

Experiences in the Use of Superplasticizers in Some Special Fly Ash Concretes

*By Kirsten Eriksen and
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Synopsis: Use of a naphtalene-based superplasticizer at high dosages in concretes made with fly ash (100-150 kg/m³) and a moderate content of portland cement (250-300 kg/m³) results in great water reductions and high strengths (75-80 MPa after 28 days) for concretes with normal workability (slump 5-10 cm). Laboratory investigations concerning mixture proportions and properties of the fresh and hardened concretes with a discussion of physical and chemical influences of the use of the superplasticizer are presented.

Increasing problems with the supply of good, inexpensive, natural coarse aggregates may be solved through combined additions of superplasticizers and fly ash to the concrete. This paper further presents experimental evidence of mixture proportions and physical data for so-called "sand-concrete", i.e. concrete without coarse aggregates but with "normal" contents of portland cement and water obtained by the addition of rather large amounts of fly ash and superplasticizers.

Keywords: coarse aggregates; compressive strength; fly ash; high-strength concretes; mix proportioning; naphthalene compounds; plasticizers; portland cements; water-reducing agents; workability.

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INTRODUCTION

The present paper is divided into two parts, both dealing with the use of rather large dosages of superplasticizer in concretes which contain fairly high quantities of fly ash.

The first part describes an experimental investigation of "normal" concrete prepared with a cement to fly ash ratio of approximately 2:1. The second part deals with an investigation of "sand-concrete" so called, because the cement/fly ash-bound material is manufactured without coarse aggregate. It has structural properties similar to those of conventional concrete.

EXPERIMENTS WITH SUPERPLASTICIZED FLY ASH CONCRETE

At the Cement and Concrete Laboratory of Aalborg Portland A/S investigations of superplasticizing admixture as water reducer has been carried out on fly ash concretes with moderate cement content producing high strength concrete with normal workability.

The aim of the investigations has been to obtain information on the properties of such concretes in the fresh and hardened state so that customers could be advised about the proper use of superplasticizers also in specialty concretes.

Materials, Experimental Procedures and Results

The two fly ashes designated as "A" and "B" used in the experiments originated from two different batches of the Danish power plant Masnedøværket. Details of composition and other characteristics are given in Table 1. Both fly ashes conform to ASTM C-618.

Only one Type III rapid hardening portland cement, conforming to ASTM C-150, was used.

The aggregates consisted of 47 weight percent quartz sand (0-4 mm) and 53 percent crushed granite (8-16 mm). The grading curve, Fig. 1, was the same throughout the investigations.

The superplasticizer used is the sodium salt of a synthetic naphthalene sulfonic acid polymer of Japanese origin. It is supplied as 42 weight percent aqueous dark brown solution under the Danish trade name of CemMix. All dosages of CemMix reported in the present section are given as weight of dry CemMix as a percentage of the cement plus fly ash weight.

Preliminary tests have been conducted in determining a suitable composition of aggregates. This has been done in concretes containing 450 kg cement per m^3 . Overdosing of CemMix (up to 1.6 percent) to secure maximal dispersion and thus minimizing the paste content (the water content) has taken place considering that the concrete should possess good workability properties and show no sign of bleeding or segregation. Concerning the workability, the German flow table (1) has been used and the spread value aimed at was $350 \text{ mm} \pm 30 \text{ mm}$. This means that the concrete can be easily placed with normal vibration equipment.

For this type of concrete with 450 kg cement per m^3 and a consistency as the abovementioned the water demand has been established for various dosages of CemMix (including 0 percent).

In the fly ash experiments it was decided to use 130 kg m^3 of fly ash, maintain the spread value at approximately 350 mm, maintain the grading of aggregates and then find what cement content would give the fly ash concrete the same workability properties and appearance as the plain concrete. The cement content for the fly ash (A) concrete was found to be 270 kg per m^3 which means a reduction in fines equal to 50 kg per m^3 compared to the plain mixes.

In the fly ash (B) concretes the same composition, 130 kg fly ash and 270 kg cement per m^3 , was maintained. Here a lower water demand was observed.

Again the water reducing effect of various dosages of CemMix was investigated for fly ash (A) and fly ash (B) concretes while the consistency was held constant.

Selected compositions of plain mixes, fly ash (A) and fly ash (B) mixes appear from Table 2. In Fig. 2 the water reduction curves for increasing CemMix dosage is drawn for the three types of concretes.

Cylinders (100/200 mm) were cast for compressive strength measurements on some of the concretes containing fly ash. These results also appear in Table 2. The cylinders were stored in air at 20°C for 24 hours, then demoulded and cured under water at 20°C until the time of testing. Only two cylinders have been tested per test date.

Heat evolution in kJ per kg cement plus fly ash and heat evolution rates have been measured by adiabatic calorimetry for two fly ash (A) concretes with 0 percent and 0.8 percent CemMix, respectively, see Table 2 and the Fig. 3 and 4.

Finally, two fresh fractures of fly ash (A) concretes, age 28 days, with 0.2 percent and 1.2 percent CemMix, respectively, have been looked at qualitatively in a scanning electron microscope with EDAX analyser (SEMEX). Fig. 5 and 6 show micrographs at 1000x magnification typical for the specimens.

Discussion

Water reduction, workability and mix design--
Owing to the lubrication effect of the fly ash particles it was possible with addition of 130 kg per m³ of fly ash (A) to reduce the cement content from 450 kg per m³ to 270 kg per m³ in obtaining the same appearance and workability properties in the fresh state as was found for the plain concrete. Without superplasticizer, the water demand for fly ash (A) concrete and the plain concrete are almost identical.

Fly ash (B) concretes have a lower water demand in general which can be subscribed to a lower loss on ignition and a little less residue on the 45 micron sieve than fly ash (A). Rasmussen (2) has found correlation between these factors and water demand.

The addition of CemMix results in water reductions which are ultimately higher for the fly ash concretes than the plain concretes. The results for a dosage of 1.2 percent CemMix are 40 percent water reduction for fly ash (A) and (B) concretes compared to the plain concrete, where 35 percent reduction was obtained. In none of the concretes further water reduction exceeding the 1.2 percent dosage are obtained which confirms earlier observations at our laboratory concerning maximal dispersing effect in normal concretes. For low dosages of CemMix the water reductions are higher in fly ash (A) mixtures than in the other mixtures. This can be explained by the fact that the cement and cement plus fly ash (B) concentrations in the paste are higher than in the fly ash (A) mixtures.

At the high dosages there appears to be an extra effect concerning workability from the fly ash particles. This can be expressed as the dispersed fly ash particles give an even greater effect concerning workability than dispersed cement particles do.

These findings are not in accordance with the conclusions that Lane and Best (3) have drawn concerning water reducing ability of superplasticizers in fly ash concretes, where they have found reductions not exceeding 15 percent for equal slumps. This can be explained by the composition of their concretes (a much lower cement content) and smaller dosages of superplasticizer. If a lean concrete gets too much dispersing agent, segregation results.

Compressive strength, heat evolution and morphology--The strength results indicate that it is possible with high CemMix dosages to obtain relatively high compressive strengths, especially at later ages. This, of course, is connected with the large water reductions and low water-cement ratios but also the fly ash plays a role, indirectly by making the water reductions exceed what is else obtainable, directly by contributing to the strength gain one way or another.

One day strengths are low with high CemMix dosages owing to the retarding effect which is well known at these dosage levels.

Obtaining 28 days' strengths near 80 MPa with only 270 kg cement per m^3 plus 130 kg fly ash per m^3 where usually a cement content of 450 to 500 kg per m^3 has been necessary even with the use of superplasticizers when good workability properties had to be maintained, indicate that fly ash particles have a better filler effect than unhydrated cement grains.

Heat evolution curves (kJ/kg cement + fly ash) have been measured under adiabatic conditions. Two concretes with fly ash (A), the one without CemMix, the other with a dosage of 0.8 percent and with water contents of 180 l/m^3 respectively 123.5 l/m^3 have been determined as seen in Fig. 3 and 4.

The heat evolution is reduced by 15 percent when reducing the water content looking at the final heats. This is in accordance with other results when reducing the water-cement ratio from 0.7 to 0.5 in normal concretes (4).

As the two concretes have exactly the same contents of cement and fly ash - but definitely different strength results - the measurements clearly demonstrate

that there are great possibilities in using superplasticizers when you wish to reduce temperature problems in hardening concrete.

Combined use of a superplasticizer and fly ash can be exceedingly beneficial compared to plain concretes if one considers strength and heat evolution. The limits for maximum content of fly ash will be set from other reasons than these.

The retarding effect of CemMix at high dosages can be seen in the rate curves (dQ/dt) where the water reduced concrete is retarded by up to approximately 12 hours.

Fig. 5 shows fly ash (A) concrete, age 28 days, and CemMix content equal to 1.2 percent. Fig. 6 shows fly ash (A) concrete, at the same age, and with a dosage of 0.2 percent.

A general impression was that the fly ash particles were much more dispersed in the high dosage concrete which also was to be expected. Many fly ash surfaces looked totally unaffected or unreacted, but all analyses showed qualitatively a bigger content of calcium than was to be expected from the fly ash composition. A closer look showed occasionally Type I gel formations on several particles. These observations are in accordance with the findings of Diamond et al. (5), referring to the formation of so-called duplex layers, although not observed here to the same extent.

EXPERIMENTS WITH SAND-CONCRETE

In the present paper, the term "Sand-Concrete" is used to describe a material consisting of Portland cement, water, aggregates, and additives, in which the contents of cement and water are at the level of conventional concrete whereas the content of *coarse* aggregates is zero.

The background of the experiments described below is the fact that there are, in many parts of the world, increasing problems with the supply of good, natural coarse aggregates for concrete production, whereas the resources of fine aggregates (sand) quite often are extensive. Furthermore, fine aggregates are normally considerably cheaper than coarse aggregates.

The purpose of the present investigation, therefore, was to examine whether it is possible, without the use of coarse aggregates, to make concrete which through the addition of superplasticizing agents and fillers (in particular pulverized fly ash) requires

similar quantities of cement and water as conventional concrete to achieve plastic consistency in the fresh state, and which exhibits similar structural properties as conventional concrete in the hardened state. As well known, cement mortar requires far more cement and water than concrete, and consequently shows a much greater drying shrinkage than concrete. Thus, cement mortar is not a suitable material for structural purposes.

Materials, Mix Proportions, and Tests

Ordinary Portland cement (conforming to the requirements of ASTM Spec. C150, Type I), fly ash "A", commercial pit sand with a residue on the 2 mm sieve of 5 percent, and a superplasticizer of the naphthalene sulfonic acid type (trade name in Denmark: CemMix) were used in the tests. Further details of the materials are given in Table 1.

Three different concrete mixtures were tested: A) a mixture with a rather high cement content (350 kg/m^3), B) a mixture as A with air-entrainment, and C) a mixture with a relatively low cement content (175 kg/m^3). Details of the mix proportions and of the properties of the fresh concrete are given in Table 3. It appears from the table that relatively big quantities of fly ash (about 200 kg/m^3) and superplasticizer (about 1 percent on solid substance basis) were added to the mixtures to achieve suitable consistency and workability.

Of each mixture, two batches were manufactured. From each batch a total of 12 cylinders ($100 \times 200 \text{ mm}$) were cast for compressive strength testing and for measurement of the stress-strain curves 1, 7, 28 and 91 days. Furthermore, a total of three $40 \times 40 \times 160 \text{ mm}$ prisms for measurement of the drying shrinkage.

The cylinders for strength and stress/strain testing were demoulded after 24 hours and then cured under water at 20°C until the time of testing. During the compressive strength testing of each cylinder, the stress/strain curve was recorded automatically by means of a special equipment which measures the strain over a gauge length of 70 mm. From each stress/strain graph the secant modulus of elasticity $E_{0.3}$ (defined as the secant through origo and the curve at the stress level of 0.3 times the failure stress) and the strain ϵ_u at maximum stress level were determined.

