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The analysis on strength and fly ash effect of roller-compacted concrete with high volume fly ash

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Abstract

In this paper, the strength of roller-compacted concrete with high volume fly ash (HFRCC) is examined. By using the notion of "specific strength," the qualified contribution of fly ash effect to construction formation and strength development of HFRCC is also analyzed. The research results show that: (1) The strength at early ages of HFRCC is poor, while the fly ash effect is low or negative. (2) The strength of HFRCC increases rapidly following its curing age; meanwhile, the fly ash effect gradually improves and is more beneficial to raising flexural strength. (3) With increasing proportion of fly ash, its effect on HFRCC at long curing age becomes more remarkable.

Keywords: High volume fly ash; Fly ash effect; Strength; Specific strength

1. Introduction

Fly ash (FA) is the residue collected from burning smoke flue. It consists of much unfixed SiO_2 and Al_2O_3, and hence possesses comparatively high potential activity. The main useful effect of FA in concrete consists of three aspects, often called morphologic effect, pozzolanic effect, and microaggregate effect. The morphologic effect states that there are many microbeads in FA working as "lubricating balls" when incorporated in fresh concrete; hence it benefits the fluidity. The microaggregate effect of FA states the microbeads in FA can disperse well in concrete and combine firmly with gel produced in cement hydration, and thus promote concrete density. The pozzolanic effect is the main effect of FA, which states that the unfixed SiO_2 and Al_2O_3 in FA can be activated by $Ca(OH)_2$ product of cement hydration and produce more hydrated gel. Since the gel produced from pozzolanic action can fill in the capillary in concrete, it effectively contributes to concrete strength, especially in concrete with high volume fly ash (often the generation of long-term strength is mainly from pozzolanic effect). Taking the cement hydration as prerequisite, the contribution of pozzolanic effect to strength can also be regarded as one part of cement contribution. It should also be pointed out here that the above three effects of FA in fact coaffect with each other, but focus on the different performance of concrete, respectively. Since it is difficult and not necessary to distinguish the previously mentioned three effects, often they are collectively called "fly ash effect" or "pozzolanic effect." In this paper, the "pozzolanic effect" of FA is just such a synthetic notion.

Roller-compacted concrete (RCC), a kind of widely used pavement material, is a sort of super-dry concrete with high density and high strength, resulting from its low water demand and formation by vibration and rolling. Incorporating FA into RCC to make RCC with fly ash (FRCC) can further reduce the cost and meanwhile specifically improve the performance. The specific improvement lies in the following aspects: (1) Incorporating FA by the method of super-substituting, a widely used design method, effectively increases the total amount of binder in RCC and makes it easier to compact. (2) Substituting FA for a part of cement in RCC can remarkably decrease the quantity of heat produced by cement hydration. (3) Formation by vibration and rolling, and also by its required low water-cement ratio, can somehow make up the early age strength of FRCC, which is often cut down by the incorporation of a large amount of FA in ordinary concrete. With the previously mentioned advantages, FRCC is gradually extended in pavement construction. Possessing so many favorable properties, the authors thought that the amount of FA in FRCC can further be promoted and the performance of pavement can still be guaranteed, while taking rational ratio design as prerequisite.

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This paper provides the test results of flexural strength, compressive strength of HFRCC, and the analysis of the effect of FA in it. To measure the contribution to the strength of the FA effect, three notions of "specific strength of cement in concrete," "specific strength of pozzolanic effect on strength," and "contribution rate of pozzolanic effect of strength" are cited [1]. Definitions are given below.

Specific strength of cement in concrete (simplified as specific strength of concrete, SP_{con}) is defined as the contribution of 1% cement to concrete strength, which can be calculated as $SP_{con} = F/P_{cem}$, where F stands for the strength of concrete and P_{cem} is representative of the percent of cement to total amount of binder.

Specific strength of pozzolanic effect (SP_{FA}) is defined as the contribution of fly ash to the strength of concrete with fly ash and can be calculated as: $SP_{FA} = SP_{Fcon} - SP_{con}$, where SP_{Fcon} stands for the *specific strength of cement in concrete with fly ash.*

Contribution rate of pozzolanic effect to strength (R_{FA}) is defined as the percent of the strength portion provided by the pozzolanic effect of FA in concrete with fly ash, which can be calculated by the formula: $R_{FA} = SP_{FA}/SP_{Fcon}$.

With the above three notions, we can see in this paper that the effect of fly ash in concrete is easily quantified.

2. Methods

2.1. Raw materials

Raw materials used in the experiment consist of 425# Portland cement with specific gravity of 3,100 kg/m^3. See Table 1 for its chemical composition.

