA is approved as Class 1st and Class 4th of JIS A 6201 "Fly ash for use in concrete" revised in February 1999, which is shown in Table 1.

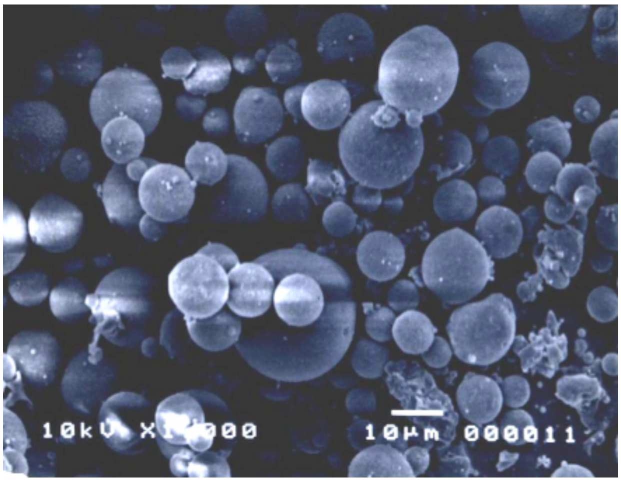

Figure 1 Scanning electron micrograph of HFA (highly functional fly ash)

Table 1 Comparison with the characteristics of HFA and Class 1st and 4th fly ash of JIS A 6201

Classification	Chemical property			Physical property				
	SiO_2	Wet percentage	Loss on ignition	Density	Specific surface	Flow value ratio*	Activity index* (%)	
	(%)	(%)	(%)	(g/cm^3)	(cm^2/g)	(%)	28 days	91 days
HFA	53.4	0.08	2.2	2.4	5450	114	94	116
Class 1st of JIS A 6201	≧45	≦1.0	≦3.0	≧1.95	≧5000	≧105	≧90	≧100
Class 4th of JIS A 6201	≧45	≦1.0	≦5.0	≧1.95	≧1500	≧75	≧60	≧70

＊means the ratio with standard mortar

HFA has much better characteristics than original fly ash before classification such as smaller the variation of quality, more round particles and higher pozzolanic reaction. When HFA is mixed with ordinary concrete, the effects of ball-bearing and granule powder will be fully demonstrated. Therefore it can be made to achieve the decreased unit water content of the concrete, enhanced long-term strength and improved water-tightness. At present, about 10,000 tons of HFA has been annually used in public works mainly in the Shikoku region in Japan.

OUTLINE OF SPRAY TESTS

The spray tests consisted of two series. The first series were spray tests at the model tunnel. The second series were on-site spray tests at the actual road tunnel. Prior to on-site spray test at the actual road tunnel, tests at the model tunnel were conducted in order to verify the effects of the shotcrete using HFA to improve the construction placement, the strength development and durability.

The result of model spray test revealed that, it is very clear that when HFA is used as an admixture of shotcrete, the unit water content of the concrete becomes less while viscosity increases and the quantity of dust and rebound rate decrease. The concrete with HFA was obtained rapid strength development and good durability, Ishii *et al* (15). Accordingly, the HFA was applied in the actual road tunnel construction and the experimental test, Fukami *et al* (16), has been done to verify the effects on the improvement of construction placement, the strength development property and durability.

SPRAY TESTS AT MODEL TUNNEL

Material used and Mix proportions

The characteristics of the concrete materials used and the mix proportions of concrete in the spray tests at model tunnel are shown in Table 2 and 3, respectively. Model tunnel spray test were conducted to formulate three types of mix., i.e., the plain mixture No.1 that is unit cement content of 360kg/m3 containing no fly ash and that is set as the standard mixture. The mixture No.2 substituted fine aggregate as 100kg/m^3 of class 4th-fly ash. The range of specific surface area of class 4th-fly ash is specified less than 2500cm^2/g and more than 1500cm^2/g according to JIS A 6201 “Fly ash for use in concrete” as shown in Table 1. The mixture No.3 substituted fine aggregate as 100kg/m^3 of HFA. The mixture No.3 was made to increase viscosity of concrete and to decrease the unit water content by 10kg/m^3 compared with other two mixtures.

