SUSTAINABLE HIGH-VOLUME FLY ASH GROUTS FOR TWO-STAGE CONCRETE

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ABSTRACT

Two-stage concrete (TSC) is a special type of concrete in which coarse aggregates are pre-placed in the formwork and subsequently injected with a grout. Beneficiating fly ash in TSC grouts increases TSC sustainability through the ecological use of large quantities of fly ash, reduced carbon-dioxide emissions associated with cement production, and enhancement of resource productivity of the concrete industry. Limited research has explored the effects of using high volume of fly ash as partial replacement for cement in TSC grout mixtures. Therefore, the flowability of grout mixtures incorporating various fly ash addition rates (i.e. 0%, 30%, 50% and 70%) was evaluated using the flow cone method and spread flow test. Correlations between the efflux time and spread flow for the grout mixtures were developed. Results show that increasing the fly ash addition reduced the grouts efflux time while increasing its spread flow. The optimum high-volume fly ash dosage for achieving high flowability and acceptable TSC compressive strength was identified.

Keywords: Two stage concrete, grout, efflux time, spread flow, compressive strength.

1. INTRODUCTION

Two-stage concrete (TSC) is a special type of concrete that is produced by first placing coarse aggregates in the formwork and then voids between the coarse aggregate particles are filled through injecting a special grout mixture (Abdul Awal 1984; Najjar et al. 2014). The ability of the TSC grout to flow and penetrate around the aggregate particles is of paramount importance in TSC production (ACI 304.1 2005). Therefore, special measuring techniques are used to evaluate the flowability of TSC grouts, including the flow cone method and spread flow test (Abdelgader 1996). The grout used in TSC normally consists of ordinary portland cement (OPC), well graded sand, water and chemical admixtures (ACI 304.1 2005).

Nowadays, fly ash (FA) has been used in the concrete industry to improve the performance of concrete in its fresh and hardened states. The use of FA in concrete mixtures provides ecological disposal of large quantities of fly ash, reduced carbon- dioxide emissions from cement production, and enhancement of resource productivity of the concrete industry. Partially replacing OPC with 33% class F fly ash was recommended to produce TSC grouts with an acceptable flowability (ACI 304.1 2005). However, limited data on TSC grout mixtures made with high volume FA addition and the corresponding TSC compressive strength are available. Therefore, the effect of fly ash addition rates (0%, 30%, 50%, and 70%) on the flowability of grout and the corresponding compressive strength were investigated in this study. Moreover, a relationship between the grout efflux time and the spread flow was developed.

2. EXPERIMENTAL PROGRAM

2.1 Materials and Grout Mixture Proportions

Ordinary portland cement (OPC) was used in the grout mixtures. Fly ash (FA) was used as partial replacement for OPC. Physical and chemical properties of the used binders (i.e. OPC and FA) are listed in Table 1. Silica sand with a fineness modulus of 1.47 and a saturated surface dry specific gravity of 2.65 was used as a fine aggregate. To control the flowability of the grout mixtures, a poly-carboxylate high-range water-reducing admixture (HRWRA) was used. Crushed limestone coarse aggregate with a maximum nominal size of 40 mm, a saturated surface dry specific gravity of 2.65 and water absorption of 1.63 % was used.

Table 1: Chemical Analysis and Physical Properties of OPC and FA

	OPC	FA
SiO_2 (%)	19.60	43.39
Al_2O_3 (%)	4.80	22.08
CaO (%)	61.50	15.63
Fe_2O_3 (%)	3.30	7.74
SO_3 (%)	3.50	1.72
Na_2O (%)	0.70	1.01
Loss on ignition (%)	1.90	1.17
Specific gravity	3.15	2.50
Surface area (m^2/kg)	371	280

Several grout mixtures were prepared using different dosages of FA (0%, 30%, 50%, and 70%). All grout mixtures had the same sand-to-binder ratio (s/b = 1.0) and different water-to-binder ratios (i.e. w/b= 0.35, 0.45, 0.55). Table 2 shows the TSC grout mixtures used in this study. Moreover, several trial grout mixtures with different dosages of HRWRA were tested to study the flowability of grouts and identify the optimum mixture that meets ACI 304.1 recommendations.