Grade II dry-moved fly ash with residual percent on 45-μm sieve was 10.3%. See Table 1 for its chemical composition and Table 2 for its physical indexes.

Ordinary river sand was used as fine aggregate, with nominal density of 2,650 kg/m^3, piled density of 1,540 kg/m^3, and fineness modulus of 2.5.

Crushed dolomite was used as coarse aggregate, with 5- to 25-mm continuous grading, while its nominal density was 2,800 kg/m^3 and piled density was 1,500 kg/m^3.

Water-reducing admixture and tap water were also used.

2.2. Mix design

Mix design took flexural strength as the design index. FA was incorporated by the method of super-substituting, and the super-substituting coefficient was 1.5. Water amount and sand ratio were determined by Marshall-compacting method, with the compacting density not less than 96%. Table 3 gives the mixing ratios of HFRCC.

Table 1
Chemical composition of cement and fly ash

	SiO_2 (%)	Al_2O_3 (%)	CaO (%)	Fe_2O_3 (%)	SO_3 (%)	MgO (%)
Cement	20.6	5.03	64.11	4.38	2.24	1.46
Fly ash	54.7	24.04	8.7	6.9	1.50	1.13

Table 2
Physical indexes of fly ash

Loss on ignition (%)	Water demand ratio (%)	Water content (%)	Specific gravity (kg/m^3)
4.98	95	<1	2200

2.3. Formation and test

Specimens were vibrated for 120 s, with a top compressive force of 50 g/cm^2. After 24 h, moulds were removed and specimens were moved into a curing room with a temperature of 20 ± 3°C and relative humidity not less than 90% for the required days.

Flexural strength was tested by the four-point flexural method and then the broken specimens were used to test the compressive strength.

3. Results and analysis

3.1. Strength

See Table 4 for the strength and ratio of compressive to flexural strength (often used to describe the embrittlement of concrete) of HFRCC. Table 4 shows that: (1) the strength of HFRCC decreases as the fly ash content increases. Three-dimensional strength of F85 and F95 are very poor, while that of F45 and F55 are still acceptable. (2) Following the curing age, the growth speed of strength of HFRCC is much greater than that of RCC (F0). At 90 days, the flexural strength of all series of HFRCC has remarkably exceeded that of RCC, while the compressive strength has also caught up with or exceeded RCC. (3) As the fly ash content and curing age increase, the ratio of compressive to flexural strength of HFRCC decreases. This conclusion supports using HFRCC as pavement material, where flexural strength is of primacy importance in structure design.

3.2. Specific strength of cement in HFRCC (SP_{con})

Taking flexural strength as an example (the trend of compressive strength is similar), we can see in Fig. 1 the developing trend of flexural SP_{con} following the curing age. Following Fig. 1, we can see the developing trend of SP_{con} is very different from that of strength. In early age, with the rise of fly ash content, SP_{con} decreases, except F45 and F55, in which FA is not great. The trend inverts afterward. When it has been cured for more than 28 days, unit cement in HFRCC with more FA tends to possess higher efficiency in developing long-term strength, despite the fact that part of the long-term strength of HFRCC is provided by FA. Since the activation of FA takes the cement hydration as a prereq-

Table 3
Mixing proportions of HFRCC (the super-substituting coefficient is 1.5)

Mix no.	Fly ash (kg/m^3) (%)	Cement (kg/m^3) (%)	Water (kg/m^3)	River sand (kg/m^3)	Dolomite (kg/m^3)	Water reducing (kg /m^3)	Water cement ratio
F0	0(0)	300(100)	106	855	1320	2.10	0.353
F45	135(45)	210(70)	113	773	1320	2.42	0.377
F55	165(55)	190(63)	117	768	1320	2.49	0.390
F65	195(65)	170(57)	121	747	1320	2.56	0.403
F75	225(75)	150(50)	125	725	1320	2.63	0.416
F85	255(85)	130(43)	129	700	1320	2.70	0.430
F95	285(95)	110(37)	133	678	1320	2.77	0.443

Table 4
Compressive flexural strength and raio of compressive to flexural strength of HFRCC

	3 days	7 days	28 days	9 days	Ratio of 28 days	Ratio of 90 days
F0	30.9/4.5	35.2/5.6	46.5/6.3	49.1/6.7	7.99	7.33
F45	25.8/3.8	38.9/4.9	55.4/7.5	66.5/9.4	7.36	7.06
F55	25.4/3.3	35.0/4.2	51.7/7.0	57.4/9.4	7.41	6.12
F65	16.0/2.0	26.2/3.6	44.3/6.4	56.0/9.3	6.88	6.00
F75	10.4/1.8	26.0/3.3	40.1/6.4	46.4/8.8	6.29	5.27
F85	7.0/0.9	18.7/2.5	39.1/5.9	46.0/7.9	6.62	5.82
F95	1.7/0.2	11.5/1.8	32.5/5.4	44.8/7.5	6.07	5.79

uisite, we can regard the contribution of FA to strength in HFRCC as one part of cement contribution.

