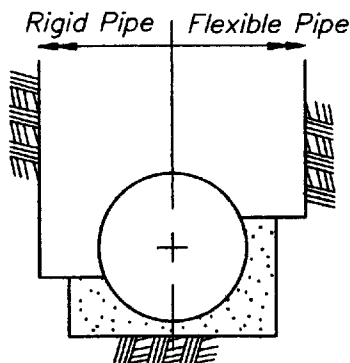
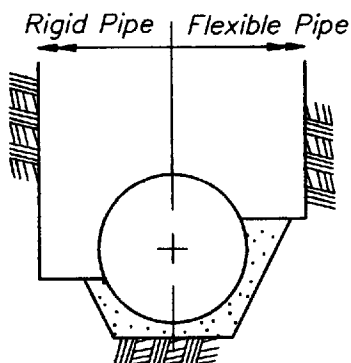
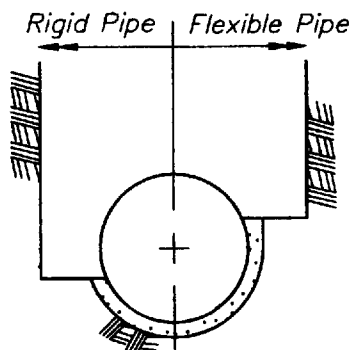


CONTROLLED LOW-STRENGTH MATERIALS

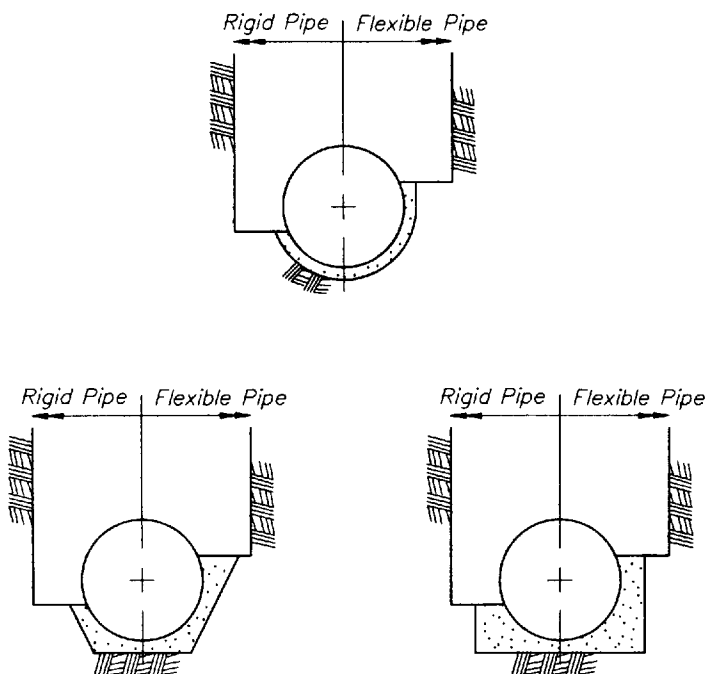


Wayne S. Adaska
Editor



SP-150

CONTROLLED LOW-STRENGTH MATERIALS



Wayne S. Adaska
Editor



SP-150

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PREFACE

Controlled Low-Strength Material (CLSM) is a self-compacted cementitious material used primarily as a substitute for compacted backfill. The material is known by many names including flowable fill, controlled density fill, unshrinkable fill and soil-cement slurry. The American Concrete Institute defines CLSM as a material with a maximum unconfined compressive strength of 1200 psi. For most applications, however, the compressive strength of CLSM does not exceed about 300 psi. This makes it possible for the material to be removed should future excavation be necessary.

At the 1992 ACI Spring Convention, two well attended technical sessions on Controlled Low-Strength Materials were held. The sessions were jointly sponsored by Committees 229 on CLSM, 232 on Fly Ash and Natural Pozzolans in Concrete, and E702 on Designing Concrete Structures. During the same year a technical session on CLSM was held during the Transportation Research Board's annual meeting in Washington, D.C. Following these sessions, papers were solicited from each of the speakers. The papers contained in this volume are a result of that solicitation.

Sincere appreciation is extended to the many members of Committee 229 for reviewing the submitted manuscripts and a special thanks to Dr. Donald Milks for serving as session chairman and co-organizer for the ACI technical sessions.

Wayne S. Adaska
Chairman, ACI Committee 229
Controlled-Low Strength Materials

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SP 150-1

Low-Strength Concrete and Controlled Low-Strength Material (CLSM) Produced with Class F Fly Ash

by T.R. Naik and B.W. Ramme

Synopsis: This paper presents results of research performed to identify optimum mix proportions for production of Controlled Low Strength Material (CLSM) with high fly ash content. CLSM is defined by the ACI Committee 229 as a cementitious material that is in a flowable state at the time of placement and having a specified compressive strength of 1,200 psi (8.3 MPa or 172,800 lbs./sq. ft.) or less at the age of 28 days. The fly ash used in this study met the requirements of ASTM C 618 for Class F material. Tests were carried out on concrete designed to have 500 - 1,500 psi compressive strength at the 28-day age with fly ash contents of approximately 500 lb/yd³. Slump was held at 8 ± 1 inch for all mixtures produced. Compressive strengths at 28 days were found to range from 290 to 1,640 psi. Construction experience and other planned applications are also discussed.

Keywords: Backfilling; compressive strength; controlled low-strength material (CLSM); density (mass/volume); flowability; flowable fill; fly ash; low strength concrete; mix proportioning; slump; slurries; tests

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ACI member **Bruce W. Ramme** is Assistant to the Plant Manager at the Port Washington Power Plant of Wisconsin Electric Power Company, Milwaukee. He received his BS and MS degrees in structural engineering from the University of Wisconsin, Milwaukee. He is a member of ACI Committees 229, Controlled Low Strength Material; and 213, Lightweight Aggregates and Lightweight Aggregate Concrete.

INTRODUCTION

This paper presents the results of research performed to identify mix proportions for low strength concrete slurry which falls under the classification of Controlled Low Strength Material (CLSM) as defined by ACI Committee 229. CLSM is defined as a cementitious material that is in a flowable state at the time of placement and has a specified compressive strength of 1200 psi (8.3 MPa or 172,800 lbs./sq. ft.) or less at the age of 28 days. It is primarily used for nonstructural applications below grade where low strength is required. In some cases it is intended to be no stronger than the surrounding soil. The CLSM described in this paper has a 28 day compressive strength of 500 psi (3.4 MPa) and higher with some mixtures actually producing strengths in excess of 1200 psi (8.3 MPa) which fall into the category of low strength concrete. Low strength, 100 psi $\pm$ 50 psi (0.7 MPa $\pm$ 0.35 MPa) CLSM flowable fly ash slurry produced as part of this overall project has already been described in a previous publication [1]. The type of CLSM selected should be based on technical and economic considerations for the specific application. The fly ash used in the CLSM for this project was produced by Wisconsin Electric Power Company (WE) at the Valley Power Plant located in Downtown Milwaukee, Wisconsin. The plant uses bituminous coal from Pennsylvania Mining District 2.