The prisms for shrinkage measurement were demoulded after 24 hours and then stored under water at 20°C until an age of 28 days. They were then stored in the laboratory (temperature: $20 \pm 1^\circ\text{C}$, relative humidity:

65 ± 5 percent), and measurements of length changes were started. At intervals, during a period of about 90 days, the distance between the end points of cast-in gauge studs was measured, and the shrinkage in percent calculated.

Test Results

The average results of the compressive strength, the modulus of elasticity, and the rupture strain are given in Table 4, and strength curves are presented in Fig. 7 together with the strength curve of conventional concrete of the same cement content (350 kg per m³) and the same type of cement as used in the present tests.

The compressive strengths versus the reciprocal of water-cement ratio, c/w , are plotted in Fig. 8; c/w being calculated as

$$c/w = \frac{C + kF}{W + A}$$

where C, F and W are the cement, fly ash, and water contents in kg per m³, A the air content in liter per m³, and k the "activity index" of the fly ash, which here arbitrarily is taken to be 0.25.

The modulus of elasticity is somewhat lower than for ordinary concrete which has an elastic modulus of the order of 30,000 - 40,000 MPa. The ultimate strain, on the other hand, is somewhat greater than for conventional concrete which normally is considered to have an ultimate strain of the order of 0.2 percent.

The results of the measurements of the drying shrinkage exhibited large variations between similar test prisms. Due to these variations, no significant difference between the shrinkage of the prisms from the three mixtures could be ascertained. Consequently, all the results applying to the same test age were used to calculate a mean value. These mean values versus time are plotted in Fig. 9.

Discussion of Results

As seen from Table 4, the rich mixtures (A and B) gave *compressive strengths* at 28 days of the same order as conventional concrete. At early ages, a somewhat lower strength level whereas at later ages a considerably higher strength level were obtained than with conventional concrete. The strength reduction caused by the high air content (5-7 percent) was more than compensated by the strength increase contributed by the pozzolanic action of the fly ash. The lean mixture

(C), however, yielded a somewhat lower compressive strength than would be obtained with conventional concrete of the same cement content. This might be due to a too high fly ash to cement ratio.

The Bolomey plot in Fig. 8 has been supplemented by test results on sand-concrete obtained by Andersen (6). Also for his tests a value of 0.25 for the fly ash activity index k was used for calculation of the $(c + kf) / (w + a)$ ratio. As seen from Fig. 8, a straight line

$$f_c = K \left(\frac{c + kf}{w + a} - 0.5 \right)$$

through 0.5 at the c/w -axis (to compare with the conventional Bolomey line) seems to fit the results quite well where the constant K takes the value of approximately 38 MPa. For comparison, it can be mentioned that the value of K is of the order of 25 MPa for conventional concrete made with the same cement.

As appears from Fig. 9, the *drying shrinkage* after drying out for 3 months at 20°C and 65 percent relative humidity was about 0.06 - 0.07 percent. Conventional concrete with the same water and cement contents as in the present tests will, according to (7) have a drying shrinkage of approximately 0.07 percent.

CONCLUSIONS

For the two limited experimental investigations reported above, the following conclusions may be drawn:

1. The dispersive action of a superplasticizing admixture is considerably greater in concrete mixtures which incorporate fly ash than in comparable concrete mixtures without fly ash.
2. This fact may be utilized to produce high-strength concrete with moderate cement content (250 - 300 kg per m^3) but with rather high dosages of fly ash (cement to fly ash ratio of the order of 2:1) and superplasticizer.
3. Similarly, this fact may be utilized to produce sand-concrete, i.e. "concrete" to which no coarse aggregates have been added but which, nevertheless, yield approximately the same structural properties (strength, shrinkage) as conventional concrete.

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TABLE 1
Material data of cements, fly ashes and sand*

Cements	Clinker composition (%)				Specific surface (m ² /kg)								
	C ₃ S	C ₂ S	C ₃ A	C ₄ AF									
Type I	55	20	8	8	319								
Type III	53	21	8	8	409								
Fly ashes	Chemical composition (%)									Loss on ignition (%)	Specific surface (m ² /kg)	Residue on 45 micron sieve (%)	Apparent density (kg/m ³)
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O	TiO ₂				
(A)	53.3	25.7	8.5	5.2	3.2	0.9	2.8	0.8	-	4.8	438	14.4	2363
(B)	53.3	24.6	8.6	5.5	3.3	1.0	2.5	0.9	0.9	2.6	458	11.6	2413
Sand*	Residue (%) on sieve												
	8 mm	4 mm	2 mm	1 mm	0.5 mm	0.25 mm	0.125 mm						
	1	5	10	21	53	87	99						

* sand used in sand-concrete

TABLE 2
Mixture proportioning and test results

Series	Mixture no.	Cement content (kg/m ³)	Fly ash content (kg/m ³)	Water content (kg/m ³)	CemMix (%solid of cement + fly ash)	Water-cement- ratio	Water-(cement+ fly ash)-ratio	Spread value (mm)	Slump (mm)	Air content (%)	Compressive strengths (MPa)				
											1 day	3 days	7 days	14 days	28 days
Plain	P11	450	-	178	0	0.395	-	330	40	1.3	-	-	-	-	-
"	P3	450	-	115	1.2	0.255	-	335	-	1.5	-	-	-	-	-
Fly ash (A)	A2	270	130	180	0	0.67	0.45	350	85	1.3	12.2	25.1	32.0	34.8	37.9
"	A4	270	130	162.5	0.2	0.60	0.41	345	75	1.4	13.0	26.6	29.9	36.4	39.5
"	A6	270	130	123.5	0.8	0.46	0.31	380	-	2.1	21.3	-	49.7	56.5	62.3
"	A3	270	130	108	1.2	0.40	0.27	320	-	2.0	6.8	42.5	52.1	60.8	65.4
Fly ash (B)	B27	270	130	157.5	0	0.58	0.39	355	80	1.3	-	25.2	-	38.8	47.3
"	B28	270	130	95	1.2	0.35	0.24	320	50	2.2	-	45.7	-	65.0	78.3

TABLE 3

Mixture proportions and data for the fresh sand-concrete

		Mix A	Mix B	Mix C
Mixture proportions (kg/m ³)	Cement (C)	348	339	174
	Fly ash (F)	199	194	198
	Water (W)	186	181	186
	Sand	1482	1443	1627
	Superplasticizer (solid substance)	2.7	2.6	1.7
	Air entrain. agent	0	0.17	0
Fresh Concrete data	Slump (mm)	130	140	45
	Air content (A) (%)	4.8	7.2	5.2
	Density (kg/m ³)	2220	2160	2190

Note: All figures are averages of data for two batches.

TABLE 4
Test results for sand-concrete

Age	Comp. Strength (MPa)			Elastic Modulus (10^4 MPa)			Rupture strain (%)		
	Mix A	Mix B	Mix C	Mix A	Mix B	Mix C	Mix A	Mix B	Mix C
1 day	9.9	8.5	1.8	1.41	1.39	0.43	0.36	0.28	0.53
7 days	29.4	27.2	7.6	2.44	2.46	1.43	0.32	0.29	0.27
28 days	44.7	40.3	12.7	2.58	2.68	1.56	0.35	0.29	0.29
91 days	59.9	54.1	22.0	3.33	x) 3.20	x) 2.60	0.29	xx) 0.27	xx) 0.28

Note: All figures are averages of 6 single observations, except those marked x) (average of 3 observations) and xx) (only one observation).