Table 2 Materials used of shotcrete tests at model tunnel

Materials	Characteristics
Cement	Normal portland cement, Density: 3.16 g/cm^3
HFA	Density: 2.40 g/cm^3, Specific surface area: 5530 cm^2/g
Class 4th- FA	Density: 2.20 g/cm^3, Specific surface area: 1770 cm^2/g
Fine aggregate	River sand, Density: 2.59 g/cm^3, Finess modulus: 2.87
Coarse aggregate	Crush stone, Density: 2.64 g/cm^3, Finess modulus: 6.19
Water ruducing admixture	Lignosulphpnate, Density: 1.04～1.06g/cm^3
Set accelerator	Calcium aluminate, Density: 2.80g/cm^3

Table 3 Mixture proportions of shotcrete tests at model tunnel

Mixture No.	Kind of FA uesd	W/C (%)	W/(C+F) (%)	s/a (%)	Unit content (kg/m^3) W	C	FA	S	G	Water ruducing admixture	Set accelerator
1		54.2	54.2	60.0	195	360	-	1075	737	4.32 (C×1.2%)	21.6 (C×6%)
2	Class 4th-FA		42.4		195	360	100	958	737		
3	HFA	51.4	40.2		185	360	100	982	748		

Note: Max. Size of coarse aggregate: 15 mm. Slump: 12 ± 2 cm.

Figure 2 Overview of model tunnel used

Figure 3 Nozzlemen shooting mock-up

Figure 4 Shooting the disc container and the panel frame

Spray tests

Figure 2 shows the overview of model tunnel used. Figure 3 shows the nozzlemen shooting mock-up made of shotcrete. Figure 4 shows the shooting the disc container and the panel frame in order to examine the properties of strength and durability of shotcrete.

The spray tests were conducted at the model tunnel set up outside which is 3.5m in height, 3.5m in width and 7.0m in length. A piston-pump-system SUPREMA (Max. discharge: 14m^3/h) was used for a spraying gun and a powder accelerator compressor (Max. discharge: 3.2kg/min) was adopted for adding accelerator. In terms of piping outlet piping, a 3-inch flexible hose was attached at the pump outlet piping, which extended approximately 30m to the end of the nozzle considering the length in actual tunnels.

Prior to the spray tests, two types of Shotcrete mixture selected was produced in a ready-mixed concrete plant and transported to the test site by agitator truck. Here, the properties of fresh concrete were measured and samples for base concrete strength tests were prepared at the same time.

In the spray tests, at first samples were prepared by spraying the disc container and the panel frame (50×50×20cm) set in the model tunnel. The former was for initial compressive strength tests (3 hours and 4 hours) and the latter was for preparing samples for compressive tests. Next, after a vinyl sheet was spread in the model tunnel, spraying is conducted manually to the arch part circumferentially in the range of 2m and toward the tunnel inside in the range of 4m at an spray angle 45°with keeping the distance of 1.5m from the nozzle tip for 8 minutes (Volume of spray: 1.0m^3), and the amount of dust was measured with a digital dust meter. At measurement, both mouths of the tunnel are covered with sheets to prevent rebound materials and dust from splashing out of the tunnel. The rebound rate was evaluated, after the completion of spray, by collecting rebound materials fallen down on the vinyl sheets and measuring the weight.

After the completion of spray tests, measurement of initial compressive strength was carried out in 3 and 24 hours with pull-out test method. The strength tests at the age of 7 days, 28 days and 91 days were carried out after a core sample (φ10cm×20cm) was cut off from the panel frame for strength tests. Moreover the accelerating-neutralization test and the drying shrinkage test were conducted using the core prismatic specimen (10cm×10cm×40cm) cut off the panel frame.

Compressive strength test, neutralization test and dry shrinkage test

After the completion of spray tests, the initial compressive strength in 3 hours and 24 hours was measured with pull-out test method. The compressive strength test was carried out using the core specimen (φ10cm×20cm) cut out in the shape of a cylinder from the panel form. Moreover, the core cylindrical specimen (φ10cm×20cm) for the accelerating-neutralization test and the core prismatic specimen (10cm×10cm×40cm) for drying shrinkage test are cut out. These tests shall be done under specified ages.