The mix proportions for the CLSM used in this project were selected to obtain a moderate strength material in the 500 psi (3.4 MPa) to 1500 psi (10.3 MPa) (72 to 216 kips/sq. ft.) range. This level of strength is similar to that of many naturally occurring bedrock formations and, therefore, provides excellent support for foundations and can assist in distributing foundation loads over greater areas.

The scope of the research phase reported in this paper is limited to developing mix proportions consistent with specified strength and flowability requirements.

Literature Search

A library search was conducted to identify existing similar work with respect to the development of high fly ash low strength concrete. Published reports by federal and state organizations, engineering periodicals and journals, and professional organizations were reviewed.

The primary search covered the period from January, 1970 to June, 1988. The only similar work found on low strength fly ash concrete was done by the Detroit Edison Company, Detroit, Michigan, and the Kuhlman Corp., Toledo, Ohio in 1970[2]. The investigation done by these companies resulted in the development of a new product that was called K-Krete. As a result of this development, a K-Krete Corporation was formally organized in 1974. The K-Krete mix consists of Portland cement, fly ash and a filler. The primary use of K-Krete is as a replacement for compacted granular materials. Such uses include street utility backfills, sanitary backfills, backfills around foundations, etc. The compressive strength for K-Krete mixes ranges between 100 - 1600 psi (0.7 MPa - 11.0 MPa). The permeability ranges between 0.001 to 0.00003 ft/min (0.3 to 0.009 mm/min), which indicate that the K-Krete mixes have comparable permeabilities when compared to regular backfill materials (e.g., silty sand permeability varies from 0.002 to 0.00002 ft/min (0.6 to 0.006 mm/min). The K-Krete materials had resistance to direct wearing erosion similar to that for a comparable granular fill. It was suggested that for removability K-Krete mixes should be designed for about 100 psi (0.7 MPa) compressive strength at one year age. It was recommended that research is needed to investigate and develop the fly ash low strength concrete to meet user needs.

The July 1990 issue of Concrete International featured articles on CLSM. An article written by Ron Larsen [3] sites several excellent application examples on uses of this material including filling of abandoned underground fuel tanks, protecting under-road petroleum pipes, placing culverts, erosion prevention, saving bridges and steel arch pipe culverts and filling voids.

Several fly ash concrete and slurry publications [4-21] are identified in the bibliography to give the reader leads to other work with similar fly ashes and their applications.

OBJECTIVES AND SCOPE

The mix proportions for the low strength concrete in this project were selected to obtain a low strength material in the 500 to 1500 psi (3.4 to 8.3 MPa) range. This level of strength makes it suitable as a low cost material for pipe bedding, utility duct envelopes, for filling over-excavated zones under structural foundations, as a high quality road base, and in similar applications. This material can serve as a non-structural material at a cost lower than normal structural concrete in applications where lower strengths are adequate. The material should not be used for above grade applications without being properly protected, i.e., covered, since

it does not possess qualities that make it durable against freeze-thaw and abrasion exposure.

Valley Plant Class F Fly Ash

Valley Plant Class F fly ash is a by-product of Eastern United States bituminous coal combustion. The fly ash is captured by electrostatic/precipitators from flue gases prior to discharge by exhaust chimneys. It meets the requirements of ASTM C618 Class F Designation, see Table 1.

Materials and Mixing

The high fly ash low strength concrete mixes were produced for this project at a batch plant of the New Berlin Redi-Mix Concrete Co., New Berlin, Wisconsin. The fly ash was stored in separate silos in a dry state. The cement used in these tests was Type I. The mixing water was heated. The fine aggregates used were a natural sand material meeting ASTM Test Designation C-33 with a fineness modulus of 2.79. The maximum size of coarse aggregate was 3/8 in. (9.5 mm) (pea gravel). No air entraining agent was used. The materials were loaded into a ready mix truck and transported from the batching plant to an on-site location where the tests were performed. The batch quantity for each mix was approximately two cubic yards (1.5 cubic meters). The concrete batch in the truck was allowed to mix at the transit speed of the mixer drum for about 30 minutes. A small front end loader was used to obtain the desired quantity of concrete, about 4 cu. ft. (0.11 cu.m.) to perform the tests and make the test cylinders for each mix. Each time about two front end loaders full of concrete, about 8 cu. ft. (0.23 cu.m.) were discarded before taking the final sample for testing and cylinder casting to assure homogeneity of the product.

Preliminary Mix Proportioning

Preliminary mix proportions were developed to produce CLSM with a low cement factor but a high proportion of fly ash and sufficient water to produce high workability and/or fluidity. The slump was targeted for the 5 to 8 in. (127 to 203 mm.) range for the special construction applications described in the scope.

Final Mix Proportioning

Mixes F-1 to F-6 were produced with a low cement content and a high fly ash to cement ratio to compensate for the low cementitious characteristics of the Class F fly ash. These mixes were all high in slump, 7 in. - 9 in. (180 mm - 230 mm) range. Adjustments which were made in the sand and pea gravel content versus the total

cementitious (cement plus fly ash) material. Generally, the sand content was decreased as the total cementitious material, in particular the fly ash content, was increased. These adjustments were necessary in order to produce the required volume of concrete as the fly ash amount was increased in order to maintain the batch yield. These adjustments have no significant influence on the concrete properties.

All Mixes were produced in 2 cu. yd. (1.5 cu.m.) batches. The total batch weights were recorded for each mix. The final mix proportions per cubic yard were calculated for all mixes using the actual material weights and unit weights of each batch. (Table 2).

Specimen Preparation and Testing

Each batch of concrete produced was tested for acceptability before proceeding with the other tests. Tests for slump, concrete and ambient air temperatures, air content and unit weight were performed for each batch. Observations were made to determine the workability of the concrete. All batches of concrete were homogeneous and cohesive.