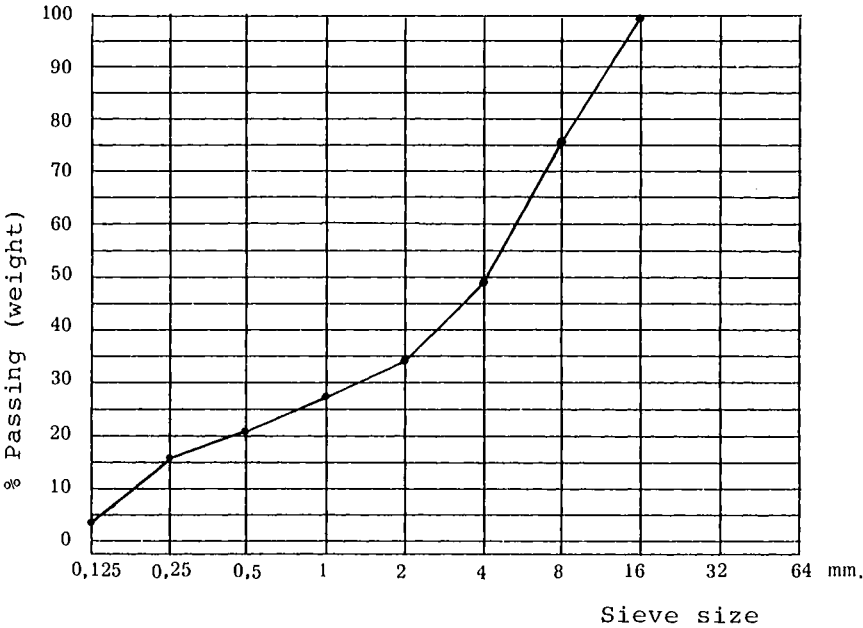


Fig. 1--Grading curve for total aggregate

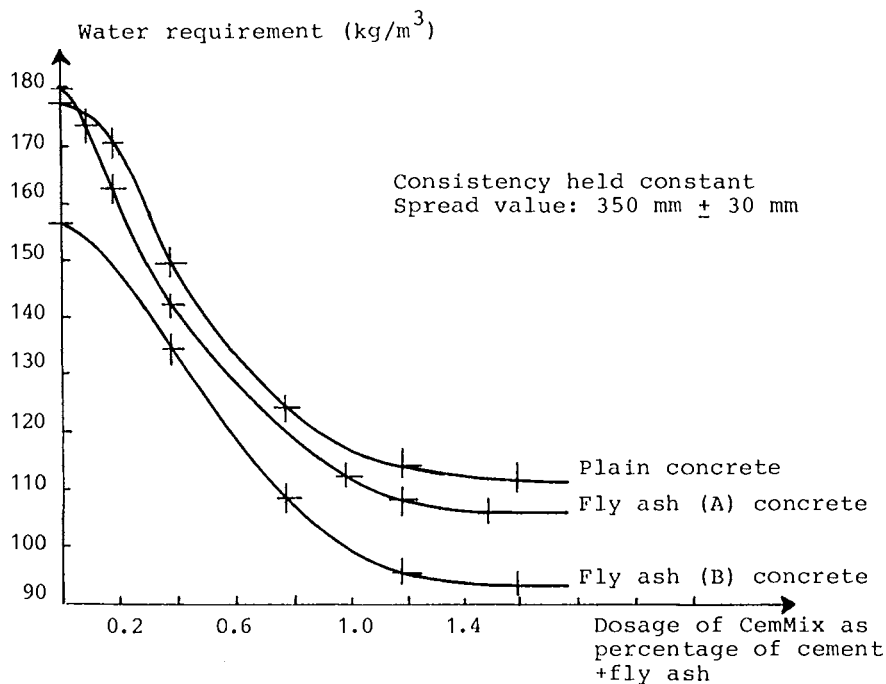


Fig. 2--Water reduction, constant workability

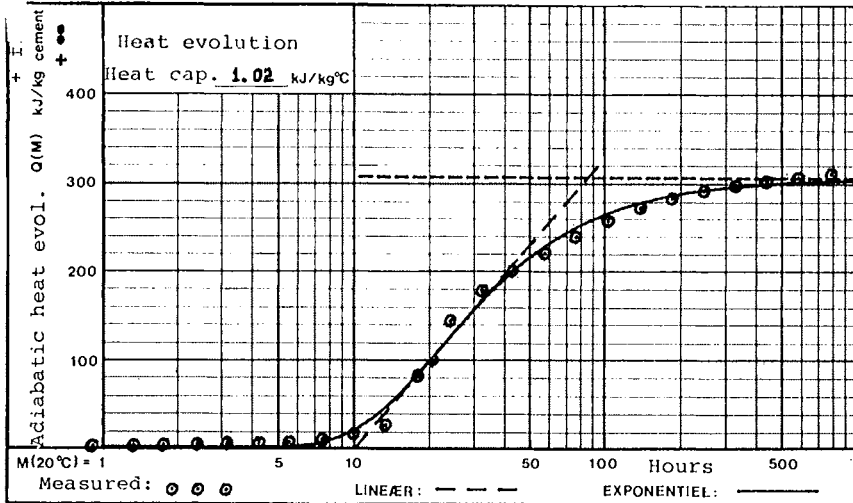
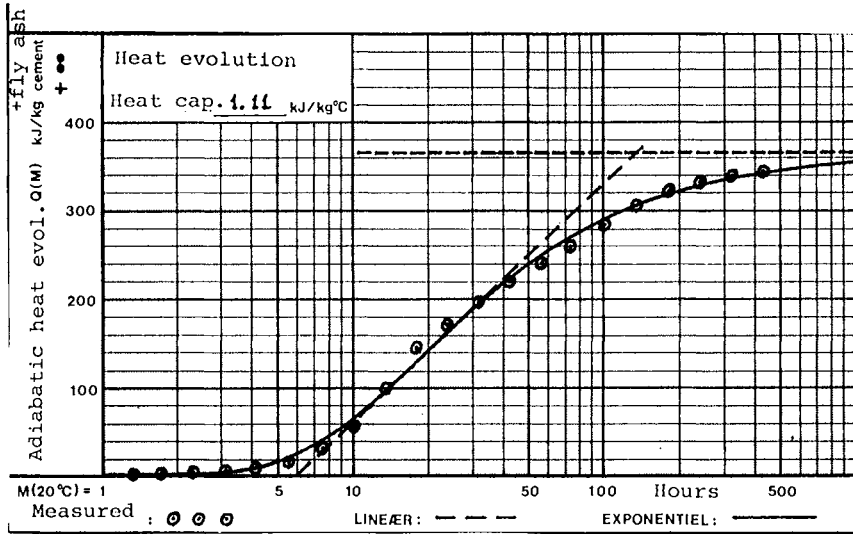


Fig. 3--Heat evolution, 0 percent CemMix

Fig. 4--Heat evolution, 0.8 percent CemMix

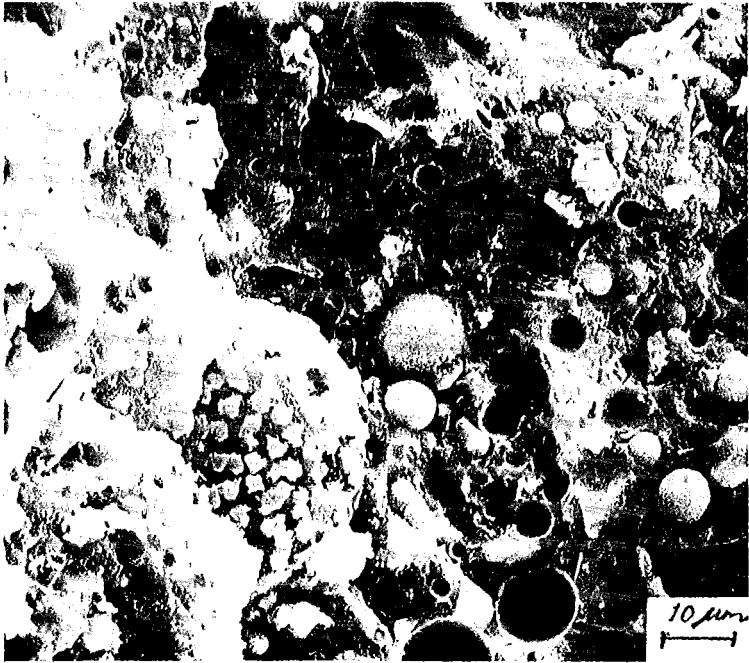


Fig. 5--SEMEX micrograph 1000x, 28 days, fly ash (A), 1.2 percent CemMix

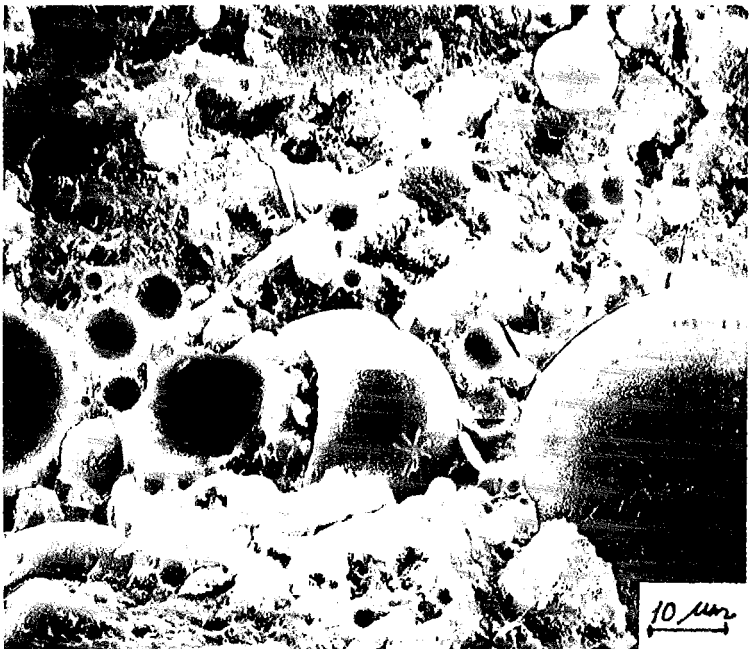


Fig. 6--SEMEX micrograph 1000x, 28 days, fly ash (A), 0.2 percent CemMix

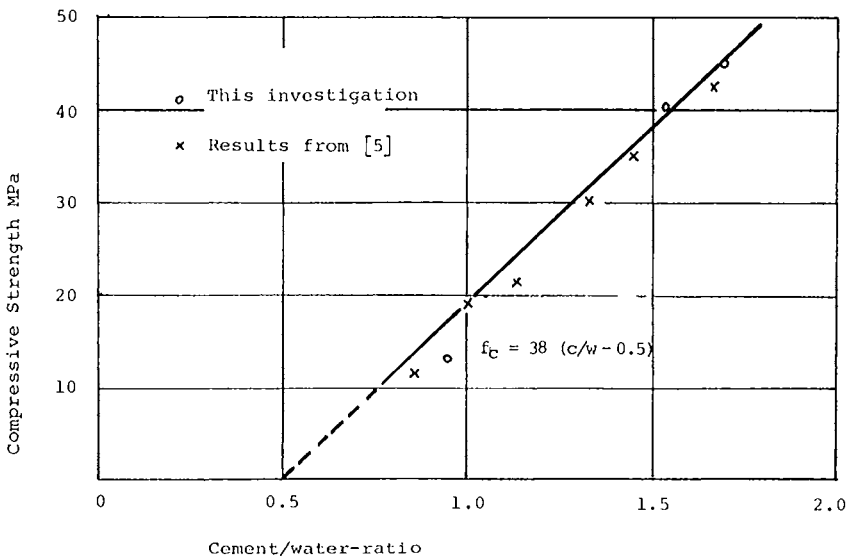
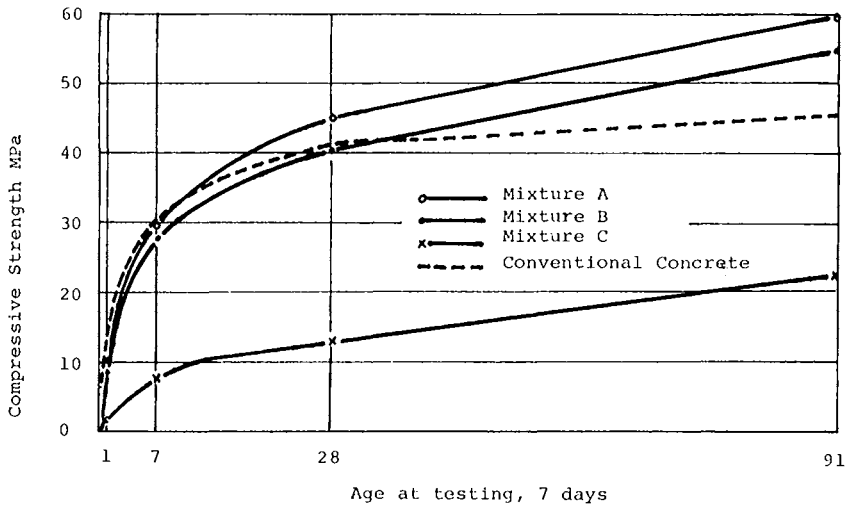


Fig. 7--Change of compressive strength with time. The curve for the conventional concrete applies to concrete with same cement content as mixtures A and B

Fig. 8--Relation between compressive strength and water-cement ratio for sand-concrete, the water-cement ratio being calculated as $(C + 0.25 F)/(W + A)$, cfr. Table 3. To compare with the conventional Bolomey equation, the line is drawn through 0.5 at the water-cement axis although this is not the one that best fits the test results

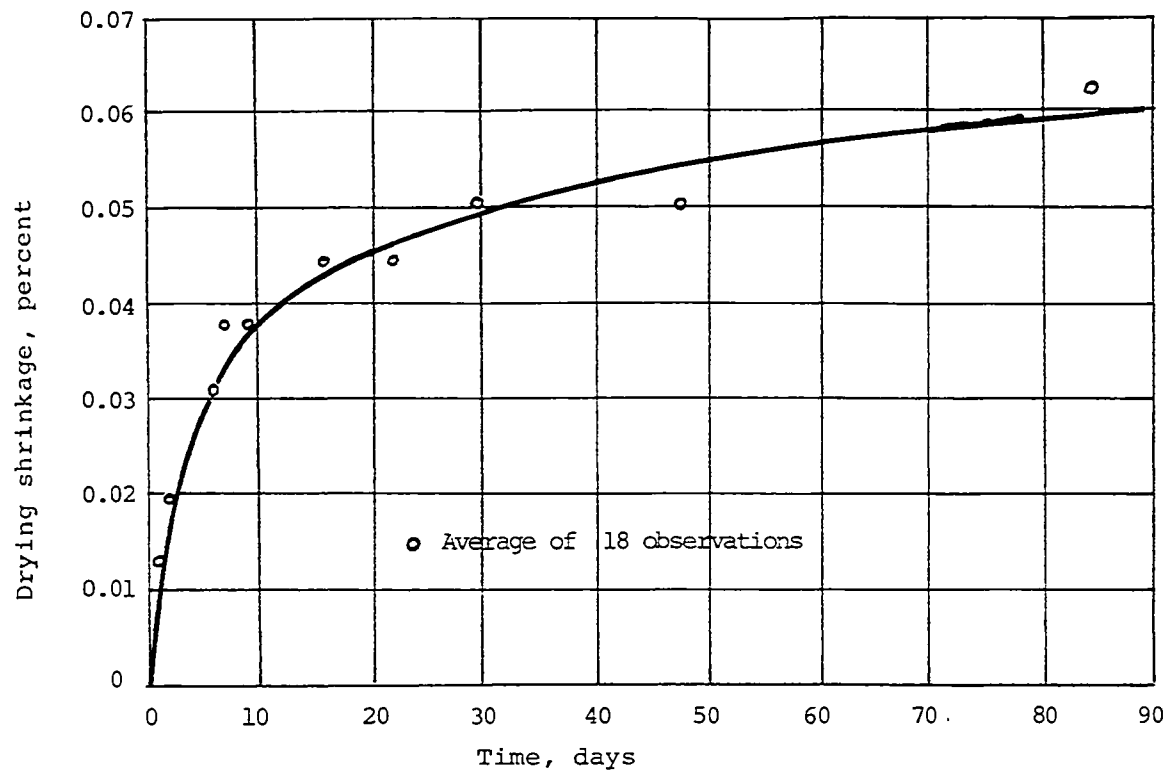


Fig. 9--Drying shrinkage of sand-concrete as a function of time from the start of drying of 40 x 40 x 160 mm prisms

Use of a Superplasticizer in the Manufacture of Extra-High-Strength Block

By Lucas E. Pfeifferberger and Thomas B. Ray

Synopsis: The purpose of this study was to examine the effect of adding various dosages of a melamine-based superplasticizer in the manufacture of extra-high strength block.

