SILICA FUME AS A STRENGTH ENHANCER IN LOW DENSITY SLURRIES

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ABSTRACT

Silica fume is a pozzolanic material composed of extremely fine, amorphous spheres produced as a by-product in the manufacture of silicon metals. It has a high water demand and is more reactive than natural pozzolan or fly ash. When added to cement it makes an excellent extender and produces significant increases in compressive strengths.

This paper examines the compressive strengths of low density slurries made with different blends of portland cement, fly ash, and silica fume. Both Class C and Class H slurries, mixed at 11.5 ppg to 13.0 ppg, and cured at temperatures ranging from 80 to 170 degrees F were tested. These compressive strengths are compared with the strengths of conventional slurries extended with anhydrous sodium metasilicate or bentonite to the same density.

The results show that silica fume is beneficial as a strength enhancer at low densities over a range of temperatures.

INTRODUCTION

Silica fume is a pozzolanic material collected by filtering gases escaping from furnaces during the manufacture of ferro-silicon and silicon metals. The material is spherical, has an extremely high surface area, and is almost totally amorphous or uncrystallized. Fig. 1 illustrates the fineness of the material by comparing it to other fine materials.(1) A typical fume generally contains more than 90 percent silicon dioxide, about 2 percent alumina, 1 percent carbon, and small amounts of iron, magnesium, and calcium. The chemical content of fume varies with the type of metal produced in the furnace but for a given production it is very constant due to the purity of the raw materials used.

Silica fume has been used in the construction industry as a cement additive since the 1950's. Numerous papers have been published in concrete construction journals citing its benefits in compressive strength enhancement, decreased permeability, increased chemical resistance, and durability under repeated cycles of freezing and thawing. It has been only in recent years, however, that its benefits have been taken seriously as a strength enhancer in oil well cements. The fume has been used primarily as a replacement for part of the fly ash and bentonite commonly used in low density slurries. This use as a strength enhancer is the emphasis of this paper and accompanying laboratory tests.

DISCUSSION

It has been observed that the use of even a small quantity of silica fume in a cement slurry results in significant gains in compressive strength when compared with neat cements or fly ash/cement blends. This strength enhancement property is efficient even in high water-to-cement ratios.

A paper by Grutzeck et al.(2) explored in detail the chemical reaction responsible for this strength increase. Put in simple terms, the increase in strength is primarily due to the silica fume reacting with free lime in cement to form a new cementitious compound C-S-H (calcium silicate hydrate). This compound increases strength in direct proportion to the fineness and total silica content of the material.(3)

Fly ash, commonly known as "poz" and actually a artificial pozzolan, is capable of yielding a strength increase over time, but its reactivity is too low to compete with the reactivity of silica fume. This lower reactivity can be explained by examining how fly ash is manufactured and its physical properties.

Fly ash is produced during the combustion of powdered or ground coal. During combustion the volatile matter is burned off while most of the mineral impurities go up with the flue gas. This ash is consequently removed by electrostatic precipitators. The silica and other mineral content of the ash can vary significantly depending of the type of coal burned. The ASTM classifies fly ashes as Class F and Class C based primarily on the total content of silica, aluminum, and iron oxide. Class C ashes are usually produced from subbituminous or lignite coals and Class F ashes are produced from anthracite or bituminous coals. The silica content of of Class C ash is normally between 30 and 45 percent. The silica content of the Class F poz is higher, usually between 45 and 60 percent. The spherical particles are glassy smooth and 50 to 100 times larger than silica fume particles. Actually fly ash is not discreet particles of silica but a mixture of silica and alumina. Because of this large particle size and surface characteristics it may take several days or weeks before the pozzolanic reaction is significant.

The fineness of silica fume and its textured raspberry-like surface makes it a very active material. It can start contributing to strength development almost from the beginning of portland cement hydration. It can be likened to a super pozzolan. The extreme fineness of the material also increases the water demand resulting in excellent free water control without the addition of bentonite or other water control additives.

TESTS

In order to compare compressive strengths, lab tests were conducted according to API Spec 10 requirements using two silica fume/fly ash/portland cement blends and two other common low-density blends at densities ranging from 11.5 ppg to 13.0 ppg. These densities were studied since they are most commonly used in light weight slurries where early compressive strengths are difficult to obtain. In the case of the two standard slurries, strength tests were run only at the standard densities for each. Following common field practices, salt was added as a mild accelerator and dispersant. Each blend was tested using Class C and Class H cements. The fly ash used was a Class F. The Class C blends were tested at 80 and 120 degrees F; the temperature range common for Class C. The Class H blends were tested at 120 and 170 degrees F. The free water content of the slurries was also tested using API Spec 10 procedures. Tables 1, 2, and 3 list the results.