The accelerating-neutralization tests were conducted under the circumstances of 20 centigrade in temperature, 60% in relative humidity, and 5% in carbon dioxide concentration on the core cylindrical specimen which is placed after 4 weeks' cure in the 20 centigrade water and another 4 weeks' cure in the 20 centigrade normal air. The neutralization depths were measured at 1 week, 4 weeks, 8 weeks, 13 weeks and 26 weeks after started the accelerating-neutralization tests. The dry shrinkage tests were performed according to the JIS A 1129 after the core prismatic specimen cured for one week in the 20 centigrade water with gauge plugs stuck. The ages of test were set as the age at 1 week, 2 weeks, 4 weeks, 8 weeks, 13 weeks, 26 weeks, 39 weeks and 52weeks after cure in water and the initial drying shrinkage was measured at 1 week old.

Results and discussion

Effects of construction placement and the property of strength

The result of dust concentration and rebound rate in spray tests at model tunnel is shown in Figure 5. The dust concentration of the mixture No.3 with HFA decreased as much as 70% approximately, compared with that of the mixture No.1 without fly ash and the mixture No.2 with class 4th-FA, respectively. The use of HFA can produce very good dust reducing effect. At the same time, the rebound rate of the mixture No.3 greatly reduced to 60% approximately compared with the standard mixture No.1, also to 75% compared with the mixture No.2 with class 4th-FA. This

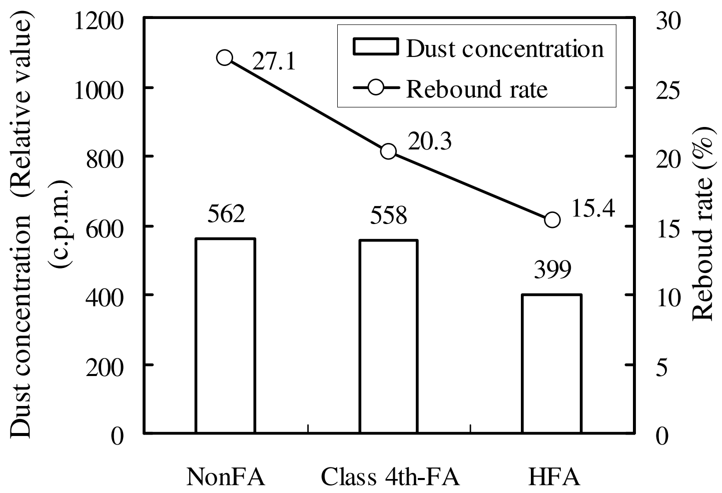

Figure 5 Dust concentration and rebound rate in spray tests at model tunnel

possibly shows that mixing HFA in shotcrete increases viscosity of concrete properly and the cohesion gained by the viscosity reduces segregation and splash of fine particles as well as improves adhesion of concrete.

The result of compressive strength in model tunnel is shown in Figure 6. The compressive strength of mixture No.3 with HFA at early 3 hours obtained 110% increased strength in comparison with that of mixture No.1 without fly ash and 70% increased strength in comparison with that of mixture No.2 with class 4th-FA. It shows an excellent property to develop initial strength. In general the initial strength of shotcrete is proportional to the amount of accelerator added in concrete. In Japan, it is usually that the amount of accelerator is 6% by unit cement content for tunnels by NATM. It is considered that the excellent initial strength gained above is caused by further acceleration of hydration of cement by accelerator by the effect of fine particle of HFA. The compressive strength at the medium and long age were observed that