Seven batches of block were cast as follows: a) reference mixtures in which no admixture was added; b) reference mixtures using a conventional block plasticizer; c) four mixtures using various dosages of superplasticizer: 1% by weight cement, 2%, 3%, and 2% with additional water. Halfway through each batch, the feed/finish times were increased. The block were steam-cured at low pressure.

The testing program consisted of a) impact-resistance and compressive strength at 24 hours; b) absorption and unit weight; and c) compressive strengths at 7, 14, and 28 days.

All block exceeded the 5000 psi (34.5 MPa) net compressive strength requirement of extra-high strength block. The effect of the superplasticizer increased as the dosage increased. The superplasticizer also allowed for shorter feed times to achieve the same finish times.

The encouraging results of this preliminary study indicate more work needs to be done to investigate the possibility of leaner cement mixes, lower temperature curing conditions, and possibly shorter feed/finish times to achieve the economic advantages inherent with the use of superplasticizers.

Keywords: absorption; admixtures; compressive strength; concrete blocks; high-strength concretes; impact strength; manufacturing; melamine resins; mix proportioning; plasticizers.

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INTRODUCTION

The increased use of concrete masonry units for high-rise buildings and other heavy load-bearing construction has created a need for more information concerning recommended practices for manufacturing extra-high strength block, as well as concerning various admixtures that may be used to improve the efficiency in making this type block. The purpose of this study was to evaluate the effect of using a commercially available superplasticizer* in the manufacture of extra-high strength block.

Superplasticizers have been used during the last decade in the ready-mixed concrete industry as a plasticizing agent which produces a flowing concrete. In ready-mixed concrete, the admixture acts as a dispersant to provide fluidity, but at the same time has a cohesive effect which prevents segregation. In addition, the dispersive action allows for more surface area of the cement to be in contact with water. Therefore, once the plasticizing effect of the superplasticizer subsides, hydration of the cement can take place more rapidly, resulting in higher early strengths.

For block manufacturing, it was theorized that a superplasticizer would plasticize the mix to allow for greater compaction. In addition, higher early strengths would allow safe handling of the block.

* Melment L10, manufactured by American Admixtures and Chemicals Corporation, Chicago, Illinois

SCOPE OF INVESTIGATION

The goal of the study was to produce block having a net compressive strength exceeding 5000 psi (34.5 MPa). (1)

Mixture Ratio

Sinnicks(2) reports various mixture designs which have successfully produced extra-high strength block with low pressure curing. The range of cement-to-aggregate ratios reported was 1:4.8 to 1:10.0. The Besser Company (3) recommends a cement-to-aggregate ratio of 1:6 to 1:8 in the manufacture of split block. Taking into consideration this information, a ratio of 1:7 was chosen. ASTM Type III (high early strength) cement was used to insure high strength within 28 days.

Aggregate

The aggregate was a blend of sand and stone having an average fineness modulus of 3.67, based on the sieve analysis of four of the seven batches. A combined graph of the four sieve analyses is given in Figure 1. Although the combined aggregate exceeded desired limits for some sieves, it was believed to represent a blend which might realistically be encountered.

Admixture

The quantity of superplasticizer was proportioned as a percentage of the cement content by weight. With little data available in using superplasticizers for block manufacture, a dosage of 2% was chosen since that dosage is frequently used for ready-mixed concrete. Additional dosages of 1% and 3% were chosen to bracket the 2% addition. The second dosage of 2%, but with additional water, was decided on after manufacturing had begun. This was at the recommendation of the batch man, who felt the mixture could handle more water and still retain shape after de-molding.

Machining

In the manufacture of block, the total vibration time is a combination of the feed time, finish time, and delay time. The feed time is the time during which the drawer holding the concrete is above the molds, allowing concrete to enter the molds. The finish time is

the time during which the compression head is pressing the concrete into molds. The delay time is the length of time during which the mold is vibrated to allow the block to be removed from the mold without sticking. It is generally accepted that the longer the vibration time during molding, the higher the density and, correspondingly, the compressive strength of the block. To further study this principle, two different feed times and finish times were used with each batch. For the mixtures without the superplasticizer (A, B, and G), the first half of each batch was molded with a 2.5 second feed and 3.0 second finish time. The remaining half was made with a 3.0 second feed and 4.0 second finish time.

For the superplasticized batches (C, D, E, and F), the feed times were decreased to 2.0 seconds and 2.5 seconds since the desired 3.0 and 4.0 second finish times could not be achieved with longer feed times. Shorter feed/finish times are designed "I" batches, longer times as "II" batches.

The testing program consisted of a) impact resistance at 24 hours; b) absorption and unit weight; and c) compressive strength at 1, 7, 14, and 28 days.

MANUFACTURING PROCEDURE

A total of seven batches of 8"x8"x16" (20.3 cm x 20.3 cm x 40.6 cm) standard 2-core block were processed. Control batches with no admixture were designated batches A and G. These control batches were run at the beginning of manufacturing and at the end to compensate for any possible changes caused by room temperature or moisture content of the aggregate. Batch B contained 2 oz./100 lbs. cement (130.4 ml/kg) of a conventional block plasticizer*. The superplasticized batches were as follows:

Batch C	-	2% by weight cement
Batch D	-	3% by weight cement
Batch E	-	1% by weight cement
Batch F	-	2%, but wetter than C

Each batch was made in a 30 cu.ft. (0.85 cu.m.) mixer with a 1:7 cement-to-aggregate ratio which resulted in the following mixture: 350 lbs. (158.8 kg.) Type III cement, 708 lbs. (231.1 kg.) stone (moist), 1807 lbs. (819.6 kg.) sand (moist).

* Mark V as sold by Forrer Chemical, Butler, Wisconsin

Mixing times were controlled to four minutes after water was added. Equal amounts of water could not be used in all batches because of the effects the admixtures had on the flowability of the concrete.

A standard three (3) at-a-time 8"x8"x16" (20.3 cm x 20.3 cm x 40.6 cm) 2-core mold on a Besser V3-12 Vibrac was used for manufacturing the block. The unaltered mechanical cycle for this machine was 6.5 seconds including a 1.0 second delay time. A summary of cycling time and corresponding production rates appears in Table II.

Twenty-four (24) pallets, with three block to a pallet, were manufactured for each batch. For complete information, see Table I.

The block were steam-cured for five hours during which time the temperature uniformly rose to 165-170⁰F (73.9-76.7⁰C). During the additional fifteen hour soaking period, the temperature gradually dropped to 115⁰F (46.1⁰C). (Figure 2). After being removed from the kiln, the block were stored inside.

TEST PROCEDURE

Blocks having 3.0 and 4.0 second finish times were used for test evaluation. The units were carefully selected, free of cracks and broken corners, to correspond with the production settings set forth in Table I. The following tests were performed: Resistance to Impact, Absorption and Unit Weight, and Compressive Strength.

Resistance to Impact

This test is used to predict if the block can be handled for cubing and storage without damaging the corners*. Four batches with a 3.0 second finish time were chosen for this test. The block had been cured for approximately 20 hours. Three block were tested from each batch.

Absorption and Unit Weight

Absorption and Unit Weight tests were conducted according to ASTM C-140. A total of six (6) block were tested from each batch: three with a 3.0 second finish time and three with a 4.0 second finish time. The block

* For complete description of the "Resistance to Impact" test, see Appendix A.

were at various ages between 14 and 28 days.

Compressive Strength

The Compressive Strength tests were conducted at ages of 1, 7, 14, and 28 days. Unfortunately, only four batches were tested at 1 day and only from the 3.0 second finish times. Block tested at 7, 14, and 28 days were stored inside, free to dry out under ambient conditions.

Compressive strength testing was conducted according to A.S.T.M. C-140, except that the block had to be cut in half at 7, 14, and 28 days due to the capacity of the compression machine. Two full-sized block were tested at 7 days resulting in damage to the shear pin of the compression machine each time. After cutting, the front half of the block were used as that is the weaker half.

For the 1-day tests, three block were used and the average of the three reported. For the 7, 14, and 28-day testing, six block were tested.

DISCUSSION OF RESULTS

Resistance to Impact

Evaluation of the Resistance to Impact shows that all the block easily met the requirement of 70.0 deci.ft. lbs./sq.in. (0.015 MJ/sq.m.)* not only for fracture, but for cracking as well. (Figure 3). This block could obviously be handled without fear of damage at 24 hours. Ranked in order, Batch F (with the 2% superplasticizer wetter mix) was the best performer followed closely by Batch D (with 3% superplasticizer), then Batch G (the second reference batch), and finally Batch E (1% superplasticizer). The Resistance to Impact test was only performed on Batches D, E, F, and G.

Unit Weight and Absorption

Analysis of the Unit Weight and Maximum Absorption tests showed some unexpected results. (Figures 4 and 5 and Table I) Generally, increased vibration time (feed/finish) should result in higher unit weight and lower absorption. Batch A, the first reference mix, showed the opposite. However, the other batches exhibited

*This value has been determined by the Besser Company as the minimum required to allow for safe handling of the block after curing. See Appendix A.

results one would expect with Batch F, the wetter 2% superplasticizer at 4.0 second finish time, having the least percent maximum absorption. All of the block easily met the A.S.T.M. C-90 requirement of no more than 13 lb./ft.³ (208.26 kg./m.³) absorption.

Compressive Strength

Compressive Strength testing was done at 24 hours, 7, 14, and 28 days (Table I and Figures 6-9). Only four batches were tested at 24 hours and all of these were at a 3.0 second finish time. Batch D, with 3% superplasticizer, tested at 4981 psi (34.3 MPa), virtually exceeding at 1 day the 5000 psi (34.5 MPa) hoped for in ultimate strength.

At 7 days, all of the block surpassed the 5000 psi (34.5 MPa) hoped for. At the 3.0 second finish time, Batches D and F (3% superplasticizer and 2% wetter superplasticizer) both tested around 7000 psi (48.3 MPa). At the 4.0 second finish time, the 3% superplasticizer mixture and the second reference mix showed the greatest increase in strength, approximately 700 psi (4.8 MPa).

At 14 days and a 3.0 second finish time, once again Batch D (3% superplasticizer) was clearly the strongest, breaking at around 8300 psi (57.2 MPa). The increased feed/finish time did not appear to have as much of an effect on the block at 14 days as it did at 7 days. Batch D continued to be the strongest at 8300 psi (57.2 MPa).

The data at 28 days showed some unexpected results. With eight different batches tested, one or two of the six breaks occurred at considerably lower loads than other breaks in the same series. This also occurred with four batches at 14 days. These values were rejected through statistical analysis(4). However, even after rejecting the extraneous values, six of the thirteen batches tested at 28 days showed a decrease in strength between 14 and 28 days. Subsequent examination of the compression machine clearly indicated that the shear pin had been bent and was deteriorating, which caused improper loading of the specimens. Hence, the authors view the 28 day results as highly suspect.

CONCLUSIONS

Based on the limited test data, the following tentative conclusions can be drawn:

- 1) At 24 hours, the use of the superplasticizer did significantly increase compressive strength at 1%, 2%, and 3% addition rates.
- 2) The superplasticized mixture at a 3% dosage rate was clearly the best performer at all ages.
- 3) The 2% superplasticized mixtures also performed well in terms of 14 day strengths. The wetter 2% mixture performed better at a shorter vibration time.
- 4) The superplasticized mixtures allowed the block to be made at a shorter feed time, resulting in a time of production savings of about 4%.
- 5) With the wetter 2%, and the 3% dosage rates of the superplasticizer, longer total vibration time did not appear to increase ultimate (14-day) strengths.
- 6) The basic mixture proportions could have been altered to a leaner (less cement) mixture since even the reference mixtures easily met the 5000 psi (34.5 MPa) requirement.