The cement blends tested were:

Slurry #1: 47 lbs. portland cement + 20 lbs. fly ash + 17 lbs. silica fume + 5% salt

Slurry #2: 61 lbs. portland cement + 15 lbs. fly ash + 11 lbs. silica fume + 5% salt

Slurry #3: 61.1 lbs portland cement + 25.90 lbs. fly ash + 6% bentonite extender + 5% salt

Slurry #4: 94 lbs. portland cement + 3% chemical extender

OBSERVATIONS

1. Slurry #1 with its higher silica fume content showed better compressive strength than silica fume Slurry #2 over the entire range of time and temperature. This study did not attempt to determine the optimum silica fume content but other studies have suggested that excessive amounts of silica fume produces a brittle cement.(4)

2. The silica fume slurries were inferior in compressive strengths to the conventional slurries only at the 11.5 ppg and the 24 hr. 80 degrees F test. This would indicate that the reaction of the silica fume and early C-H-S development declines to an inefficient level at a certain high water ratio and low temperature when compared to blends with a relatively high cement content.

3. The improvement in compressive strength increases with increased density and temperature. At 120 degrees F the silica fume slurries are at least 75% better than any of the conventional slurries.

4. It is generally recognized that cement blends using Class F fly ash yield better early compressive strengths than blends using Class C fly ash. No attempt was made to compare the silica fume slurries using a Class C ash. However, experience would suggest that the compressive strengths would be lower.

5. The silica fume free water was lower than the free water for any standard slurry at every density. Fluid loss tests were not run for this study but lab experience has shown good fluid loss numbers for silica fume slurries. The slurries have also responded well to fluid loss additives.

6. Several observations were made outside the lab and cannot be dealt with in detail here. Experience in the field indicates that mixing problems can be encountered with the silica slurries at densities above 12.5 ppg. The problems become more severe as the silica fume content increases in the blend and the water ratio decreases. These problems have been remedied by adjusting the ratio of fine silica fume and coarser fly ash to make a workable slurry. The alternative is the addition of a dispersant which has a tendency to extend set time and compressive strength development.

CONCLUSIONS

This study set out to compare the compressive strengths of various cement blends containing silica fume and cements without the material. The results show that silica fume is an effective strength enhancer over almost every range of density and temperature. Furthermore, silica fume slurries show good free water and fluid loss control. The amount of silica fume substituted for portland cement and fly ash in a blend can be varied to yield a range of compressive strengths while maintaining a workable slurry. More options are available with the use of dispersing additives and fluid loss additives.

REFERENCES

(1) V.M. Malhotra and G.G. Carette, "Silica Fume Concrete - Properties, Applications, and Limitations," Concrete International, May 1983

(2) M.W. Grutzeck, D.M. Roy, and D. Wolfe-Confer, "Mechanism of Hydration of Portland Cement Composites Containing Ferrosilicon Dust," Proceedings of the 4th International Conference on Cement Microscopy, March 28-April 1, 1982

(3) John Wolsiefer, "Ultra High-Strength Field Placement Concrete With Silica Fume Admixture" Concrete International April 1984

(4) M. Regourd and B. Mortureux, "Microstructure of Field Concretes Containing Silica Fume" Department Microstructures, Paris -- France

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Table 1

LEGEND:	
SLURRY #1C:	47 LBS. CLASS C + 20 LBS. FLY ASH + 17 LBS. SILICA FUME + 5% SALT
SLURRY #2C:	61 LBS. CLASS C + 15 LBS. FLY ASH + 11 LBS. SILICA FUME + 5% SALT
SLURRY #3C:	61.1 LBS. CLASS C + 25.90 LBS. FLY ASH + 6% BENETONITE EXTENDER + 5% SALT
SLURRY #4C:	94 LBS. CLASS C + 3% CHEMICAL EXTENDER + 5% SALT

COMPRESSIVE STRENGTHS AT 80F;

DENSITY IN PPG	SLURRY #1C 24	/ 72HR	SLURRY #2C 24	/ 72HR	SLURRY #3C 24	/ 72HR	SLURRY #4C 24	/ 72HR
11.5	225	275	225	675			250	450
12.0	425	1575	325	950			350	475
12.5	1025	2200	375	1325	525	938		
13.0	1125	2850	850	1650	750	1275		

COMPRESSIVE STRENGTHS AT 120F;

DENSITY IN PPG	SLURRY #1C 24	/ 72HR	SLURRY #2C 24	/ 72HR	SLURRY #3C 24	/ 72HR	SLURRY #4C 24	/ 72HR
11.5	1375	1906	950	1250			425	600
12.0	1650	2187	1275	1925			500	650
12.5	2050	2812	1825	2250	900	1375		
13.0	3188	3462	2350	2888	1000	1475		

Table 2

LEGEND:	
SLURRY #1H:	47 LBS. CLASS H + 20 LBS. FLY ASH + 17 LBS. SILICA FUME + 3% SALT
SLURRY #2H:	61 LBS. CLASS H + 15 LBS. FLY ASH + 11 LBS. SILICA FUME + 3% SALT
SLURRY #3H:	61.1 LBS. CLASS H + 25.90 LBS. FLY ASH + 6% BENETONITE EXTENDER + 3% SALT
SLURRY #4H:	94 LBS. CLASS H + 3% CHEMICAL EXTENDER + 3% SALT