Table 2: TSC Grout Mixture Proportions

Grout Mixture No.	Grout Mixture Notation	Binder (kg/m^3)		Sand (kg/m^3)	Water (kg/m^3)
		OPC	FA		
C-0.35	100OPC	960	--	960	335
F3-0.35	70OPC-30FA	670	290	960	335
F5-0.35	50OPC-50FA	480	480	960	335
F7-0.35	30OPC-70FA	290	670	960	335
C-0.45	100OPC	875	--	875	390
F3-0.45	70OPC-30FA	610	265	875	390
F5-0.45	50OPC-50FA	440	435	875	390
F7-0.45	30OPC-70FA	265	610	875	390
C-0.55	100OPC	805	--	805	440
F3-0.55	70OPC-30FA	595	210	805	440
F5-0.55	50OPC-50FA	405	400	805	440
F7-0.55	30OPC-70FA	210	595	805	440

2.2 Experimental Procedures

The grout mixture was mixed for 6 minutes using a high-speed mixer according to ASTM C938 (Standard Practice for Proportioning Grout Mixtures for Preplaced-Aggregate Concrete 2010). Immediately after mixing, the grout's efflux time was measured according to ASTM C939 (Standard Test Method for Flow of Grout for Preplaced-Aggregate Concrete - Flow Cone Method 2010). The flow cone test consists of measuring the time of efflux of 1725 ml [0.06 ft^3] of the grout through a specific cone having a 12.7 mm [0.5 in.] discharge tube (Figure 1). Moreover, the spread flow was used to determine the flowability of the grout. The basic principle of the spread flow test is that a fixed volume of grout (i.e. 250 ml) is filled into a cylinder then poured from a height of 1 cm on a scaled plate

(Figure 2). The distance that the grout flows along the plate is an indication of the flowability of grout (Abdelgader 1996). The mixing and flowability measurements were conducted at room temperature (23±2°C) [73.4±3.6°F].

Figure 1: Grout flowability measurement using flow cone method.

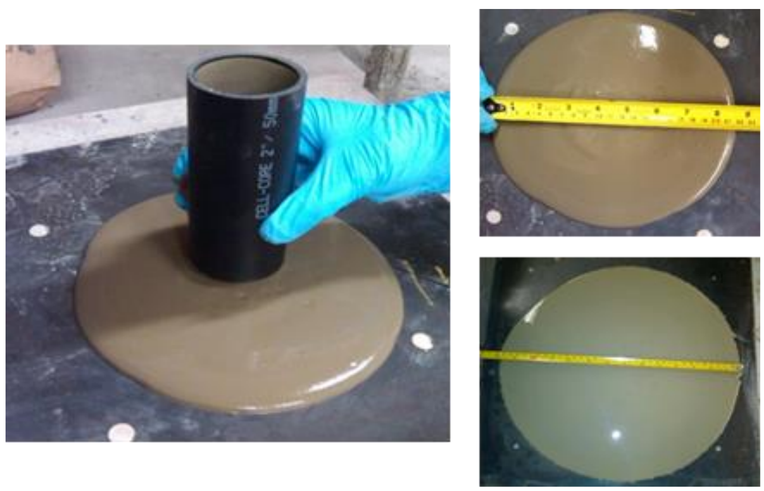

Figure 2: Grout flowability measurement using spread flow test.

The compressive strength of grouts that achieved the recommended grout efflux time (i.e. 35 to 40± 2 s) was evaluated on 50 mm [2 in.] cubic specimens at ages of 7, 28, and 56 days according to ASTM C 942 (Standard Test Method for Compressive Strength of Grouts for Preplaced-Aggregate Concrete in the Laboratory 2010). Immediately after demolding, specimens were moved to a moist curing room (T = 25°C [77°F] and RH = 98%) until the testing age. Furthermore, cylindrical TSC specimens (150 mm × 300 mm [3 in. × 6 in.]) were prepared. The molds were first filled with coarse aggregates and then the grout was injected into the voids. Specimens were covered with wet burlap to prevent surface drying. After 24 h, specimens were demolded and cured in the moist room described above. At each testing age (i.e. 7, 28 and 56 days), the compressive strength of TSC was evaluated according to ASTM 943 (Standard Practice for Making Test Cylinders and Prisms for Determining Strength and Density of Pre-placed-Aggregate Concrete in the Laboratory 2010).