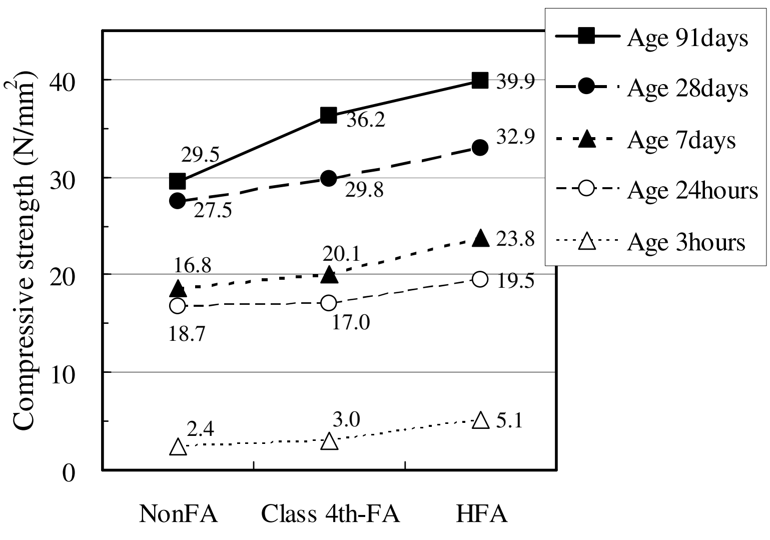

Figure 6 Compressive strength in spray tests at model tunnel

the strength of mixture No.3 at the age of 7, 28 and 91 days is increased 27%, 20% and 35% respectively compared with the mixture No.1 and 18%, 10% and 10% respectively compared with the mixture No.2. It showed an excellent property to develop strength. Thus it is considered that the use of HFA causes densification of hardened concrete with the effect of gap-filling and pozzolanic reaction as well as decrease of unit water content. As a result, the use of HFA contributes to the improvement of strength development of shotcrete.

Effects of accelerating neutralization and dry shrinkage

The results of accelerating neutralization test and dry shrinkage test are shown in Figure 7 and Figure 8, respectively. As shown in Figure 7, the neutralization rate of mixture No.3 with HFA was almost 60% less than that of standard mixture No.1 and 70% less than that of mixture No.2 with class 4th-FA. The neutralization of mixture No.3 with HFA was no problem. As shown in Figure 8, the dry shrinkage at of mixture No.3 with HFA was almost 65% less than that of standard mixture No.1 and 80% less than that of mixture No.2 with class 4th-FA. Thus the use of HFA can be reduced the dry shrinkage by 40% compared with non use.

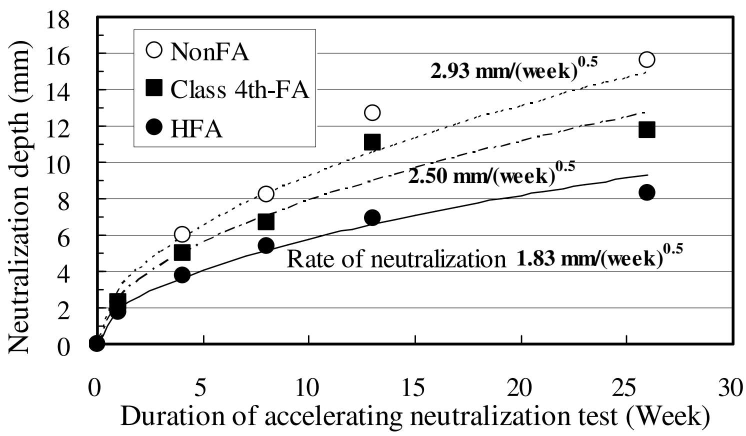

Figure 7 Result of accelerating neutralization test in spray tests at model tunnel

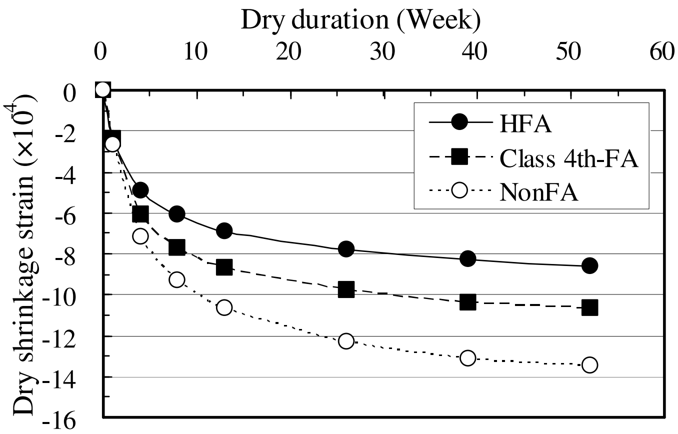

Figure 8 Result of dry shrinkage test in spray tests at model tunnel

We considered that this is because, the unit water content decreases due to the use of HFA compared with the unit water content of normal shotcrete, and the shotcrete using of HFA has good resistance for neutralization and dry shrinkage so that the microstructure of cement matrix in the shotcrete becomes dense caused by both the fill-out effect and the pozzolanic effect.