From each concrete mixture, 6 in. diameter by 12 in. high (150 mm x 300 mm) cylinders were prepared for compressive strength and other tests. Three cylinders were tested from each mix at nominal ages of 3, 5, 7 and 28 days. Cylinders were stored at room temperature, $65 \pm 5^\circ\text{F}$, for three days before being transported to the testing laboratory for storage in a moist room and strength testing at specified ages.

All mixes showed good flowability and workability. Shrinkage ranged from 0 to 1/32 in. (0 to 1 mm). The cylinders were stripped without problems when they were brought to the laboratory and their sidewalls appeared smooth.

DISCUSSION OF RESULTS

The compressive strength test results are shown on Table 3 and Figure 1. Twenty eight day strengths ranged from 500 psi (3.4 MPa) to 1600 psi (11 MPa). The ratio of fly ash to cement ranged from 5.5 to 2.2. The ratio of water to total cementitious material was approximately 0.60 by weight.

Mixes F-1 to F-6 show that a high slump, low cement, and high amount of Class F fly ash concrete can be produced that can attain strengths in the 1600 psi range. The data indicates that the presence of a large proportion of non-cementitious material present in Class F fly ash limits the strength gain that can be attained for this type of mix. Figures 2 and 3 show that this limit is in the order of 1600 psi. An increase in the cement to fly ash ratio might produce somewhat higher compressive strengths by providing more available cement for the pozzolan used.

Field observations also confirmed that these mixes showed good flowability and good workability, however, they did not lend themselves to a high grade of trowel finishing which isn't really required for the intended applications.

Figure 4 shows the influence of varying the cement content on the 28-day compressive strength. For similar workability, the cement content was an important factor for the Class F fly ash concrete, mixes F-1 to F-6. As the cement content was increased the 28-day strength also increased proportionately.

WE Project Experience with Low Strength Concrete

Low strength concrete with Class F fly ash was used in 1977 for backfilling a steam main extension trenchbox excavation. The mix proportions were:

Cement	50 lbs.
Fly Ash	600 lbs.
Sand	2900 lbs.
Water	320 lbs.

The compressive strength produced was in the range of 400 psi, at 28 days and set hard enough to walk on in 8-10 hours. Since the material flowed very easily it was possible to do the backfilling with the steel plates in place over a street crossing, thus keeping the street open for use throughout the backfilling operation.

The majority of WE's experience with low strength concrete in recent years involves the use of Class C fly ash and is described in another paper [21]. This is largely because local ready mix suppliers maintain an ample supply of the material for structural concrete applications and do not have additional storage silos. However, this Class F fly ash has been used for some large volume projects in the form of a flowable fly ash slurry CLSM material [1].

As supplies of the highly desired Class C fly ash diminish because of demand and local ready mixed concrete suppliers begin to offer the flowable fly ash slurry for smaller jobs (which means they will have a silo or another method of storing Class F fly ash), WE expects to also use more of the low strength concrete produced with Class F ash.

CONCLUSIONS

- 1) Generally, as the water to cementitious material ratio increased, the compressive strength decreased. The cement content was very important in these mixes as the fly ash used possessed very little cementitious property of its own.
- 2) All mixes showed good flowability and workability. Shrinkage was minimal or non existent.

- 3) All mixes performed well and can be used as the basis for selecting mix proportions for CLSMs or low strength high fly ash concrete with high slump for non-structural applications using the same materials.
- 4) High fly ash content low strength concrete and CLSMs can be made with Class F fly ash and can be successfully used in construction.

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TABLE 1 — CHEMICAL AND PHYSICAL TEST DATA FOR CLASS F FLY ASH FROM VALLEY POWER PLANT

Chemical Composition	Number of Samples	Range, Percent	Average Percent	ASTM C-618
Silicon Oxide, SiO_2	4	50.06-50.20	50.14	---
Aluminum Oxide, Al_2O_3	4	25.24-25.36	25.27	---
Iron Oxide, Fe_2O_3	4	14.66-15.39	14.93	---
Total, $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$	4	89.96-90.82	90.36	70 Min.
Sulfur Trioxide, SO_3	4	0.20-0.33	0.26	5.0 Max.
Calcium Oxide, CaO	4	1.18-1.44	1.27	---
Magnesium Oxide, MgO	4	0.70-0.74	0.71	5.0 Max.
Loss on Ignition	4	3.59-6.94	5.08	6.0 Max.
Available Alkalis as Na_2O	4	1.61-1.70	1.65	
Sulfur			0.22	

Physical Tests				
Fineness, % Retained on #325 Wet Sieve	1	25	25	34.0 Max.

Note: 145 psi = 1 MPa
 1 inch = 25.4 mm
 $1^\circ\text{F} = 1.8^\circ\text{C} + 32$
 1 cu. yd. = 0.7646 cu.m.
 1 pound = 0.4536 kg

TABLE 2 — MIXTURE PROPORTIONS AND FIELD TEST DATA FOR HIGH FLY ASH
LOW STRENGTH HIGH SLUMP CONCRETE USING CLASS F FLY ASH
(Supplier: New Berlin Redi-Mix, Inc.)

Mix No.	F-1	F-2	F-3	F-4	F-5	F-6
Specified Strength at 28-day age, psi	500	1000	1500	500	1000	1500
Cement, lb./cu. yd.	102	151	229	138	211	263
Fly Ash, lb./cu. yd.	499	519	500	452	459	446
Water, lb./cu. yd.	439	375	422	323	294	320
SSD Sand, lb./cu. yd.	1206	1198	1111	1090	1053	1060
SSD Pea Gravel, lb./cu. yd.	1614	1697	1680	1783	1774	1688
Slump, in.	9	7-3/4	8-1/4	9	7-1/4	8-1/4
Air Content, percent	1.0	1.8	1.9	0.5	1.4	1.7
Air Temperature, °F	38	36	35	32	33	33
Concrete Temperature, °F	65	64	64	58	60	62
Concrete Density, pcf	143.0	145.9	146.0	140.2	140.4	139.5
Concrete Weight, lb./cu. yd.	3861	3940	3942	3786	3791	3777
W/C W/C+FA*	4.3 0.73*	2.5 0.56*	1.8 0.58*	2.34 0.55*	1.39 0.44*	1.22 0.45*
Date Cylinders Cast	11/22/88	11/22/88	11/22/88	02/13/89	02/13/89	02/13/89

* May not be meaningful because all of the Type F fly ash probably should not be accepted as cementitious.