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Effect of FA Addition Rate on Flow Properties of TSC Grouts

Table 3 reports efflux time and spread flow results for grouts incorporating different FA dosages. It can be observed that the FA replacement rate had a significant effect on the grout flowability along with the effect of the w/b ratio.

For grouts with 0% HRWRA, it can be observed that the efflux time decreased as the w/b ratio increased, while the grout spread flow increased as the w/b ratio increased. For example, the F3-0.45 grout mixture exhibited 41% shorter efflux time and 68% greater spread flow compared with that of the F3-0.35. This can be attributed to the fact that increasing the w/b ratio results in a higher amount of free water in the grout mixture (i.e. excess water), which acts as a lubricating agent between the solid particles, leading to greater grout flowability (Kismi et al. 2011).

Moreover, it can be observed that the efflux time decreased as the FA addition rate was increased. For example, at w/b = 0.55 and 0 % HRWRA, grout mixtures F3 and F7 exhibited 48.6 % and 62.9 % shorter efflux time compared to that of the control grout mixture (C). Also, it was found that the grout spread flow increased as the FA replacement rate increased. For instance, at 0% HRWRA dosage, the spread flow of F3-0.55 and F7-0.55 was 1.2 and 1.6 times that of control grout, respectively. This is because FA addition reduces frictional forces among particles due to the spherical shape of its particles, which have smooth vitreous surfaces, leading to a lubricant ball-bearing effect, thus facilitating mobility (Yung et al. 2013). Moreover, FA particles can be adsorbed on oppositely charged cement particle surfaces, preventing flocculation and enhancing particle dispersion, which consequently results in better flowability with higher amount of free water, leading to a shorter efflux time (Kismi et al. 2011).

3.2 Effect of HRWRA Dosage on Flow Properties of TSC Grouts

Adding adequate dosages of HRWRA into grout mixtures had a great effect on the grout's flowability as illustrated in Table 3. The higher the HRWRA dosage, the shorter was the efflux time and the greater was spread flow of the grout mixture. For instance, increasing the HRWRA dosage from 0% to 0.4% shortened the efflux time of the grout mixture F3-0.45 by about 73% and increased the spread flow of the same grout mixture by 88%. The poly-carboxylate admixture prevents the binder-water agglomeration and formation of flocs through its steric repulsion mechanism. Furthermore, it has unique poly-ethylene oxide side chains, which move in water and steer the binder grains to disperse evenly into the grout mixture (Safiuddin 2008). Hence, the addition of the HRWRA reduced the inter-particle friction (i.e. flow resistance) between solid particles, and hence improved the grout's flowability.

3.3 Relationship between Efflux Time of Grout and Corresponding Spread Flow

Based on the results presented in Table 3, it can be observed that grout mixtures having a short efflux time resulted in a high grout spread flow. In fact, the relationship between efflux time of TSC grouts and corresponding spread flow has not yet been defined. Therefore, an empirical relationship between efflux time and spread flow of grout mixtures based on the results of this study was proposed (Figure 3). As mentioned above, the flowability of the grout mixture is mainly affected by the amount of water used, which depends on the amount of required water to cover powder particles and fill the inter-granular porosity in the mixture. Therefore, this relationship is significantly affected by the w/b ratio used in the grout mixtures as illustrated in the proposed equations (Eq. 1, 2 and 3).