ON-SITE SPRAY TESTS AT ACTUAL ROAD TUNNEL

Mix proportions and materials used

The characteristics of the concrete materials used and the mix proportions of concrete in the actual road tunnel spray tests are shown in Table 4 and 5, respectively.

On-site spray tests were conducted to formulate three types of mix, i.e., the plain mixture No.1 that was unit cement content of 360kg/m^3 containing no HFA and that was set as the standard mixture, mixture No.2 that was made by adding to the standard mixture with conventional dust reducing agent of 0.1% mass of the cement, and mixture No.3 that substituted fine aggregate as 100kg/m^3 HFA. The mixture No.3 was made to increase viscosity of concrete and to decrease the unit water content by 9kg/m^3 compared with the standard mixture.

Table 4 Materials used of shotcrete on-site spray tests at actual road tunnel

Materials	Characteristics
Cement	Normal portland cement, Density: 3.15 g/cm^3
HFA	Density: 2.40 g/cm^3, Specific surface area: 5450 cm^2/g
Fine aggregate	Sea sand, Density: 2.59 g/cm^3, Finess modulus: 2.40
Coarse aggregate	Crush stone, Density: 2.68 g/cm^3, Finess modulus: 6.29
Conventional dust reducing agent	Nonionic cellulose ether water soluble macro molecule
Set accelerator	Calcium aluminate, Density: 2.64g/cm^3

Table 5 Mix proportions of shotcrete on-site spray tests at actual road tunnel

Mixture No.	Amount of HFA uesd (kg/m^3)	W/C (%)	s/a (%)	Unit content (kg/m^3)						
				W	C	HFA	S	G	Conventional dust reducing agent	Set accelerator
1	0	61.4	60.3	221	360	-	1038	707	-	25.2
2				221	360	-	1038	707	0.36	25.2
3	100	58.9		212	360	100	943	718	-	25.2

Note: Max. Size of coarse aggregate: 15 mm. Slump: 8 ± 2 cm. Dosage of set accelerator: C × 7%.

Spray tests

The spray tests were conducted with an integral piston-pump-system spray gun (Max. capacity: 20m^3/h) by spraying 2m^3 concrete on the arch parts of the half section of a tunnel at the volume of approximately 12m^3/h. The concentration of dust generated during the spraying operation was measured with a digital dust meter at six locations that are 5m, 10m and 15m apart from the working point, and every location was measured for four times (once per minute). The weighted mean value of the average dust concentration at the six locations were computed and set as the average dust concentration during spraying operation. Besides, after spreading a waterproof sheet was spread front of the working point and then 2m^3 concrete was sprayed, the weight of rebound concrete was measured to calculate the rate of rebound. Afterwards, the container was placed in front of the working point to measure the initial compressive strength and the panel from for preparing the core specimen to be used in each of the compressive strength test, the accelerating-neutralization test and the dry shrinkage test, and then we conducted the spraying to these containers.

Compressive strength test, neutralization test and dry shrinkage test

The method and procedure of compressive strength test, neutralization test and dry shrinkage test of on-site spray tests at the actual road tunnel was same method and procedure as the spray tests at model tunnel above refereed to **4.3**. However the ages of neutralization test and dry shrinkage test were different. The ages of neutralization test were 1 week, 4 weeks, and 8 weeks after started the accelerating-neutralization tests. The ages of dry shrinkage test were 1 week, 2 weeks, 4 weeks, 8 weeks and 12 weeks after started the dry shrinkage tests.

Results and discussion

Effects of construction placement and the property of strength

The result of dust concentration and rebound rate in actual road tunnel tests is shown in Figure 9. The dust concentration of the mixture No.3 containing 100kg/m^3 HFA decreased as much as 53%, compared with that of the standard mixture No.1 and the mixture No.2 with conventional dust reducing agent, respectively. The use of HFA can produce very good dust reducing effect. At the same time, the rebound rate of the mixture No.3 greatly reduced to 48% compared with the mixture No.1 and this figure is even better than the mixture No.2 reduction of 84%. As mentioned above, HFA is an excellent rebound reducing agent.