Note: 145 psi = 1 MPa
1 inch = 25.4 mm
1°F = 1.8°C + 32
1 cu. yd. = 0.7646 cu.m.
1 pound = 0.4536 kg

TABLE 3 — HIGH FLY ASH LOW STRENGTH CONCRETE TEST DATA 1000, 1500, 2000 psi
SPECIFIED STRENGTH AT 28-DAY AGE

Mix No.	F-1		F-2		F-3		F-4		F-5		F-6	
Specified Strength, psi	500		1000		1500		500		1000		1500	
Class of Ash	F		F		F		F		F		F	
Slump, in.	9		7-3/4		8-1/4		9		7-1/4		8-1/4	
Test Age, days	C O M P R E S S I V E S T R E N G T H , p s i											
	act.	avg.	act.	avg.	act.	avg.	act.	avg.	act.	avg.	act.	avg.
3	110 110 100	110	270 270 270	270	490 500 500	500	110 140 150	123	260 250 280	263	430 450 380	420
5							200 200 200	200	390 390 370	383	620 640 630	630
6	200 220 200	210	430 480 490	470	820 810 820	820						
7							230 230 250	237	400 460 470	443	710 680 690	693
8	220 220 230	220	500 520 520	510	870 890 880	880						
28	490 500 480	490	940 900 950	930	1690 1600 1620	1640	650 700 680	677	1000 900 800	900	1050 1180 1400	1210

Note: 145 psi = 1 MPa
 1 inch = 25.4 mm
 $1^{\circ}\text{F} = 1.8^{\circ}\text{C} + 32$
 1 cu. yd. = 0.7646 cu.m.
 1 pound = 0.4536 kg

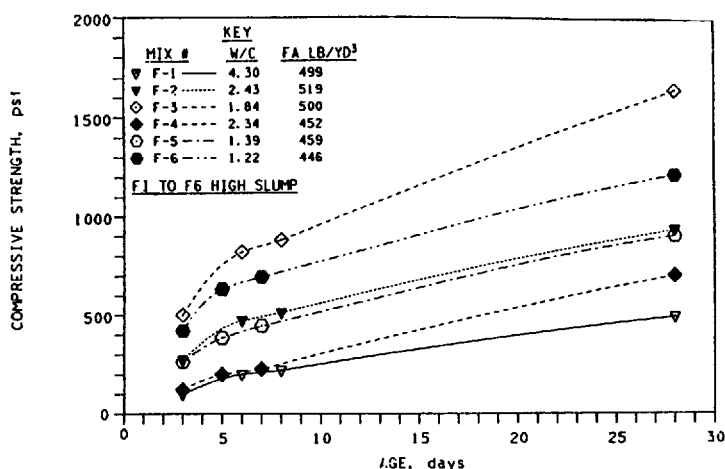


Fig. 1—Compressive strength versus age comparison. Class F fly ash mixes

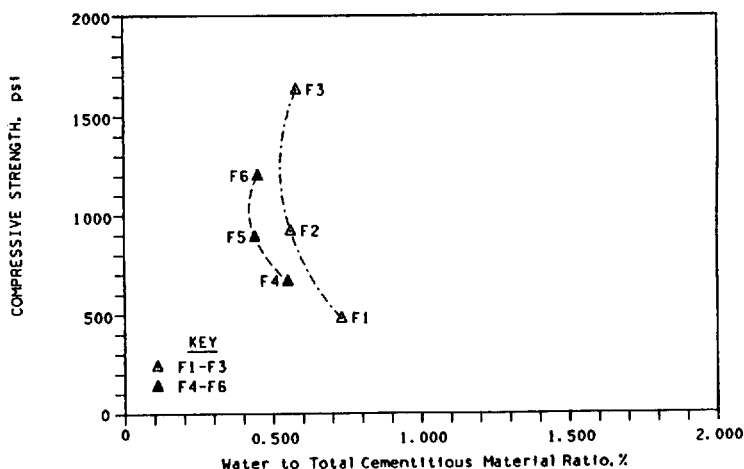


Fig. 2—28-day compressive strength versus water to cementitious material ratio

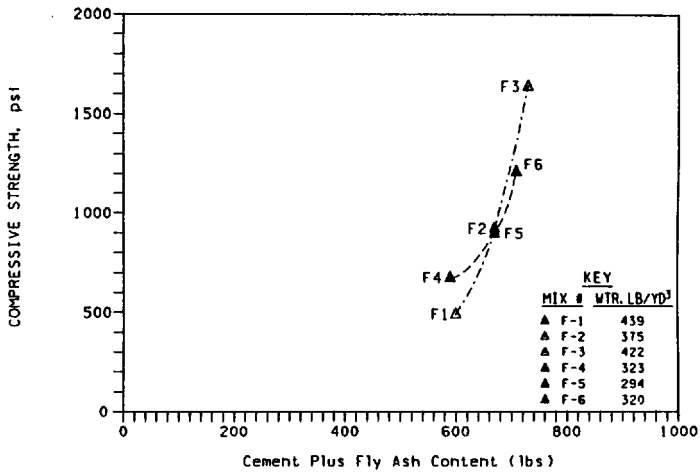


Fig. 3—28-day compressive strength versus total cementitious material

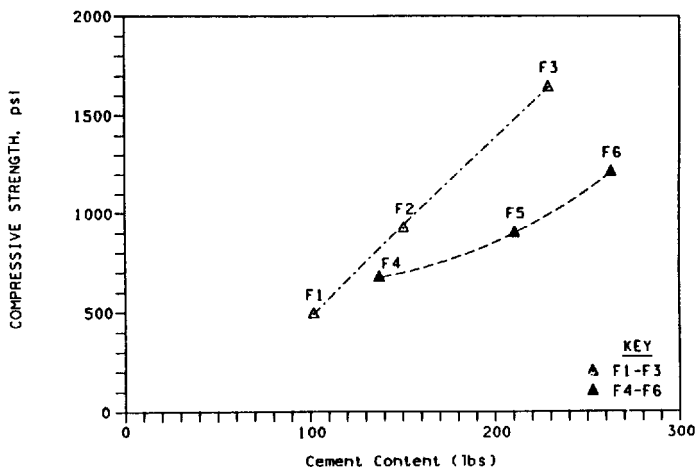


Fig. 4—28-day compressive strength versus cement content

SP 150-2

Optimization of Flowable Fill Mix Proportions

by M.E. Ayers, S.Z. Wong, and W. Zaman

Synopsis: The effect of mix proportions on the compressive strength of flowable fill is investigated in this study. Flowable fill, composed of Type I cement, class "C" fly ash, sand, and water meets the requirements of ACI Committee 229 as a controlled low strength material (CLSM) if the 28-day compressive strength is 1200 psi (8.3 MPa) or less. Extensive laboratory tests were conducted to determine the effects on the engineering properties of varying the water/cement plus fly ash, sand/cement plus fly ash, and fly ash/cement ratios. A wide range of ratios was evaluated in order to provide a cost effective mix design for various material costs. Compressive strengths were determined at 1, 7, 14, and 28 days, providing an indication of the rate of strength development and ultimate compressive strength.