The study raised more questions which should be addressed with future investigations:

- 1) When using a superplasticizer, how lean of a cement-to-aggregate ratio can be used and still achieve 5000 psi (34.5 MPa) block?
- 2) Can satisfactory results be achieved using a normal ASTM Type I cement rather than a Type III?
- 3) Considering the relatively high 24-hour strengths of all the block, is it possible to cure the block at lower temperatures resulting in energy savings?
- 4) Can the extra-high strength block be made with an even lower machining time?
- 5) Can a superplasticizer be used in conjunction with a normal-type block plasticizer to achieve optional machining time and compressive strength?

These and other questions need to be studied to more fully determine the economic advantages inherent in the use of superplasticizers in the block industry.

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APPENDIX A

Resistance to Impact Test

This test, developed by the Besser Company, provides information regarding whether or not block can be safely handled without cracking or chipping corners*. The test consists of dropping a 0.2 lb. weight on each corner of the block at increased heights until the corner cracks and finally fractures. The force exerted by the weight falling from the various heights has been calculated and is shown in Table III.

TABLE III

Accumulative Impact for 0.2 lb. Weight

<u>Position</u>	<u>Deci.ft.lb./sq.in.</u>
1	3.3
2	10.0
3	20.0
4	33.3
5	50.0
6	70.0
7	93.3
8	120.0
9	150.0
10R	33.3 additional

If the block does not crack or fracture at position 9, then the weight is repeatedly dropped from position 10. For each impact at position 10, 33.3 deci.ft.lb./sq.in. is added to the total impact. Both the crack and fracture point is determined for each of the four corners and then averaged. This procedure is followed for three different block. Then a final average is determined from the three. A sample calculation follows:

* The following conversion factors apply throughout:
 a) to change lbs. to kg., multiply by 0.45
 b) to change deci.ft.lb./sq.in. to MJ/sq.in., multiply by 2.1×10^{-4} .

For Block No. H12-R:

<u>Corner</u>	<u>Position Causing Crack</u>	<u>Position Causing Fracture</u>
1	8	9+2R
2	9+4R	9+4R
3	9+6R	9+8R
4	9+1R	9+1R
Average	8.75+2.75R	9+3.75R

	<u>Crack</u>	<u>Fracture</u>
Average Impact Resistance: (deci.ft.lb. per sq.in.)	234	275

Discussion

To determine the average position resulting in a crack, average the whole numbers separately and then the "R" values:

$$\text{Whole numbers} - 8 + 9 + 9 + 9 = 35 \quad 35 \div 4 = 8.75$$

$$\text{"R" Values} - 0R + 4R + 6R + 1R = 11R; \quad 11R \div 4 = 2.75R$$

Therefore, 8.75 + 2.75R is the average position.

Using Table III, each "R" value is equivalent to 33.3 deci.ft.lb./sq.in. Therefore:

$$2.75R \times 33.3 = 91.575 \text{ deci.ft.lb./sq.in. (1)}$$

The whole number portion, 8.75 is 0.75 between 8 and 9. Using Table III, the difference between position 8 and 9 is 30.0 deci.ft.lb./sq.in. Therefore:

$$30.0 \times 0.75 = 22.5 \text{ deci.ft.lb./sq.in. (2)}$$

The impact from position 8 is 120 deci.ft.lb./sq.in. (3) Therefore, total impact from a position of 8.75 + 2.75R is (from equations 1, 2, and 3 above):

$$91.575 + 22.5 + 120 = 234.075 \quad 234 \text{ deci.ft.lb./sq.in.}$$

This value represents the average of the four corners of one block. The data reported in the study is the average of three different block.

The Besser Company has determined that a value of at least 70.0 deci.ft.lb./sq.in. is desired to safely handle block.

TABLE I

Data on Mixtures and Test Performance of Extra High Strength Concrete Units

Average Values of Units Made With 3.0 Seconds Finish Time

Batch No. (a)	Admixture (b)	Feed Time (sec.)	Concrete Moisture Content (c)	Oven Dry Weight Of Block (lbs.)	Maximum Absorption %	lb./cu.ft.	1 day	Compressive Strengths (Net Area), psi		
								7 day	14 day	28 day (d)
A-I	None	2.5	5.9	40.24	4.43	6.26	----	6111	7317	----
B-I	Normal Plasticizer	2.5	5.8	39.54	4.86	6.76	----	6120	6999	6529
C-I	2% Superplasticizer	2.0	5.1	39.62	4.92	6.91	----	6563	7149	7315
D-I	3% Superplasticizer	2.0	4.8	39.66	4.48	6.27	4981	6991	8356	7852
E-I	1% Superplasticizer	2.0	5.7	39.42	5.09	7.13	4313	6716	6699	7287
F-I	2% Superplasticizer (e)	2.0	5.4	39.52	4.46	6.28	4717	7019	7689	7900
G-I	None	2.5	5.8	39.84	4.59	6.48	3788	6473	6943	6580

Average Values of Units Made With 4.0 Seconds Finish Time

Batch No. (a)	Admixture (b)	Feed Time (sec.)	Concrete Moisture Content (c)	Oven Dry Weight Of Block (lbs.)	Maximum Absorption %	lb./cu.ft.	1 day	Compressive Strengths (Net Area), psi		
								7 day	14 day	28 day (d)
A-II	None	3.0	5.9	39.67	4.75	6.64	----	6622	7464	7800
B-II	Block Plasticizer	3.0	5.8	39.70	4.77	6.67	----	6034	7026	6983
C-II	2% Superplasticizer	2.5	5.1	39.82	4.75	6.66	----	6889	7629	7287
D-II	3% Superplasticizer	2.5	4.8	39.78	4.42	6.22	----	7751	8330	7254
E-II	1% Superplasticizer	2.5	5.7	39.75	5.02	7.02	----	6698	6881	7398
F-II	2% Superplasticizer (e)	2.5	5.4	40.59	3.96	5.64	----	7069	7259	7897
G-II	None	3.0	5.8	40.27	4.35	6.15	----	7116	7096	7650

NOTES:

- (a) All batches were cement-to-aggregate ratio of 1:7; 2NS sand - 1807 lbs. (moist), 31D stone - 708 lbs. (moist), Type III cement - 350 lbs.
- (b) Superplasticizer additions are percent by weight of cement. Forrer's Mark V is 2 oz./100 lbs. cement.
- (c) Value based on moisture on aggregate plus water added during mixing. Does not take into account water contained in admixture.
- (d) Evidence of eccentric loading was discovered during 28-day breaks; therefore, 28-day results are questionable. See discussion in paper under "Results".
- (e) Batches C and F differ in that F was intentionally made wetter by addition of one gallon extra water.



TABLE I
(SI Units)

Data on Mixtures and Test Performance of Extra-High Strength Concrete Units
Average Values of Units Made With 3.0 Seconds Finish Time

Batch No. (a)	Admixture (b)	Feed Time (sec.)	Concrete (c) Moisture Content (%)	Oven Dry Weight Of Block (kg.)	Maximum Absorption %	kg./cu.m.	Compressive Strengths (Net Area), MPa			
							1 day	7 day	14 day	28 day (d)
A-I	None	2.5	5.9	18.25	4.43	100.5	----	42.1	50.4	----
B-I	Normal Plasticizer	2.5	5.8	17.94	4.86	108.5	----	42.2	48.5	45.0
C-I	2% Superplasticizer	2.0	5.1	17.97	4.92	110.7	----	45.3	49.3	50.4
D-I	3% Superplasticizer	2.0	4.8	17.99	4.48	100.4	34.3	48.2	57.6	54.1
E-I	1% Superplasticizer	2.0	5.7	17.88	5.09	114.2	29.7	46.3	46.2	50.2
F-I	2% Superplasticizer (e)	2.0	5.4	17.95	4.46	100.6	32.5	48.4	55.0	54.5
G-I	None	2.5	5.8	18.07	4.59	105.8	26.1	44.6	47.9	45.4

Average Values of Units Made With 4.0 Seconds Finish Time

Batch No. (a)	Admixture (b)	Feed Time (sec.)	Concrete (c) Moisture Content (%)	Oven Dry Weight Of Block (kg.)	Maximum Absorption %	kg./cu.m.	Compressive Strengths (Net Area), MPa			
							1 day	7 day	14 day	28 day (d)
A-II	None	3.0	5.9	17.99	4.75	106.4	----	45.7	51.5	53.8
B-II	Forrer's	3.0	5.8	18.00	4.77	106.8	----	41.6	48.4	48.1
C-II	2% Superplasticizer	2.5	5.1	18.06	4.75	106.7	----	47.5	52.6	50.2
D-II	3% Superplasticizer	2.5	4.8	18.04	4.42	99.6	----	55.4	57.4	50.0
E-II	1% Superplasticizer	2.5	5.7	18.03	5.02	112.4	----	46.2	47.4	51.0
F-II	2% Superplasticizer (e)	2.5	5.4	18.41	3.96	90.3	----	48.7	50.0	54.4
G-II	None	3.0	5.8	18.27	4.55	98.5	----	49.1	48.9	52.7

NOTES:

- All batches were cement-to-aggregate ratio of 1:7; 2NS sand - 1807 lbs. (819.6 kg.) (moist), 310 stone - 708 lbs. (321.1 kg.) (moist), Type III cement - 350 lbs. (158.8 kg.)
- Superplasticizer additions are percent by weight of cement. Forrer's Mark V is 130.4 ml./kg. cement
- Value based on moisture on aggregate plus water added during mixing. Does not take into account water contained in admixture.
- Evidence of eccentric loading was discovered during 28-day breaks; therefore, 28-day results are questionable. See discussion in paper under "Results".
- Batches C and F differ in that F was intentionally made wetter by addition of 3.8 liters extra water.

TABLE II
Manufacturing Cycles and Production Rates

<u>Batch No.</u>	<u>Admixture</u>	<u>Feed Time</u>	<u>Finish Time</u>	<u>Delay Time</u>	<u>Pallet Feed</u>	<u>Length Of Cycle</u>	<u>Production Rate (Cycle Per Minute)</u>
A-I	None	2.5	3.0	1.0	5.5	12.0	5.0
B-I	Normal Plasticizer	2.5	3.0	1.0	5.5	12.0	5.0
C-I	2% Superplasticizer	2.0	3.0	1.0	5.5	11.5	5.2
D-I	3% Superplasticizer	2.0	3.0	1.0	5.5	11.5	5.2
E-I	1% Superplasticizer	2.0	3.0	1.0	5.5	11.5	5.2
F-I	2% Superplasticizer (wetter)	2.0	3.0	1.0	5.5	11.5	5.2
G-I	None	2.5	3.0	1.0	5.5	12.0	5.0

Batches Made With 4.0 Second Finish

<u>Batch No.</u>	<u>Admixture</u>	<u>Feed Time</u>	<u>Finish Time</u>	<u>Delay Time</u>	<u>Pallet Feed</u>	<u>Length Of Cycle</u>	<u>Production Rate (Cycle Per Minute)</u>
A-II	None	3.0	4.0	1.0	5.5	13.5	4.4
B-II	Normal Plasticizer	3.0	4.0	1.0	5.5	13.5	4.4
C-II	2% Superplasticizer	2.5	4.0	1.0	5.5	13.0	4.6
D-II	3% Superplasticizer	2.5	4.0	1.0	5.5	13.0	4.6
E-II	1% Superplasticizer	2.5	4.0	1.0	5.5	13.0	4.6
F-II	2% Superplasticizer (wetter)	2.5	4.0	1.0	5.5	13.0	4.6
G-II	None	3.0	4.0	1.0	5.5	13.5	4.4