3.3. Specific strength of pozzolanic effect of fly ash in HFRCC (SP_{FA})

Also taking flexural strength as an example, we can calculate the flexural SP_{FA} on the basis of its definition and illustrate its trend following the fly ash content in Fig. 2. Fig. 2 shows that SP_{FA} of HFRCC possesses the apparent increase tendency with increase of fly ash content. When HFRCC is in its early age, the pozzolanic effect of fly ash in it is very low or negative (F65 to F95), but it increases rapidly with curing age and fly ash content. In the long-term view, high fly ash content in

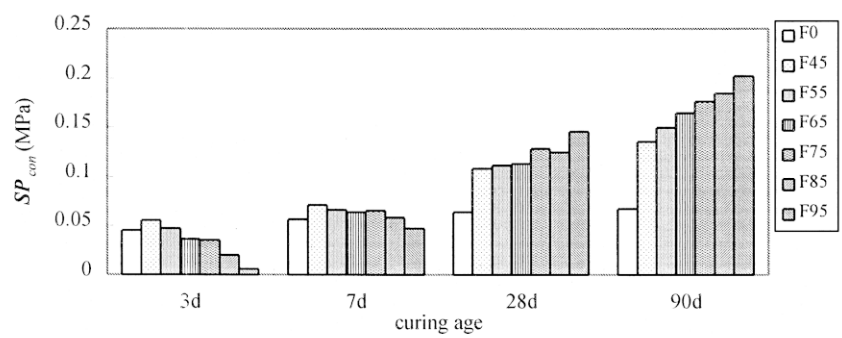

Fig. 1. Flexural specific strength of HFRCC following curing age.

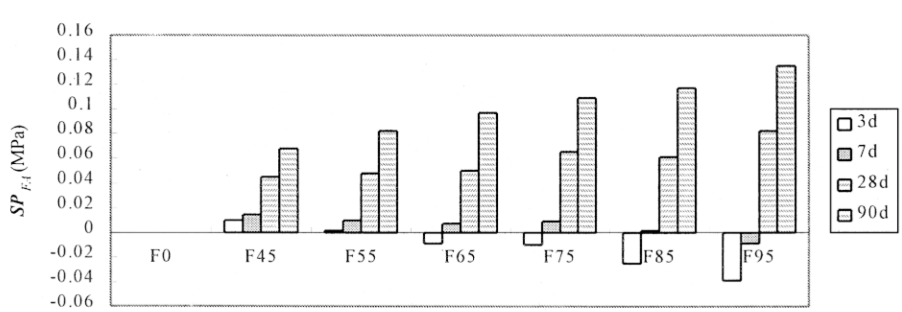

Fig. 2. Flexural specific strength of pozzolanic effect of fly ash as influenced by fly ash content.

Table 5
Contribution rate of pozzolanic strength to the compressive/flexural strength of HFRCC (R_{FA}, %)

	3 days	7 days	28 days	90 days
F0	0	0	0	0
F45	16.2/18.2	37.5/21.1	40.5/41.7	48.4/50.4
F55	22.5/4.3	37.5/15.2	42.7/43.2	46.2/55.0
F65	−10.7/−25.0	23.9/11.1	39.7/44.2	50.0/59.1
F75	−47.6/−28.6	32.7/13.8	41.2/50.8	47.3/61.9
F85	−93.7/125.0	16.3/3.4	48.4/49.2	54.2/63.6
F95	−520.0/−650.0	−12.9/−19.7	46.6/56.6	58.1/66.8

HFRCC provides a highly effective fly ash effect (pozzolanic effect).

The negative effect of fly ash in F65 to F95 at early curing age can be interpreted as the cement being severely diluted by fly ash and the hydration action being delayed.