COMPRESSIVE STRENGTHS AT 120F;

DENSITY IN PPG	SLURRY #1H 24	/ 72HR	SLURRY #2H 24	/ 72HR	SLURRY #3H 24	/ 72HR	SLURRY #4H 24	/ 72HR
11.5	525	868	650	981			250	350
12.0	1350	1937	1087	1450			300	525
12.5	1450	1925	1400	1775	462	631		
13.0	2375	3031	1988	2255	850	1175		

COMPRESSIVE STRENGTHS AT 170F;

DENSITY IN PPG	SLURRY #1H 24	/ 72HR	SLURRY #2H 24	/ 72HR	SLURRY #3H 24	/ 72HR	SLURRY #4H 24	/ 72HR
11.5	750	1005	800	1075			335	500
12.0	1400	1850	1375	1625			425	700
12.5	2550	3100	1650	1950	525	1025		
13.0	2750	3375	2100	2350	1100	1325		

Table 3

FREE WATER AT AMBIENT TEMPERATURE
MILLILITERS/2 HOURS

DENSITY IN PPG	SLURRY #1C mls	SLURRY #2C mls	SLURRY #3C mls	SLURRY #4C mls
11.5	0.5	2.0		4.5
12.0	0.0	TRACE		
12.5	0.0	0.0	1.8	
13.0	0.0	0.0	0.8	

FREE WATER AT AMBIENT TEMPERATURE
MILLILITERS/2 HOURS

DENSITY IN PPG	SLURRY #1H mls	SLURRY #2H mls	SLURRY #3H mls	SLURRY #4H mls
11.5	0.5	3.0		5.9
12.0	TRACE	TRACE		0.8
12.5	0.0	0.0	4.8	
13.0	0.0	0.0	0.0	

Table 4
Slurry Physical Properties

SLURRY #1C: 47 LBS. CLASS C + 20 LBS. FLY ASH + 17 LBS. SILICA FUME + 5% SALT

WEIGHT (LBS/GAL)	YIELD (CU FT/SK)	% WATER	GAL/SK
11.5	2.37	136	13.71
12.0	2.03	111	11.19
12.5	1.77	92	9.28
13.0	1.57	77	7.79

SLURRY #2C: 61 LBS. CLASS C + 15 LBS. FLY ASH + 11 LBS. SILICA FUME + 5% SALT

WEIGHT (LBS/GAL)	YIELD (CU FT/SK)	% WATER	GAL/SK
11.5	2.54	144	15.04
12.0	2.17	118	12.32
12.5	1.89	98	10.24
13.0	1.67	83	8.67

SLURRY #3C: 61.1 LBS. CLASS C + 25.90 LBS. FLY ASH + 6% BENTONITE + 5% SALT

WEIGHT (LBS/GAL)	YIELD (CU FT/SK)	% WATER	GAL/SK
12.5	2.02	107	11.17
13.0	1.80	91	9.52

SLURRY #4C: 94 LBS. CLASS C + 3% CHEMICAL EXTENDER + 5% SALT

WEIGHT (LBS/GAL)	YIELD (CU FT/SK)	% WATER	GAL/SK
11.5	2.99	163	18.39
12.0	2.55	134	15.10

Table 5
Slurry Physical Properties

SLURRY #1H: 47 LBS. CLASS H + 20 LBS. FLY ASH + 17 LBS. SILICA FUME + 3% SALT

WEIGHT (LBS/GAL)	YIELD (CU FT/SK)	% WATER	GAL/SK
11.5	2.39	137	13.86
12.0	1.91	104	10.49
12.5	1.89	98	9.88
13.0	1.52	75	7.56

SLURRY #2H: 61 LBS. CLASS H + 15 LBS. FLY ASH + 11 LBS. SILICA FUME + 3% SALT

WEIGHT (LBS/GAL)	YIELD (CU FT/SK)	% WATER	GAL/SK
11.5	2.47	140	14.62
12.0	2.12	115	12.01
12.5	1.85	96	10.03
13.0	1.38	82	8.56

SLURRY #3H: 61.1 LBS. CLASS H + 25.90 LBS. FLY ASH + 6% BENTONITE + 3% SALT

WEIGHT (LBS/GAL)	YIELD (CU FT/SK)	% WATER	GAL/SK
12.5	1.99	105	10.96
13.0	1.78	90	9.39

SLURRY #4H: 94 LBS. CLASS H + 3% CHEMICAL EXTENDER + 3% SALT

WEIGHT (LBS/GAL)	YIELD (CU FT/SK)	% WATER	GAL/SK
11.5	2.90	158	17.82
12.0	2.49	131	14.77

SILICA FUME	: 20,000 m2/kg
TOBACCO SMOKE	: 10,000 m2/kg
FLY ASH	: 400 to 700 m2/kg
PORTLAND CEMENT	: 300 to 400 m2/kg

Figure 1 - Specific surface areas of various materials