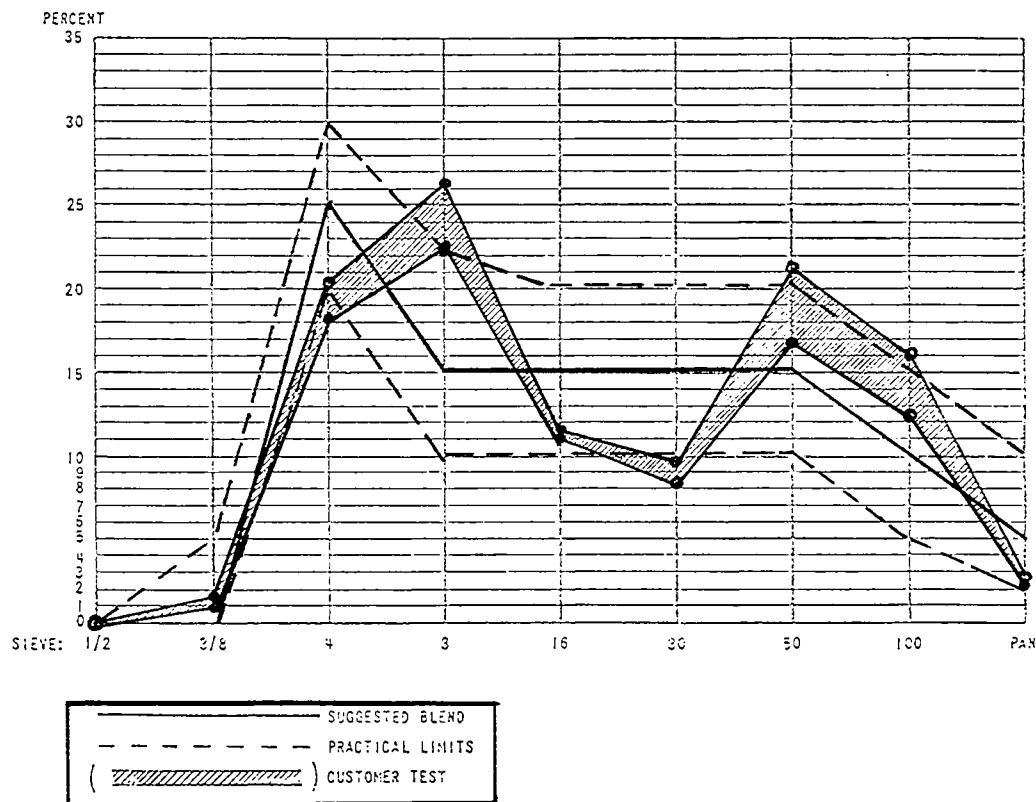


Figure 1 - Graph of Four Sieve Analyses of Aggregate

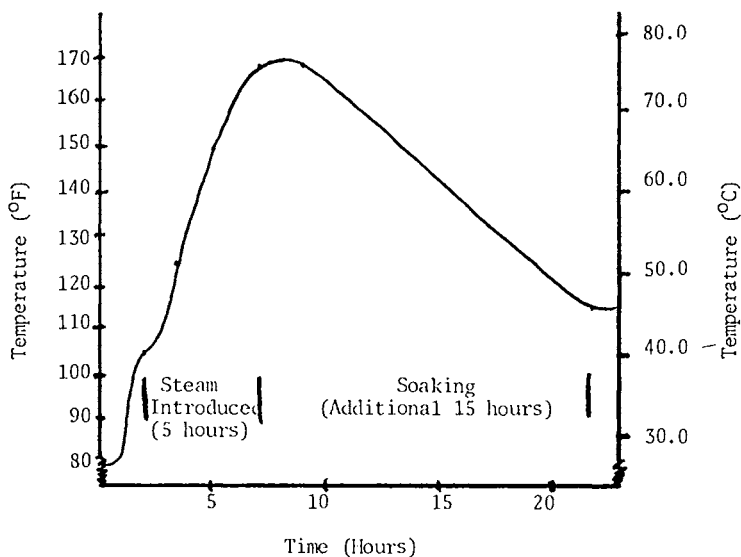


Figure 2 - Kiln Temperature

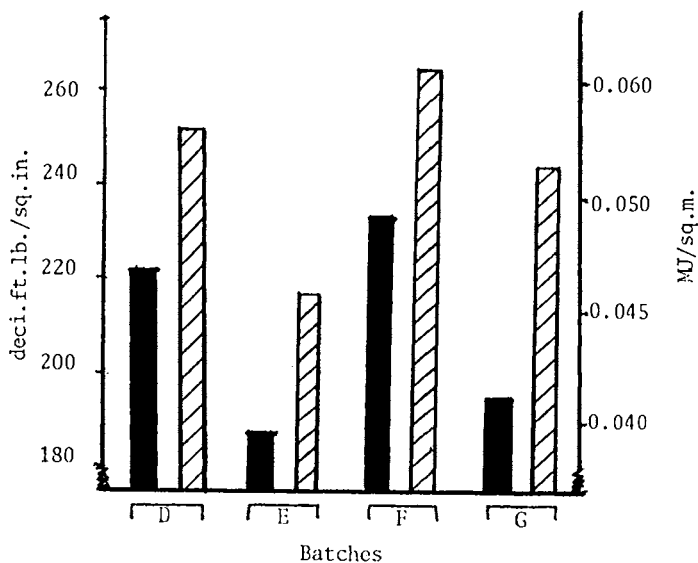


Figure 3 - Resistance To Impact



Crack



Fracture

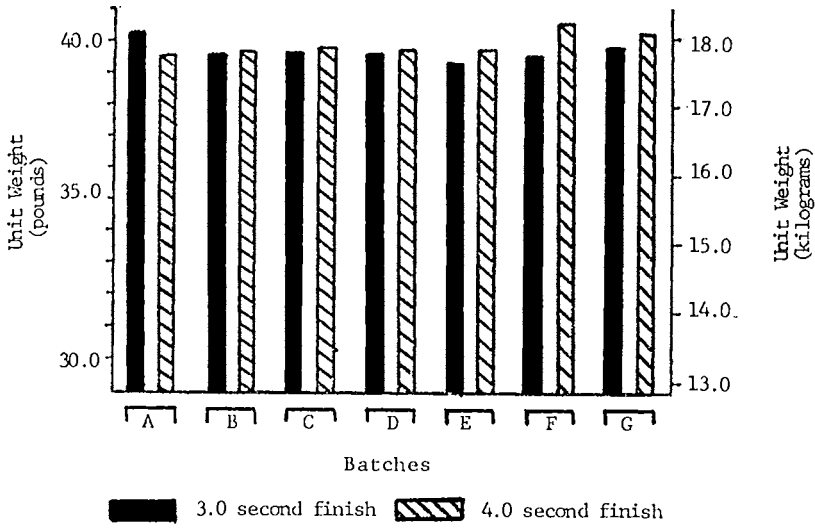


Figure 4 - Unit Weight of Block (Oven Dry)

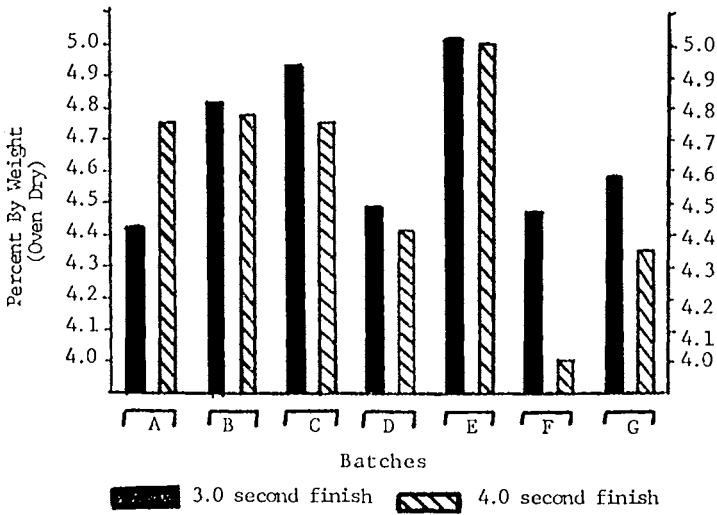
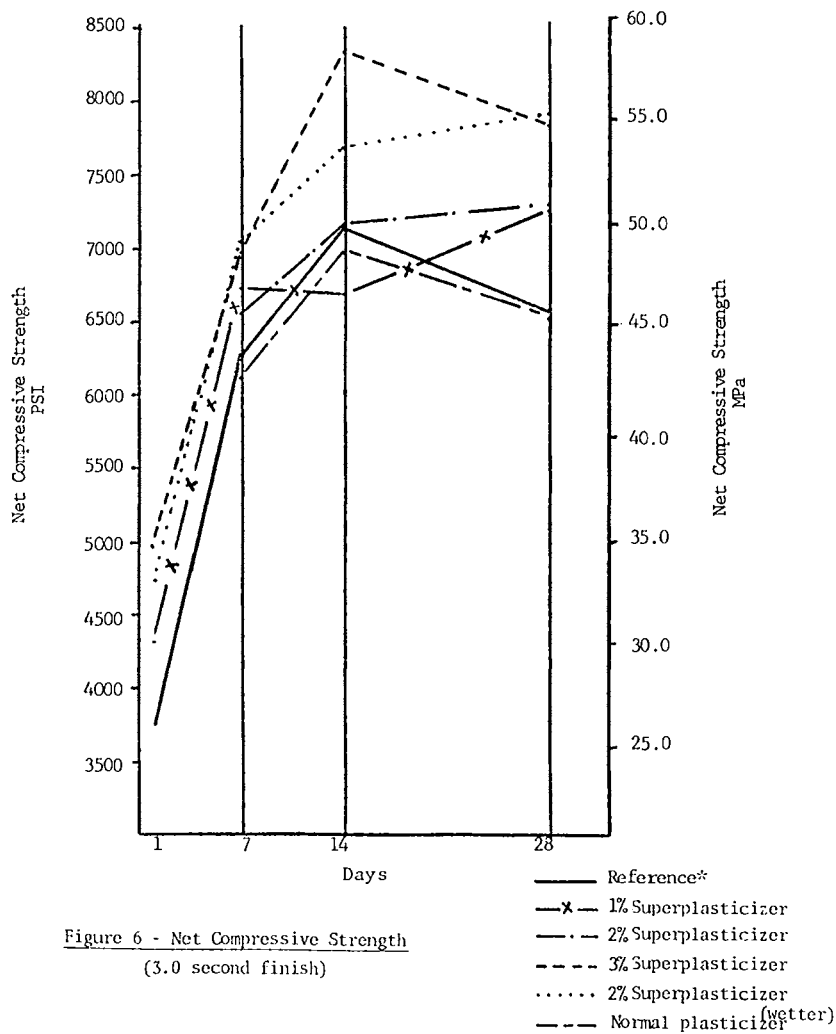
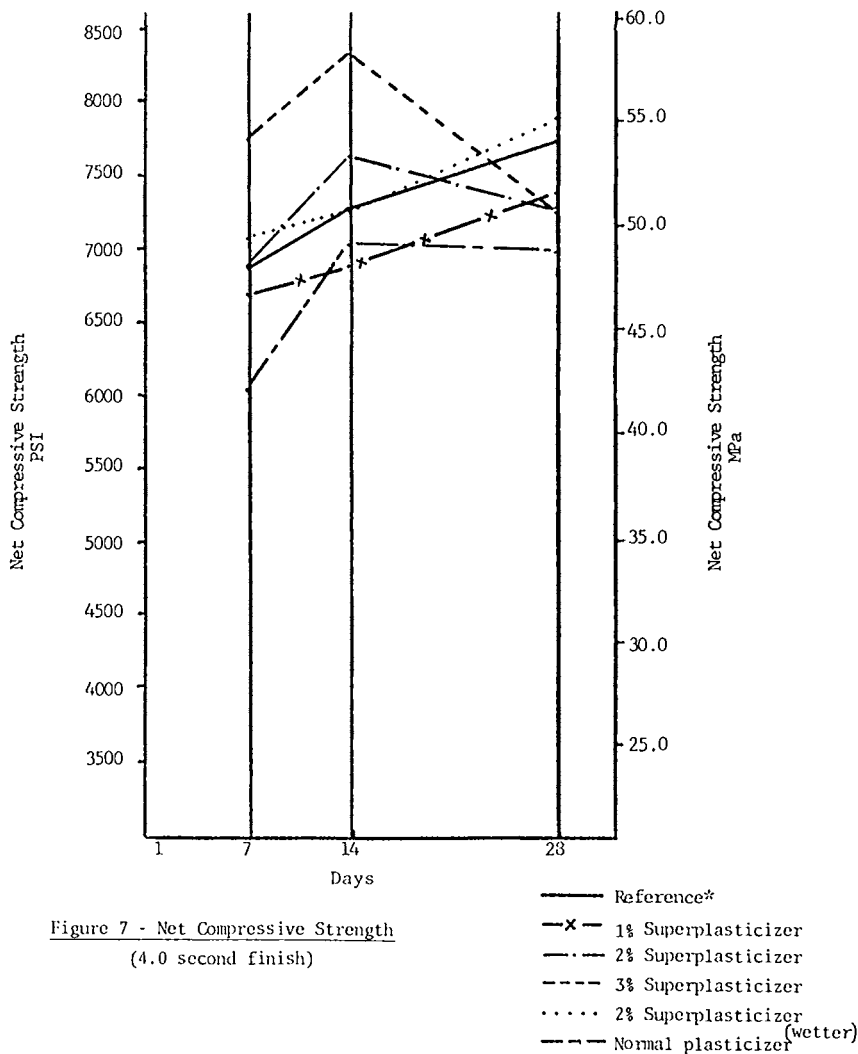