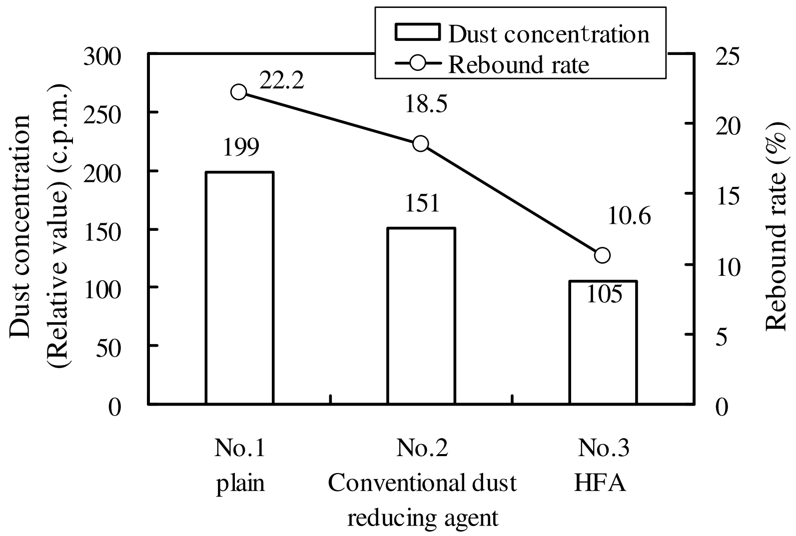

Figure 9 Dust concentration and rebound rate in actual road tunnel tests

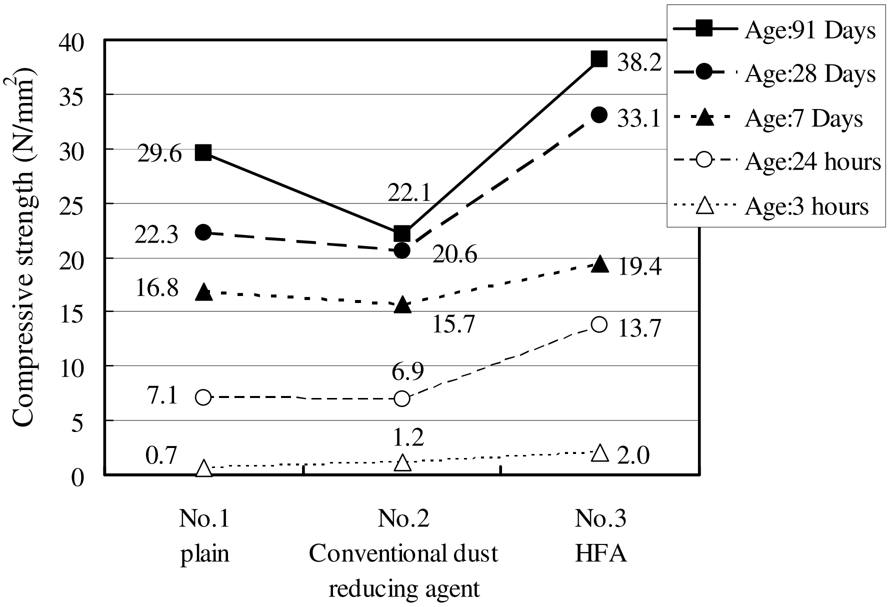

Figure 10 Compressive strength in actual road tunnel tests

The result of compressive strength in actual road tunnel is shown in Figure10. The compressive strength of mixture No.3 with HFA at the early 3 hours and 24 hours increased up to 286% and 193%, respectively in comparison with that of mixture No.1, and it demonstrated good strength development. The compressive strength of mixture No.2 with dust reducing agent of 24 hours showed similar strength development with the standard mixture.

The compressive strength of mixture No.3 at 7 days, 28 days and 91 days increased by 15%, 48% and 29%, respectively, compared with that of the standard mixture No.1. On the other hand, the compressive strengths of the mixture No.2 at every age were a little bit lower than that of the mixture No.1.

Effects of accelerating neutralization and dry shrinkage

The result of accelerating neutralization test is shown in Figure 11.