Keywords: Backfilling; compressive strength; controlled low-strength material (CLSM); flowability; flowable fill; fly ash; mix proportioning; sands; slump

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BACKGROUND

Flowable fill is a self-leveling, high slump mixture of portland cement, fly ash, sand, and water. It is classified as a controlled low strength material (CLSM) by ACI Committee 229 if it has a 28-day compressive strength not exceeding 1200 psi (8.3 MPa). In situations where the material may be removed at a later date, the compressive strength should be less than 100 psi (0.7 MPa)

Flowable fill was developed during the late 1970s in response to a need for a low-cost, high-quality backfill material. Flowable fill has significantly improved engineering properties and is, in many cases, more economical than conventional backfill materials.

Several of the more widespread applications of flowable fill include: use as a backfill material for abandoned underground tanks and structures, as a base/subbase for foundations and slabs, as a backfill material for utility trenches, and as a "grout" material for filling voids and cracks. However, there are several limitations of flowable fill that preclude general application including: lack of abrasion resistance, high permeability, and low freeze/thaw resistance.

Flowable fill is an economical alternative to conventional granular backfill materials primarily because of reduced labor and equipment costs for placement and removal. The material is self-leveling and does not require densification during placement. The ease of removal is based upon the initial mix design proportions. Three levels of strengths are generally specified corresponding to: removal with hand tools (less than 100 psi), removal by mechanical means (less than 200 psi), and removal with power equipment (less than 1200 psi).

RESEARCH SIGNIFICANCE

The results of this study are significant in that the materials evaluated provide a wide range of mix designs that meet specific strength criteria. The most economical mix design may be selected based on material costs, desired compressive strength, and the rate of strength development.

EXPERIMENTAL PROGRAM

Materials

- Cement:** Sufficient Type I cement was obtained for preparation of all samples. A single source material was used to assure uniformity. The chemical constituents of the cement are presented in Table 1.
- Fly ash:** Several samples of class "C" fly ash were obtained and blended prior to sample preparation. The materials were representative of those available in central Oklahoma. The chemical constituents of the fly ash blend are provided in Table 2.
- Sand:** Class A concrete sand was used to prepare all samples. The sand gradation and specification criteria is presented in Table 3. Gradation was confirmed throughout the sample preparation procedures. The absorption of the sand was determined and accounted for in the mix design data presented in Table 4.
- Water:** Tap water was used for preparation of all samples.

Sample Preparation

The mix design proportions evaluated in this study are presented in Table 4. The ranges of water/cement plus fly ash, sand/cement plus fly ash, and fly ash/cement were selected to "bracket" several commonly used flowable fill mix proportions.

Three compartment, 2-inch (50-mm) molds were used to prepare duplicate samples. Microcrystalline wax was used to seal the molds and eliminate leakage. Sample uniformity is dependent on the integrity of the seal due to the relatively high water/cementitious material ratios. A silicone-based, mold release agent was used to minimize sample contamination.

Sample preparation included: dry blending the cement, fly ash, and sand, adding the appropriate amount of water, and hand mixing the sample to achieve a uniform, flowable mixture. All of the mix designs evaluated were self-leveling; however, each sample was vibrated on a low amplitude, low frequency vibrating table for 5-seconds to eliminate excess voids. Twelve duplicate samples were prepared for each water/cement plus fly ash, sand/cement plus fly ash, and fly ash/cement ratio corresponding to 1-, 7-, 14-, and 28-day curing.

Curing

Demolding of the samples was completed after approximately 16 to 20 hours. The samples were cured immediately upon removal from the molds. A moist room, maintained at 95% relative humidity and at 77°F (25°C), was chosen to simulate rapid “field” curing. The elevated temperature and humidity, relative to in-place backfill materials, result in slightly higher short-term compressive strengths, as reported in this study.

Test Procedure

Compressive strength tests were performed according to ASTM Standard C 109-88 (Standard Method of Test for Compressive Strength of Hydraulic Cement Mortar Using 2-inch or 50-mm Cube Specimens). A constant load rate was maintained for all specimens and all samples were tested immediately upon removal from the moist room.

Significant Engineering Properties

In addition to compressive strength, several other engineering properties significantly affect the performance of flowable fill including the degree of self-leveling and densification, segregation potential, and excessive bleeding. These parameters are somewhat subjective and depend on the method and type of placement.

Flowable fill is designed to be self-leveling and able to achieve reasonable density without external consolidation. The mix designs evaluated in this study are self-leveling in a laboratory environment.

The segregation potential of flowable fill is dependent on the relative proportions of cement and fly ash, sand, and water. Due to the cohesive nature of the cement and fly ash paste, and the relatively small aggregate, segregation is rarely a problem in flowable fill. No appreciable segregation was noted for the mix designs evaluated.

Excessive bleeding in flowable fill is possible due to the relatively high water/cementitious material ratio. This behavior was noted for several of the mix designs evaluated. If bleeding potential exists, it tends to occur immediately after placement.

RESULTS

The results of the compressive strength tests are presented in Table 5 and Figures 1 through 24. A minimum of three tests were conducted for each mix design and curing period. The Coefficient of Variation (C.O.V.) values shown in Table 5 indicate that there is significant error associated with testing low strength materials at early stages of curing. If the difference in the three test results was deemed significant, additional samples were prepared and tested.

The observed trends in the data include: increased compressive strength with decreased water/cement plus fly ash ratio, decreased fly ash/cement ratio, and increased curing times. There is no clearly defined trend in the sand/cement plus fly ash data. The rate of strength gain is a combination of mix design parameters and cannot be accurately predicted from the data obtained.

Segregation was not observed in any of the mix designs evaluated either during casting or on examination following testing. Bleeding was observed in samples with a water/cement plus fly ash ratio exceeding 0.8 regardless of the other mix design parameters. All of the mix designs evaluated are self-leveling.

CONCLUSIONS AND RECOMMENDATIONS

The results of this study may be used to estimate mix proportions corresponding to desired levels of compressive strength and strength gain. Several alternatives exist for each criteria, allowing the supplier to choose the mix design that is the most economical to produce. It is emphasized that the results presented in this paper are based entirely on laboratory tests and for the specific materials evaluated; in-service conditions may differ significantly.