3.4. Contribution rate of pozzolanic effect to strength in HFRCC (R_{FA})

Further determining the contribution rate of pozzolanic effect to strength (R_{FA}), as shown in Table 5, we can see that at early curing age, R_{FA} possesses a tendency to decrease as the fly ash content in HFRCC increases. At 3 days of age, fly ash effect in HFRCC with FA content exceeds 65% (F65 to F95) and shows no significant contribution to strength (negative value in Table 5 shows that the fly ash effect is negative, which has been interpreted in 3.3). But the growth rate of R_{FA} increases with the curing age and fly ash content. After 28 days, HFRCC with a high content of FA shows a higher contribution rate of FA effect to strength. At 90-day curing age, contribution rate of fly ash effect to strength already approaches or exceeds 50%.

Another characteristic of the FA effect in HFRCC, as shown in Table 5, is that the FA effect is apparently more beneficial to compressive strength at early age, while in the long term, it is more useful to increase flexural strength.

3.5. Research on microlevel of FA effect in HFRCC

To further realize the microstructure of HFRCC, at 90-day curing age pore volume and its distribution were tested. According to Professor Wu's classification (when diameter <20 nm, pore is harmless; 20 to 100 nm, less harmful; 100 to 200 nm, harmful; >200 nm, very harmful), the pores in HFRCC were classified and the proportion of pores with different sizes and total volumes are given in Table 6.

From Table 6 we can see that pore volume in per gram HFRCC is low, less than PCC (ordinary Portland cement concrete), the total volume of which is 0.067 cm^3/g [2]. Incorporating a high content of fly ash is beneficial to reducing the proportion of harmful pores in HFRCC, as the harmful pore ratios for F0, F60, F75, and F90, respectively, are 45.30, 0, 22.53, and 9.45%. From this result, we can conclude that the FA effect in HFRCC can minimize pore diameter and reduce the amount of harmful pore. As the pore diameter is reduced, the concrete becomes dense and its strength and durability are improved.

3.6. Mechanism analysis of FA effect

1. Since the pozzolanic reaction between FA and cement lags behind cement hydration, HFRCC strength at early curing age is poor and decreases with increasing FA content. In F75 to F95, where fly ash content is fairly high, cement is remarkably diluted, thus producing little hydration product in HFRCC and not enough to form a strong structure. The "diluting action" of FA at early curing age makes FA effect negative.
2. Following the curing age, greater amounts of FA are activated and cause the strength of HFRCC to continuously develop.
3. Incorporating fly ash by high content and super-substituting method makes HFRCC easier to compact, and together with the amount of crystal phase $Ca(OH)_2$ and harmful pore reduction, HFRCC at long-term curing age becomes dense and homogeneous. These improved properties are more beneficial to flexural strength, which is more sensitive to inner structure characteristic than compressive strength.

4. Conclusions

1. Increasing fly ash content in HFRCC decreases the strength. Although the strength of HFRCC is very poor at early curing age, it develops rapidly with

Table 6
Pore distribution test result of HFRCC

		Diameter (nm)					
		>2,000	1,000–200	200–100	100–20	20–2.5	Total volume (cm^3/g)
F0	Pore volume (cm^3/g)	0.0005	0.0119	0.0024	0.0038	0.0170	0.0356
	Distribution	1.63%	36.09%	7.40%	11.73%	39.55%	
F60	Pore volume (cm^3/g)	0	0	0	0.0016	0.0100	0.0116
	Distribution	0	0	0	10.23%	64.62%	
F75	Pore volume (cm^3/g)	0.0002	0.0052	0.0039	0.0066	0.0253	0.0412
	Distribution	0.47%	12.64%	9.40%	15.93%	61.54%	
F90	Pore volume (cm^3/g)	0	0.0016	0.0017	0.0125	0.0191	0.0349
	Distribution	0	4.58%	4.87%	35.80%	54.70%	

longer curing age, resulting in long-term strength exceeding that of ordinary RCC (with no fly ash).

2. At early curing age, specific strength of HFRCC decreases with the increasing fly ash content. Since the developing rate of specific strength increases with fly ash content and curing age, HFRCC with more fly ash shows higher long-term specific strength.
3. By the analysis shown in this paper, fly ash effect in HFRCC becomes positive after 7 days of curing age, and it develops rapidly. The contribution of fly ash in HFRCC with 90-day curing age to strength exceeds or approaches 50%, and is more remarkable for flexural strength than compressive strength.
4. Pore distribution test results show that incorporating a high content fly ash in roller-compacted concrete is beneficial to reducing the amount of harmful pores and total pore volume.
5. Finally, cement contribution to strength of HFRCC can be divided into two aspects. The first is through the hydrated products produced in the hydration of itself, and the second is the fly ash effect activated by it. At early curing age, the former is the dominant factor, while the latter is more significant afterward. After 90 days, the contribution of fly ash effect to strength of HFRCC approaches or exceeds 50%.

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