[1] $S = 101.15 \times T^{(-0.233)}$ (w/b = 0.35)
[2] $S = 113.74 \times T^{(-0.412)}$ (w/b = 0.45)
[3] $S = 118.34 \times T^{(-0.534)}$ (w/b = 0.55)

Where S is the grout spread flow (cm) and T is the grout efflux time (s). The proposed equations were assessed statistically based on the fraction absolute of variance, which yielded 0.866, 0.925 and 0.893 for Eqs. 1, 2 and 3, respectively. Moreover, the proposed Eq. 2 was validated using further experimental results of efflux time and corresponding spread flow for various grout mixtures made with w/b = 0.45. It was found that Eq. 2 achieved reasonable prediction relation to experimental results as shown in Figure 4. It is believed that, the grout flowability is of paramount importance since it directly affects the TSC engineering properties. Therefore, these proposed equations can be used to estimate the required grout spread flow based on the recommended efflux time for TSC applications.

Table 3: Results of Grout Flowability (Efflux Time and Spread Flow)

Grout Mixture Number	Grout Efflux Time (sec)				Grout Spread Flow (cm)			
	HRWRA Dosage %				HRWRA Dosage %			
	0.0	0.6	0.8	1.0	0.0	0.6	0.8	1.0
C-0.35	>300	390	270	148	8.0	23.0	28.5	34.0
F3-0.35	153	117	103	86	9.5	32.0	35.5	38.0
F5-0.35	80	80	77	72	10.0	35.0	38.0	39.0
F7-0.35	61	54	53	53	12.5	36.0	39.0	40.0
	HRWRA Dosage %				HRWRA Dosage %			
	0.0	0.2	0.4	0.6	0.0	0.2	0.4	0.6
C-0.45	>300	91	39	39	11.5	18.0	23.0	28.0
F3-0.45	90	34	24	22	16.0	25.0	30.0	33.0
F5-0.45	39	25	22	20	18.0	30.0	32.0	34.0
F7-0.45	26	22	20	19	19.0	30.0	33.0	35.0
	HRWRA Dosage %				HRWRA Dosage %			
	0.0	0.1	0.2	--	0.0	0.1	0.2	--
C-0.55	35	25	16	--	18.0	22.0	24.0	--
F3-0.55	18	16	14	--	22.0	28.5	30.0	--
F5-0.55	16	14	13	--	27.0	29.0	31.0	--
F7-0.55	13	13	13	--	28.0	30.0	32.0	--

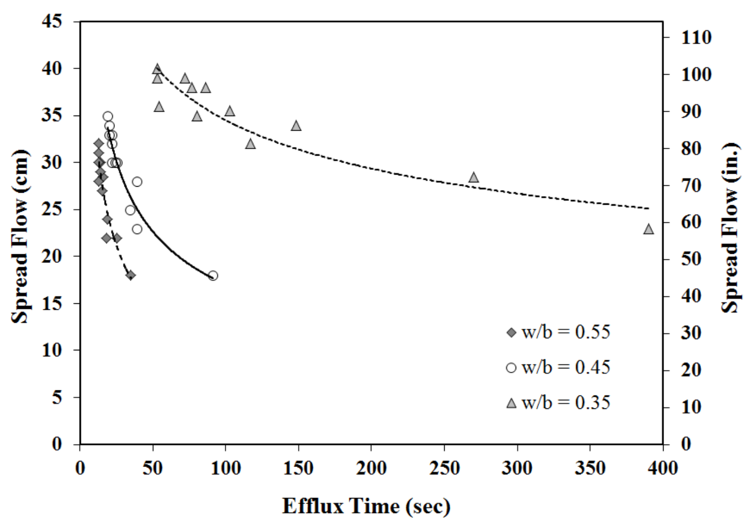

Figure 3: Relationship between efflux time of grout and corresponding spread flow at different w/b ratios.