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TABLE 1 — TYPE I CEMENT COMPOSITION

Chemical Constituent	Percent
SiO_2	21.27
Al_2O_3	4.93
Fe_2O_3	2.04
CaO	64.40
MgO	2.32
SO_3	3.01
Na_2O	0.33
K_2O	0.59
C_3S	56
C_2S	19
C_3A	10
C_4AF	7
Blaine =	3460

TABLE 2 — CLASS C FLY ASH COMPOSITION

Chemical Constituent	Percent
SiO_2 ; Al_2O_3 ; Fe_2O_3	62.16
SO_3	2.57
MgO	4.92
CaO	25.95

TABLE 3 — SAND GRADATION

Sieve Size	Percent Passing	Specification (Percent Passing)
3/8 inch	100	100
No. 4	100	95-100
No. 16	84	45-85
No. 50	13	5-30
No. 100	2.1	0-10
No. 200	0.9	0-3

TABLE 4 — MIX DESIGN DATA

Sample Designation	Water; Cement Plus Fly Ash	Sand; Cement Plus Fly Ash	Fly Ash; Cement
1	0.6	5;1	3;1
2	0.6	5;1	4;1
3	0.6	5;1	5;1
4	0.6	5;1	6;1
5	0.6	6;1	3;1
6	0.6	6;1	4;1
7	0.6	6;1	6;1
8	0.6	6;1	6;1
9	0.6	7;1	3;1
10	0.6	7;1	4;1
11	0.6	7;1	5;1
12	0.6	7;1	6;1
13	0.6	8;1	3;1
14	0.6	8;1	4;1
15	0.6	8;1	5;1
16	0.6	8;1	6;1
17	0.7	5;1	3;1
18	0.7	5;1	4;1
19	0.7	5;1	5;1
20	0.7	5;1	6;1
21	0.7	6;1	3;1
22	0.7	6;1	4;1
23	0.7	6;1	5;1
24	0.7	6;1	6;1
25	0.7	7;1	3;1
26	0.7	7;1	4;1
27	0.7	7;1	5;1
28	0.7	7;1	6;1
29	0.7	8;1	3;1
30	0.7	8;1	4;1
31	0.7	8;1	5;1
32	0.7	8;1	6;1
33	0.7	9;1	7;1
34	0.7	9;1	8;1
35	0.7	9;1	9;1
36	0.7	10;1	7;1
37	0.7	10;1	8;1
38	0.7	10;1	9;1
39	0.7	11;1	7;1
40	0.7	11;1	8;1
41	0.7	11;1	9;1
42	0.8	5;1	3;1
43	0.8	5;1	4;1
44	0.8	5;1	5;1
45	0.8	5;1	6;1
46	0.8	6;1	3;1
47	0.8	6;1	4;1
48	0.8	6;1	5;1
49	0.8	6;1	6;1

TABLE 4 cont. — MIX DESIGN DATA

Sample Designation	Water; Cement Plus Fly Ash	Sand; Cement Plus Fly Ash	Fly Ash; Cement
50	0.8	7;1	3;1
51	0.8	7;1	4;1
52	0.8	7;1	5;1
53	0.8	7;1	6;1
54	0.8	8;1	3;1
55	0.8	8;1	4;1
56	0.8	8;1	5;1
57	0.8	8;1	6;1
58	0.8	9;1	7;1
59	0.8	9;1	8;1
60	0.8	9;1	9;1
61	0.8	10;1	7;1
62	0.8	10;1	8;1
63	0.8	10;1	9;1
64	0.8	11;1	7;1
65	0.8	11;1	8;1
66	0.8	11;1	9;1
67	0.9	9;1	7;1
68	0.9	9;1	8;1
69	0.9	9;1	9;1
70	0.9	10;1	7;1
71	0.9	10;1	8;1
72	0.9	10;1	9;1
73	0.9	11;1	7;1
74	0.9	11;1	8;1
75	0.9	11;1	9;1
76	1.0	9;1	7;1
77	1.0	9;1	8;1
78	1.0	9;1	9;1
79	1.0	10;1	7;1
80	1.0	10;1	8;1
81	1.0	10;1	9;1
82	1.0	11;1	7;1
83	1.0	11;1	8;1
84	1.0	11;1	9;1

TABLE 5 — COMPRESSIVE STRENGTH TEST DATA

Sample	Compressive Strength (psi)							
Designation	1 Day	C.O.V.	7 Day	C.O.V.	14 Day	C.O.V.	28 Day	C.O.V.
1	89	2.4	110	3.7	272	2.9	645	3.1
2	93	2.8	133	3.1	189	2.6	479	0.7
3	127	3.3	142	1.2	170	2.0	363	1.6
4	144	1.2	169	2.9	173	1.3	252	2.6
5	70	10.0	88	4.4	218	5.3	469	11.9
6	73	4.5	109	0.4	149	6.7	445	6.6
7	95	13.9	135	6.8	172	2.9	356	4.3
8	118	7.6	164	2.6	171	3.9	291	5.0
9	69	8.1	120	1.8	225	4.6	612	1.0
10	109	7.2	159	2.7	160	9.7	413	9.4
11	119	8.6	144	2.7	167	8.5	343	11.2
12	128	2.8	161	0.8	162	5.2	276	2.7
13	61	10.2	112	4.7	245	4.4	409	10.8
14	87	3.4	135	4.0	167	7.7	335	11.6
15	79	4.7	115	3.3	164	2.6	234	6.0
16	92	4.7	130	1.8	177	5.6	237	10.3
17	67	4.4	80	3.7	194	4.4	499	5.8
18	87	5.0	112	4.4	144	2.9	366	1.5
19	97	2.5	129	3.4	146	3.6	318	2.3
20	105	2.0	124	5.3	129	0.7	250	4.3
21	74	2.3	95	4.7	180	8.4	500	1.0
22	98	2.5	143	0.3	142	3.4	364	3.3
23	102	1.2	123	5.8	134	5.2	249	3.4
24	116	5.6	136	5.9	125	0.7	217	1.9
25	74	0.6	98	2.7	221	10.0	471	4.1
26	93	2.2	129	1.7	141	7.4	328	2.5
27	101	4.5	105	3.8	137	7.8	277	2.0
28	97	3.4	114	5.4	127	6.2	220	0.9
29	53	3.8	78	3.2	194	4.0	341	3.6
30	74	9.3	98	2.5	134	2.4	294	1.8
31	68	3.7	77	15.8	97	4.9	150	1.8
32	99	3.6	115	2.5	135	2.5	204	13.1
33	54	16.0	88	3.3	110	0.4	148	6.1
34	50	7.1	98	11.2	124	7.0	150	3.3
35	69	9.0	104	6.6	127	5.8	141	6.4
36	71	3.0	73	7.6	107	3.1	121	7.5
37	74	4.8	95	4.1	98	2.7	134	5.2
38	74	3.3	96	7.0	108	6.3	154	4.1
39	56	13.3	73	7.3	102	2.5	132	3.4
40	64	6.4	81	4.8	104	4.3	120	2.7
41	60	9.5	70	9.5	87	7.4	106	5.4
42	50	3.3	70	5.4	182	7.7	413	4.8
43	66	1.2	95	5.6	119	2.2	300	2.9
44	73	8.4	100	0.8	129	4.8	217	3.1
45	85	4.6	102	0.9	113	4.7	188	3.9
46	57	5.2	65	3.2	165	5.3	349	1.1
47	65	1.3	92	3.2	124	7.2	271	9.6
48	73	3.0	94	0.9	118	12.2	222	2.0
49	75	1.3	87	2.7	107	0.9	212	1.4