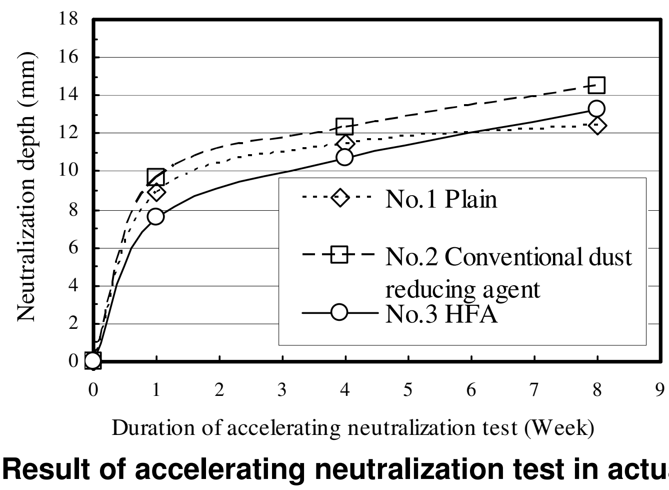

Figure 11 Result of accelerating neutralization test in actual road tunnel

As shown in Figure 11, the neutralization depth of mixture No.3 that is placed fine aggregate with HFA showed almost equal value to that of standard mixture No.1 and mixture No.2 that is added with conventional dust reducing agent, In addition, it is generally constructed concrete lining in Japan. The neutralization of mixture No.3 with HFA was no problem.

The result of dry shrinkage test is shown in Figure 12. The drying shrinkage of mixture No.3 contained with HFA was almost 60% less than that of standard mixture No.1 and mixture No.2. Thus the use of HFA can be reduced the dry shrinkage by 40% compared with non use.

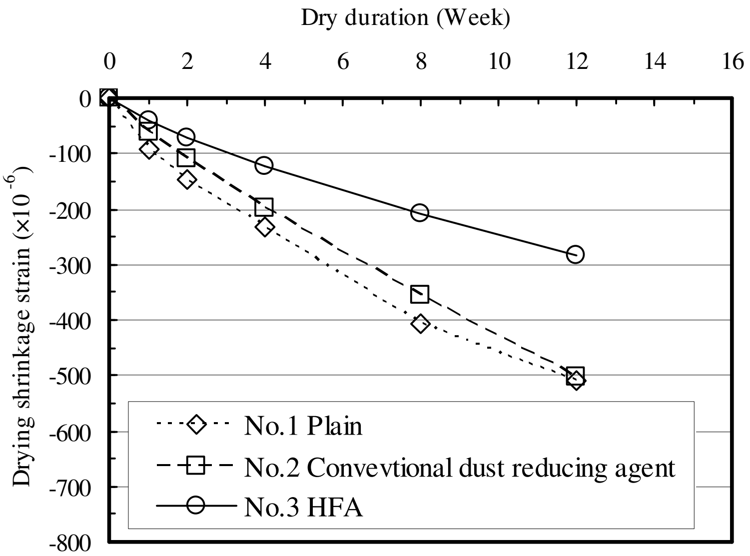

Figure 12 Result of dry shrinkage test in actual road tunnel

We considered that this is because, the unit water content decreases due to the use of HFA compared with the unit water content of normal shotcrete, and the shotcrete using of HFA has good resistance for neutralization and dry shrinkage so that the microstructure of cement matrix in the shotcrete becomes dense caused by both the fill-out effect and the pozzolanic effect.

CONCLUSION

The spray tests at the model tunnel and an actual road tunnel were conducted to evaluate the effectiveness of HFA for shotcrete. Base on result of the tests, the following conclusions can be drawn.

(1)The unit water content of shotcrete using 100kg/m^3 HFA as a part of fine aggregate was decreased and proper viscosity can be obtained compared with the plain mixture with no any mixture, due to the sphere granule particle bearing effects of HFA.

(2)The dust concentration and the rebound rate during spraying operation were reduced by approximately 50% compared with the plain shotcrete of no any mixture.

(3)The compressive strength of shotcrete using HFA was higher than that of the standard shotcrete and shotcrete with conventional dust reducing agent, due to the dense microstructure in the concrete caused by the fill-out effect and pozzolanic effect.

(4)The neutralization resistance and dry shrinkage of shotcrete using HFA were about same or good compared with the plain mixture and the mixture with conventional dust reducing agent.

From these test results, HFA is possible to improve the construction placement, to realize the effective strength development performance and resistance of neutralization and dry shrinkage

Still, by the end of August 2008, shotcrete using HFA has been applied in 54 case of tunnel construction (61km in total length).

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