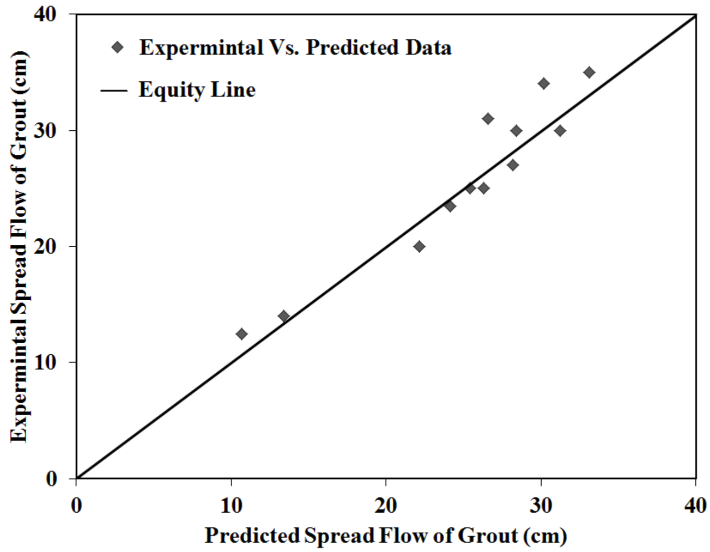

Figure 4: Experimental grout spread flow versus that predicted by Eq. 2.

3.4 Effect of FA Cement Replacement Rate on Compressive Strength of Grout and Corresponding TSC

Based on the flowability results discussed above, it can be observed that all grout mixtures made with a w/b ratio = 0.45 could achieve the efflux time of 35-40 ±2 s recommended for successful TSC production (ACI 304.1 2005). Therefore, grout mixtures with w/b = 0.45 having an optimum HRWRA dosage were selected to investigate TSC compressive strength development.

Table 4 presents the compressive strength results at different ages for the tested grouts and their corresponding TSC mixtures. Generally, the higher the FA partial replacement level for OPC, the greater was the reduction in compressive strength. For example, increasing the FA rate in the grout from 30% to 70% resulted in about 15.5 % greater reduction in the 7-days compressive strength of TSC than that of the control TSC. This is because grouts incorporating FA gain strength slowly due to slower hydration reactions at early-age (Bouzoubaâ et al. 2004).

At later ages (i.e. more than 7 days), TSC mixture incorporating 30% FA exhibited higher strength gaining rate than that of the control mixture. The strength gaining rate of this mixture was 1.6 and 3.1 times that of the control mixture at 28 and 56 days, respectively. However, the strength gaining rate of mixtures incorporating 50% and 70% FA had exceeded that of the control mixture after 28 days. For example, the strength gaining rate of F7 mixture was 0.8 and 1.8 times that of the control mixture at 28 and 56 days, respectively. Therefore, TSC mixtures incorporating FA are expected to achieve comparable or even higher compressive strength than that of the control mixture as the strength gaining rate sustained over time (Hwang et al. 2004).

Table 4: Grout and TSC Compressive Strength Versus FA addition dosage

Grout Mixture Number	Optimum HRWRA Dosage (%)	Compressive strength of grout (MPa) at days			Compressive strength of TSC (MPa) at days		
		7	28	56	7	28	56
C-0.45	0.4	33.8	50.4	54.3	25.9	31.5	33.3
F3-0.45	0.2	27.1	38.5	46.2	14.0	18.9	25.8
F5-0.45	0.0	21.0	28.0	38.2	12.0	14.1	18.5
F7-0.45	0.0	13.5	18.0	24.6	10.0	11.8	15.0

4. CONCLUSIONS

In this study, the flowability and compressive strength of two-stage concrete made with various fly ash addition rates were explored. The following conclusions can be drawn:

- The suitable TSC grout mixture proportions and FA partial replacement level for OPC are selected according to ASTM C938, which mainly depends on the grout flowability. Grouts with an efflux time of 35-40 ±2 s are recommended to achieve adequate properties of TSC.
- Partial replacement of OPC with FA significantly improved the TSC grout's flowability.
- Empirical equations for the relationship between the efflux time of grouts and the corresponding spread flow were proposed.
- The higher the FA partial replacement level for OPC, the greater was the reduction in TSC compressive strength. However, the strength gaining of TSC mixtures made with high-volume FA increased after 28 days resulting in an increase of the compressive strength over time.

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