Figure 5 - Maximum Absorption



* For "Reference" curve, values for Batches A and G were averaged



* For "Reference" curve, values for Batches A and G were averaged

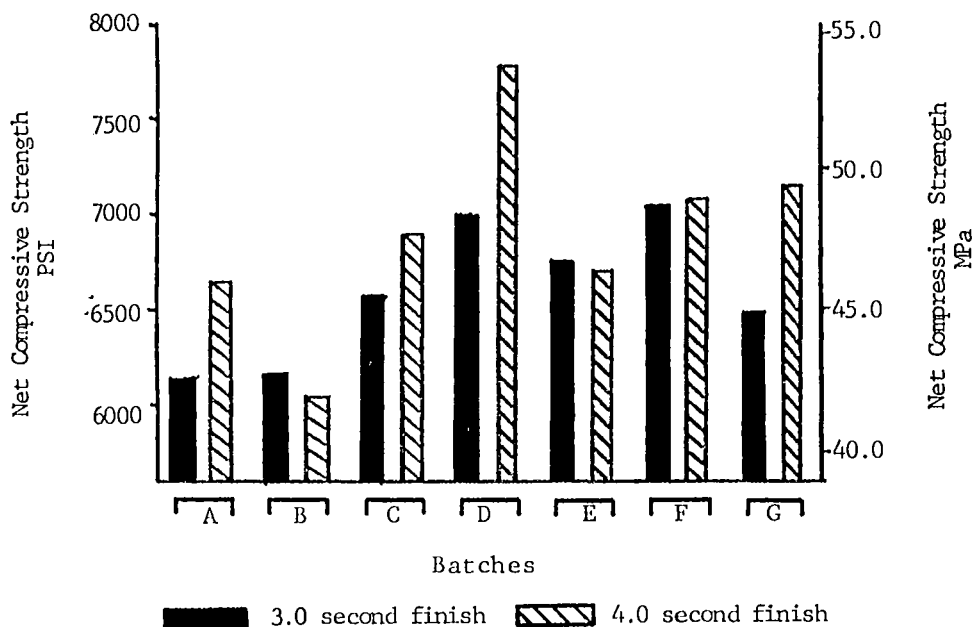


Figure 8 - 7-Day Compressive Strength

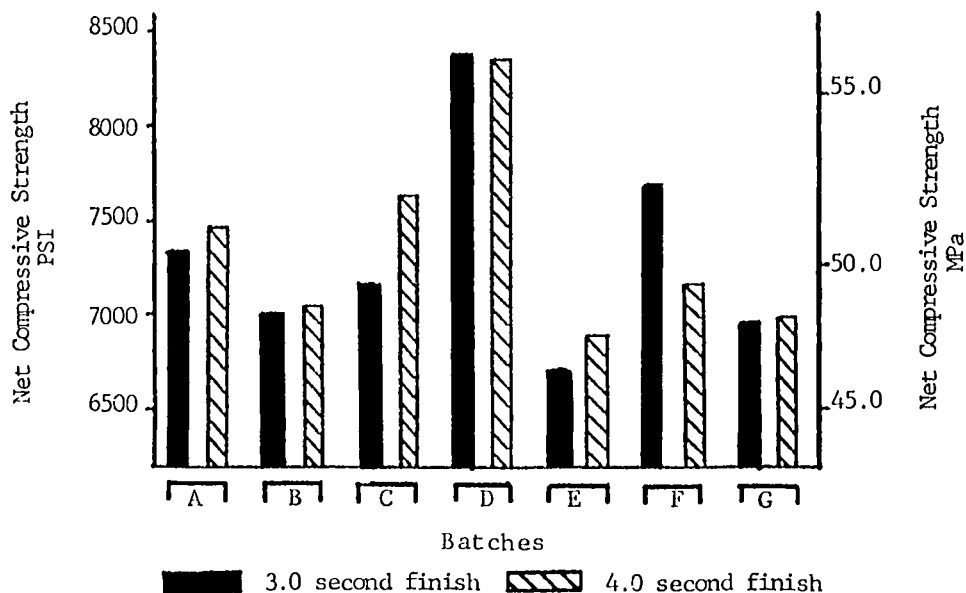


Figure 9 - 14-Day Compressive Strength

Studies on the Utilization of Water-Reduced High-Strength Concrete for Monorail Piers

*By Jiro Murata, Tadashi Kawai,
and Katsuro Kokubu*

Synopsis: The studies reported were concerned with the application of high-strength concrete to structural members as related to some aspects of their design, construction and behavior.

With regard to construction, tests were performed on the consistencies and strengths of concretes of low water-cement ratios using superplasticizers. The superplasticizers used were the 5 brands being marketed in Japan. The influence on consistency of fineness of cement was also studied.

In examinations made by design calculations, monorail piers were used as case studies. The relation between concrete strength and cross-sectional dimensions, and quality of reinforcing bars required when applying high-strength concrete to structural members were investigated.

In structural tests, the stresses, bending strengths and ductilities of model piers using high-strength concrete were studied.

Keywords: admixtures; compressive strength; consistency tests; fineness; flexural strength; high-strength concretes; mechanical tests; monorail railways; piers; plasticizers; portland cements; reinforced concrete; stresses; structural design; water-cement ratio; water-reducing agents.

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INTRODUCTION

The specified strengths of concrete for structural members are usually between 23.5 and 35.3 MPa in the case of reinforced concrete and around 44.1 MPa for prestressed concrete. For factory-manufactured prestressed concrete piles, strengths of 78.5 MPa and higher have come into practical use.

It has been made possible through the utilization of superplasticizers to place concrete in the field having a strength of 60 MPa or more without impairing workability, but there have not been very many cases of actual construction as yet. If such high-strength concrete were to be utilized, it would be possible to reduce cross-sections or switch from what had conventionally been steel structures to concrete structures. Compared with a steel structure, a concrete structure has the advantage of reduced maintenance and administrative costs.

Monorail piers constructed along urban streets were taken as case studies of members demonstrating the effects described above. In Japan, legislation has been provided on steps to be taken in constructing monorail lines along existing roads as second transportation levels in order to alleviate traffic congestion. Since monorail

piers are likely to be constructed on median strips, any horizontal dimension of a pier must not exceed 1.5 m, and since a pier using high-strength concrete would be slender, it will be necessary for it to possess adequate strength against bending failure during earthquake.

The studies described here consist of examinations of the design, construction and mechanical behaviors of piers for which high-strength concrete has been used.

CONSISTENCY AND STRENGTH OF HIGH-STRENGTH CONCRETE

Water-reducing Effect of Superplasticizer

The water-reducing effects of superplasticizers were tested using 5 brands being marketed in Japan. Slumps of 140 mm for cast-in-situ concrete and 80 mm for precast concrete were assumed to be suitable workabilities. Unit cement contents were established at 450, 500 and 550 kg/m³, while for the superplasticizers, two dosages each were selected from the ranges recommended by the makers, and unit water contents providing the required slumps were determined. Mixing was done using a pan-type mixer of 50 liters capacity, and the mixing time was 2 minutes. Full dosages of superplasticizers were dissolved in the mixing water before use.

Figs. 1 and 2 indicate the respective unit water contents needed to obtain the required slumps. The ratios of solids of superplasticizers to cement content are indicated on the abscissae. Among the 5 brands of admixtures there was a clear distinction between the water reducing effects of the two general types naphthalene sulfonate formaldehyde condensates (Type N), and sulfonated melamine formaldehyde (Type M). To obtain equal consistencies, it appears that more of the solids of Type M are needed compared with Type N. When the dosage of superplasticizer is constant, more water will be required in proportion to the increase in cement content.

Compressive Strength of High-Strength Concrete

The concretes mentioned in the preceding section were tested for compressive strengths after water curing, steam curing, or autoclave curing. The aggregate used was hard limestone crushed rock.

There was hardly any influence of differences in brands of superplasticizers and unit cement contents with respect to compressive strength. At a given slump, the compressive strength was governed by the water-cement ratio which was affected by dosage of superplasticizer. Fig. 3 shows the influences of curing conditions on compressive strength. The highest compressive strengths were obtained with autoclave curing. When the water-cement ratio was lower than approximately 0.36, compressive strengths of 60 MPa and higher were obtained, with water curing. Fig. 3

shows cases of 80 mm slump, but the results were almost the same with at a slump of 140 mm.

Split Addition of Superplasticizer

In the mix proportioning of high-strength concrete, it is important to effectively utilize the superplasticizer and to lower the water-cement ratio. Such concrete shows large slump loss and the time from mixing until placement governs the degree of workability. Cast-in-situ high-strength concrete, when transportation time is considered, needs to have a slump of about 140 mm approximately one hour after mixing. In this investigation a given quantity of superplasticizer was added divided into portions and the influence of sequential dosing on workability was tested.

The mix proportions were, water-cement ratio 0.31, unit cement content 520 kg/m³, and a total dosage of 1.55 percent superplasticizer by weight of cement added as a liquid. The method of addition was to dissolve 50% of the total quantity in mixing water, with the remainder added in various proportions 3 minutes after start of mixing and one hour after.

Fig. 4 indicates slumps immediately after mixing and one hour after. When the entire quantity of the superplasticizer was dissolved in the mixing water, a slump of 150 mm was obtained. When delayed addition was done at the time of mixing, the slump became 190 mm, and the fluidity was greatly increased. However, a decrease in slump of approximately 100 mm was found one hour later and it was expected that placement would become difficult. Since a large amount of water reduction is necessary for high-strength concrete, the slump at which uniform mixing can be done at the mixing plant with easy discharge is taken to be 50 mm. If 60% of the admixture is added at the mixing plant with the remainder added at the site one hour later a slump of 140 mm aimed for will be effectively obtained. It is thought that using as much superplasticizer as possible immediately before placement to obtain the required slump will alleviate the problem of slump loss and allow a quantity of admixture to be saved.

Influence of Cement on Consistency

The consistency of high-strength concrete was studied from the aspect of cement quality. Concretes of identical mix proportions were mixed using the 10 brands of ordinary portland cement listed in Table 1. The water-cement ratio was 0.31, the sand-aggregate ratio 36%, and the unit cement content 520 kg/m³. The dosages of superplasticizers were 1.43% (solids ratio 0.60%) by weight of cement in case of Type N and 3.65% (solids ratio 0.82%) in case of Type M. The admixtures were used dissolved in mixing water.