TABLE 5 cont. — COMPRESSIVE STRENGTH TEST DATA

Sample Designation	Compressive Strength (psi)							
	1 Day	C.O.V.	7 Day	C.O.V.	14 Day	C.O.V.	28 Day	C.O.V.
50	48	2.6	61	4.8	141	4.4	288	2.6
51	66	4.5	87	2.0	101	4.9	242	3.9
52	74	4.0	96	1.5	105	4.7	243	3.1
53	80	0.6	80	6.3	104	6.4	208	2.2
54	45	12.2	85	1.5	105	6.5	286	7.2
55	59	7.8	60	6.3	96	4.3	256	1.0
56	54	4.9	78	6.5	117	4.6	202	1.2
57	67	2.5	90	5.2	100	3.7	171	4.4
58	61	5.4	80	2.7	87	3.3	120	0.7
59	56	12.4	66	27.1	104	4.4	128	4.0
60	67	0.0	79	2.6	94	0.9	122	3.9
61	55	3.4	84	4.4	95	3.6	118	13.7
62	61	4.8	84	3.4	95	3.6	130	6.3
63	61	3.5	88	6.3	114	4.4	144	4.4
64	52	5.0	81	3.8	108	2.6	124	4.2
65	60	4.2	78	1.2	92	7.3	107	7.1
66	59	0.8	71	2.0	102	1.8	107	7.1
67	62	9.2	86	4.5	109	2.4	128	7.0
68	65	6.6	83	2.1	107	2.3	121	5.2
69	61	4.1	73	1.1	91	1.0	119	7.2
70	49	7.6	73	5.1	89	2.8	115	2.1
71	47	8.0	69	1.8	85	6.6	86	6.8
72	51	4.0	78	5.0	89	5.6	88	1.1
73	36	7.9	58	3.7	70	6.5	88	1.1
74	38	11.9	59	3.5	66	2.8	91	10.4
75	37	5.8	49	7.3	64	8.3	83	5.5
76	40	6.6	56	6.0	70	3.8	78	2.8
77	51	1.8	60	3.1	78	3.8	94	3.5
78	55	6.0	59	4.5	79	2.1	92	2.3
79	34	5.5	54	7.6	63	1.5	83	6.5
80	39	2.4	53	3.2	66	4.3	77	6.1
81	47	4.6	60	4.8	72	5.6	92	5.1
82	38	5.7	52	4.7	64	6.4	78	1.2
83	39	2.1	50	7.8	60	2.1	74	4.6
84	37	6.8	51	5.1	64	2.6	73	3.9