Fig. 5 shows the relation between slumps of concretes using Type N and Type M. The slumps of concretes using superplasticizers of differing main components indicate very similar trends and nothing can be seen to indicate that for a specific

cement a specific admixture is particularly compatible. However, it was found that there was an extreme variation from approximately 30 to 230 mm in slump with the same ordinary portland cement. It may be noted that such a great difference in slump is not found in normal concrete.

The chemical compositions and specific surfaces of the cements used were in the ranges which could be considered as applying to normally-used ordinary portland cements. As a result of studying the effects of the physical properties and chemical components of cement on slump of concrete, it was found there was a close relationship between slump and the amount of water required for normal consistency in time of setting tests of cement. As indicated in Fig. 6, it may be seen that slump was lower the more water the cement required for normal consistency. The slump superplasticized concrete and the consistency of plain cement paste showed a correspondence with each other. That is, there is the possibility that the physiochemical properties of the cement, rather than the combination of cement and superplasticizers, are the main factors influencing concrete slump.

Since large differences did not exist between the chemical compositions of the cements, fineness of cement was focused on and percentages retained on 80-, 40-, 20- and 10- μ m sieves were determined using air-jet sieves, and the results given in Table 1 were obtained. The cements used for the tests had 0.5 to 4.5% retained on the 80- μ m sieve, 7 to 20% retained on the 40- μ m sieve, and 70 to 74% retained on the 10- μ m sieve. The quantities of medium-sized particles of about 40 to 20 μ m indicated comparatively large variations. Since the specific surface by the air permeability method is generally governed by the amount passing the 10- μ m sieve, the influence of intermediate sizes is hardly seen at all, and therefore, the fineness was expressed as the fineness modulus of cement (C.F.M.) by the formula below.

$$\text{C.F.M.} = \frac{(\% \text{ retained on } 10\text{-}\mu\text{m sieve}) + (\% \text{ retained on } 20\text{-}\mu\text{m sieve}) + (\% \text{ retained on } 40\text{-}\mu\text{m sieve}) + (\% \text{ retained on } 80\text{-}\mu\text{m sieve})}{100}$$

The values obtained fell in a range of 1.2 to 1.5, signifying that the average particle size was between 12 to 15 μ m. This indicated a value for a particle size close to 50% passing.

Fig. 7 shows the relations between the amount of water required for normal consistency, the specific surface by the air permeability method, and the C.F.M. The larger that the value of C.F.M. became, the smaller the amount of water required for normal consistency hyperbolically became. However, such a relationship cannot be expressed with the specific surface determined by the air permeability method. In effect, it is conceivable that the particle-size distribution of cement has a great influence on the amount of water required for normal consistency.

Slump values in case of ordinary concrete are generally governed by unit water content, and the influence of cement is considered as being small. In contrast, with high-strength concretes having extremely low water-cement ratios, it is thought that

the particle-size distribution of cement will be an unignorable factor greatly influencing concrete slump.

CROSS SECTION OF MONORAIL PIERS USING HIGH-STRENGTH CONCRETE

To study the application of high-strength concrete to monorail piers both reinforced concrete and prestressed concrete structural designs were considered. The conditions for working stress design were as shown in Table 2. The height of a pier and the spacing between piers of the standard dimensions indicated in Fig. 8 were 10 m and 20 m, respectively. The axial force on the cross-section at the bottom end of one of these piers, as shown in Table 3, is a maximum when dead load, live load and earthquake load act on it. As a result of making comparisons of reinforced concrete and prestressed concrete designs, feasible cross-sections were found to be those indicated in Fig. 9.

With a reinforced concrete structure, a cross section of 1.0 x 1.05 m was found necessary in order to accommodate the required quantity of reinforcing bars. The material strengths required in this case were 39.2 MPa for the concrete and a yield strength of 490 MPa for the reinforcing steel. The reinforcement ratio was 4.6%.

In addition to the fact that the design bending moment due to (dead + live + earthquake) load would become very large, it is stipulated in the design guide on monorail structures that the safety factor against bending failure must be taken at the high level of 1.7, and it is necessary therefore to make the tensile resultant of the reinforcing steel large. Consequently, high-strength concrete cannot be effectively utilized unless reinforcing steel of high tensile strength and large diameter is used. With ordinary materials such as concrete having a specified strength of 23.5 MPa and a reinforcing steel yield strength of 294 MPa, the cross-sectional dimensions would be 1.40 x 1.40 m with reinforcement ratio of 2.4%.

With a prestressed concrete structure, the diameter would be 1.3 m and shell thickness 0.2 m. The specified strength of concrete would be 78.5 MPa as required by the loading conditions. The cross-sectional area of prestressing steel is determined by the safety requirement against bending failure under earthquake loads. The prestress to be transferred is determined by the condition that tensile stresses are not permitted at any cross-section under the loads. As a result, the stress in a prestressing steel bar in a state of use becomes 323 MPa, 35% of the yield strength of 932 MPa, which is very small compared with stresses in prestressed concrete girders in general.

Monorail piers are continually subject to alternating bending fatigue due to eccentric loading of coaches. In case of a reinforced concrete structure, the reinforcing bar stresses in a cross section of 1.0 x 1.05 m vary over a range of approximately

78 MPa. On the other hand, the compressive stress of concrete is 7.3 MPa and very small.

BEHAVIOR OF MODEL PIERS USING HIGH-STRENGTH CONCRETE

Method of Testing

The model piers of reinforced concrete and prestressed concrete construction indicated in Table 4 were fabricated. The design loads of the specimens were roughly equal, with the cross-sectional dimensions varying in accordance with the qualities of the materials used. The dimensions accordingly became smaller the higher the concrete strength, while the reinforcement ratios became higher. The web reinforcements of the specimens were calculated so that entire shear forces under loading conditions corresponding to those during earthquake would be carried by hoop reinforcement.

The method of loading, as shown in Fig. 10, was for axial loads to be applied by unbonded prestressing steel bars, with horizontal forces applied at pier heads. The load was increased monotonically up to a level corresponding to the load during an earthquake, at which level 10 cycles of alternating loads were applied. Following this, the load was increased until yielding of reinforcing steel, and alternating loads were applied under controlled displacement.

Concrete Stress

The concrete stresses were obtained from the values of measured strains converted by the stress-strain relationship determined by testing cylindrical specimens and are indicated in Fig. 11. The difference between the measured and calculated stresses in the concrete became greater the higher the concrete strength, and a difference of approximately 60% was found. Therefore, it is thought advisable for either of the methods below to be used in checking concrete stress by working stress design. One is to perform the calculations using a modular ratio n of 15, as in the current method of design in Japan, making the safety factor in case of determining the working stress higher. The other is to use the actual value of the modular ratio, n , in the calculations.

Bending Strength

The measured and calculated values of ultimate bending strengths of the model piers are as indicated in Table 5. Regarding yielding loads, values calculated from the yield strengths of the reinforcing bars show good approximations to the experimental results. The maximum strengths were determined assuming the stress-strain relationship of reinforcing steel to be bilinear and the ultimate strain of concrete to be 0.35%. The calculated values are smaller than measured values, and the differ-

ences are large. In order to secure a high safety factor against bending failure, the calculation formula should be examined to be able to obtain the calculated value of maximum strength with better accuracy.

In the reinforced concrete construction, failure occurred by the formation of intersecting diagonal cracks due to repetitions of alternating loads followed by concrete crushing and spalling off after yielding of the reinforcing steel.

In the case of prestressed concrete concrete construction, the columns and footings were manufactured as precast elements and were tensioned together with prestressing steel bars. At failure the joint portion was crushed locally by the loading and gaps were produced. In the actual construction of such piers the bottom parts of the piers will be covered by cast-in-situ concrete, and it is thought that there will be no problem.

Ductility

Pier-head displacements of specimens under loading corresponding to (dead + live + earthquake) load, were 4, 7, 12 and 7 mm for specimens No. 1, No. 2, No. 3 and No. 5, respectively, the displacements being larger the smaller the cross-sectional dimensions. However, as indicated in Fig. 12, when displacement and load were expressed by the ratio of deflection to yield deflection, even when the load was greatly increased after yielding of reinforcing steel, the strength did not become smaller than the load at the time of yielding under 8 cycles of alternating load applications at triple the displacement at the time of yielding. Although there was some concern that the ductility of a member using high-strength concrete and of high reinforcement ratio might be lower than with members of normal quality, it was found that a ductility factor (deflection/yield deflection) of not less than 4 could be obtained. It is thought also that the provision of adequate quantities of stirrups had a considerable effect as well.

In the case of prestressed concrete, great toughness was demonstrated and good deformation properties were apparent.

Fatigue Strength

Alternating bending tests were performed on simple beams of reinforced concrete based on the model piers No. 1 and No. 2. These tests were planned with particular regard to the quality of the reinforcing steel. The 2-million cycle fatigue limits of reinforcing bars having a yield strength of 294 MPa, which are normally used, and bars of 490 MPa, which have practically no record of use, ranged from 177 to 196 MPa.

CONCLUSIONS

The design of monorail piers, bending tests of model piers, and construction were studied with the following conclusions:

1. The compressive strength of high-strength concrete is governed by the water-cement ratio which is determined by the interrelationship of dosage of superplasticizer for obtaining the required slump and the unit water content. The water-cement ratio law is valid for high-strength concrete just as it is with ordinary concrete.

2. In mixing of high-strength concrete, it is effective to use a portion of the superplasticizer at the mixing plant for uniform mixing and for a consistency permitting easy discharge from the mixer to add the remainder of the superplasticizer immediately before placing of concrete to obtain the required slump.

3. The consistency of high-strength concrete of very low water-cement ratio is greatly influenced by the particle-size distribution of cement. The degree of the consistency can be roughly estimated by the amount of water required by cement paste for normal consistency.

4. In design of reinforced concrete members using high-strength concrete, it is necessary for high-tension reinforcing bars proportionate to the concrete strength to be available. In calculation of the cross-section, not only modulus of elasticity ratio n and working stress, but also ultimate strength and the safety factor against bending failure are of prime importance and studies should be made regarding rational evaluation of these factors.

5. If high-strength concrete and high-tension reinforcing steel are used, it is possible for the cross section having the required strength to be made smaller. If adequate shear reinforcement is provided for such members there will be ample ductility, and it was confirmed in these tests that sufficient fatigue strength will be obtained also. Consequently, it is possible to effectively apply high-strength concrete to monorail piers.

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Table 1
Properties of Cements

	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10
Physical Properties										
Specific Gravity	3.17	3.18	3.16	3.18	3.16	3.18	3.16	3.16	3.17	3.17
Specific Surface (m ² /kg)	321	331	321	314	327	313	330	328	332	324
Amount of Water Required for Normal Consistency (%)	27.4	26.5	28.4	27.2	27.3	25.6	26.3	29.6	25.8	28.0
Alpine Air-Jet Sieve Analysis (Percentage Retained)										
10- μ m Sieve	73.4	71.0	71.6	71.4	72.9	74.0	70.4	70.7	70.4	71.9
20- μ m	43.6	43.0	44.1	43.2	44.4	50.5	46.3	40.1	47.7	44.2
40- μ m	11.2	13.2	11.7	11.6	13.6	21.0	16.3	8.6	19.0	11.6
80- μ m	0.9	2.5	1.5	1.4	2.1	4.4	2.3	1.0	3.7	1.7
C.F.M.	1.29	1.30	1.29	1.28	1.33	1.50	1.35	1.20	1.41	1.29
Chemical Composition (%)										
SO ₃	1.6	1.9	1.6	1.9	2.0	2.3	1.7	1.9	1.7	1.9
Na ₂ O + 0.657K ₂ O	0.99	0.78	0.81	0.80	0.84	0.65	1.20	1.05	0.69	0.97
C ₃ S	51	48	52	50	49	44	49	49	44	43
C ₂ S	26	28	24	23	27	29	26	25	30	32
C ₃ A	8	8	10	10	9	10	9	10	10	10
C ₄ AF	9	9	9	10	9	9	9	9	9	9