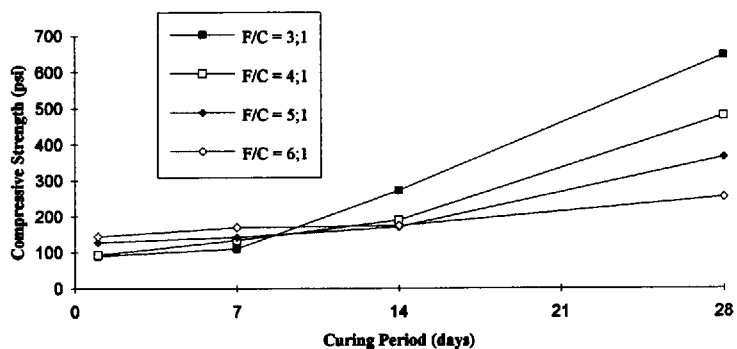


Fig. 1—W/C + F = 0.6, S/C + F = 5;1

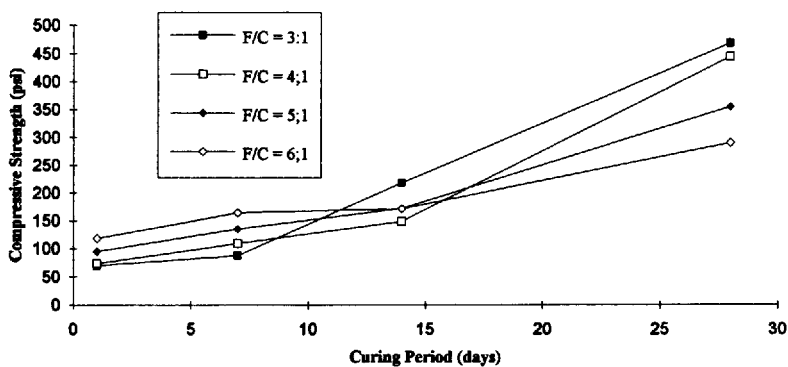


Fig. 2—W/C + F = 0.6, S/C + F = 6;1

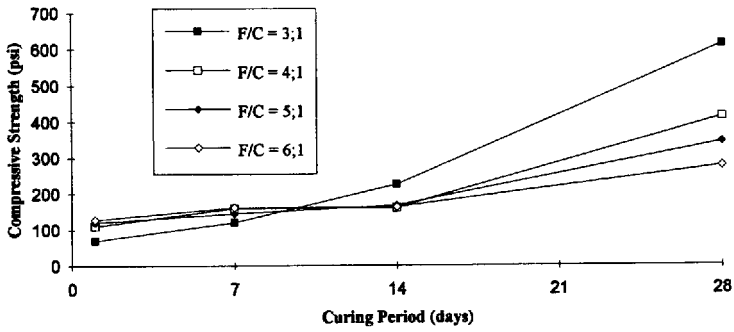


Fig. 3—W/C + F = 0.6, S/C + F = 7;1

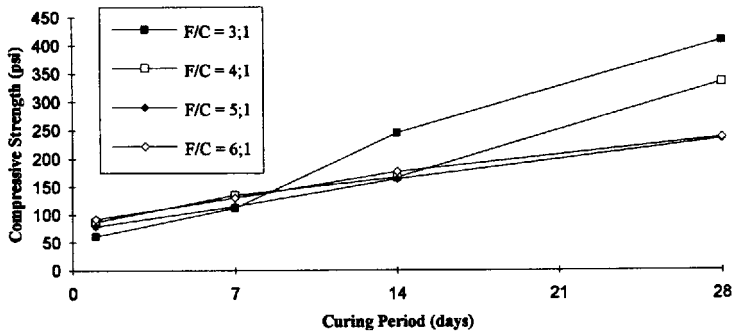
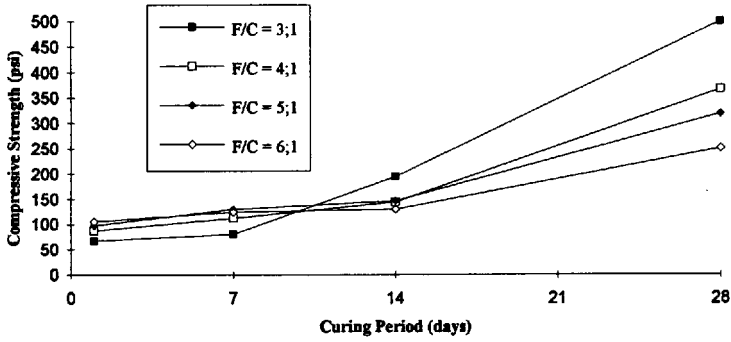
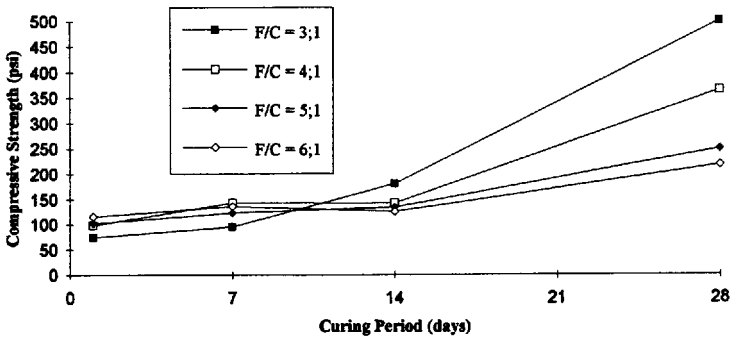


Fig. 4—W/C + F = 0.6, S/C + F = 8;1

Fig. 5— $W/C + F = 0.7, S/C + F = 5;1$ Fig. 6— $W/C + F = 0.7, S/C + F = 6;1$

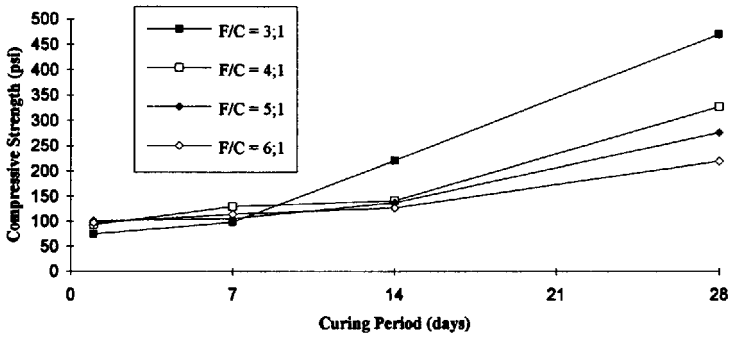


Fig. 7—W/C + F = 0.7, S/C + F = 7;1

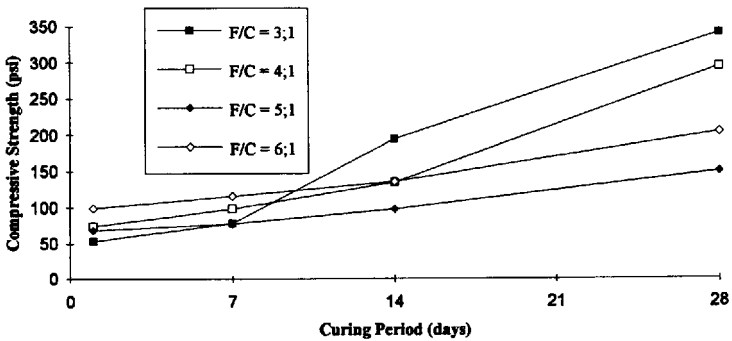


Fig. 8—W/C + F = 0.7, S/C + F = 8;1

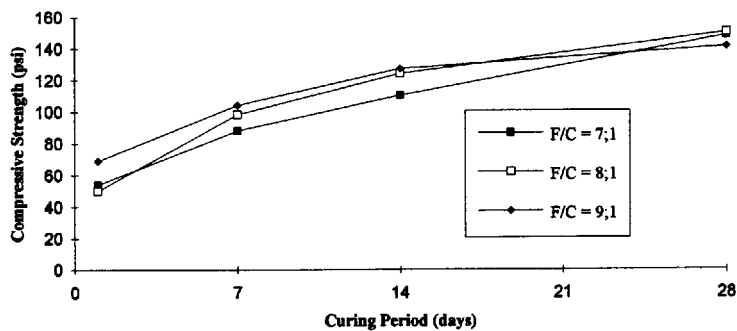


Fig. 9—W/C + F = 0.7, S/C + F = 9;1

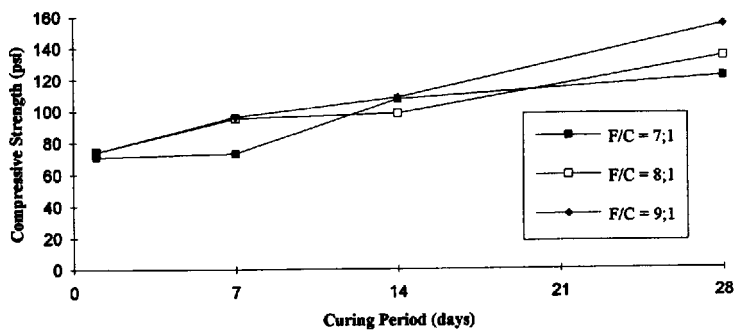


Fig. 10—W/C + F = 0.7, S/C + F = 10;1