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PERFORMANCE OF SUPERPLASTICIZERS IN CONCRETE: LABORATORY INVESTIGATION - PART I

V.M. Malhotra and D. Malanka

AUGUST 1977

MINERALS RESEARCH PROGRAM
MINERAL SCIENCES LABORATORIES
CANMET REPORT 77-65

Available by mail from:

Printing and Publishing
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Catalogue No. M38–13/77-65 Price: Canada: $1.75
ISBN 0-660-01739-3 Other countries: $2.10

Price subject to change without notice.

En vente par la poste:

Imprimerie et Édition
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N^o^ de catalogue M38–13/77-65 Prix: Canada: $1.75
ISBN 0-660-01739-3 Autres pays: $2.10

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PERFORMANCE OF SUPERPLASTICIZERS IN CONCRETE: LABORATORY INVESTIGATION - PART I

by

V.M. Malhotra* and D. Malanka**

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SUMMARY

Superplasticizers are new types of water reducers which, when added to concrete, cause large increases in its workability. The introduction of these water reducers has opened up new possibilities for concrete in construction. This report gives results of a laboratory investigation to determine the performance of superplasticizers in high-strength concrete with a water-cement ratio of 0.42.

A series of 15 concrete mixes was made at a water-cement ratio of 0.42 with a slump of 2 in. (50 mm). Various dosages of the superplasticizers - Melment L10, Mighty 150 and Mulcoplast CF - were added to the mixer after completion of initial mixing. This was followed by additional mixing for 2 minutes. Apart from the control concrete mix, all others were air-entrained. Initial setting times of concrete, increases in slumps, and their subsequent loss with time were recorded. A number of test cylinders and prisms were cast for determining mechanical strength and freeze-thaw durability.

Incorporating superplasticizers delayed initial setting time of concrete depending on the type and dosage used. The large increases in slump of superplasticized concrete were confirmed; however, the increased workability and its loss with time were functions of the type of superplasticizer used.

The compressive and flexural strengths of the test specimens cast from superplasticized concretes were comparable to or greater than those of the control specimens. The test cylinders cast without external vibration showed strengths comparable to those using external vibration.

In the superplasticized concrete under investigation,

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the bubble spacing factor varied between 0.006 and 0.01, compared with 0.006 for the reference concrete. In spite of the increased bubble spacing, durability of the superplasticized concrete test prisms is not impaired when exposed to repeated cycles of freezing in air and thawing in water.

LE RENDEMENT DES SUPER-PLASTIFIANTS DANS LE BETON: ETUDE EN LABORATOIRE - PARTIE I

par

V.M. Malhotra* et D. Malanka**

RESUME

Les super-plastifiants sont de nouveaux genres d'adjuvants réducteurs d'eau qui, lorsqu'on les ajoute au béton, en accroissent considérablement la malléabilité. La mise au point de ces adjuvants offre de nouvelles possibilités à l'utilisation du béton dans les ouvrages de construction. Le présent rapport donne le résultat d'une étude en laboratoire qui visait à déterminer le rendement des super-plastifiants dans le béton à haute résistance ayant un rapport d'eau à ciment de 0,42.

On a préparé une série de 15 mélanges de béton ayant un rapport d'eau à ciment de 0,42 et une hauteur d'affaissement de 2 pouces (50 mm). Une fois terminée la première étape de malaxage, on a ajouté des quantités variées de divers super-plastifiants - Melment L10, Mighty 150 et Mulcoplast CF; il y eut ensuite malaxage additionnel d'une durée de 2 minutes. Exception faite de mélange contrôle de béton, on a ajouté des entraîneurs d'air aux autres mélanges. On a pris note des premières durées de prise de béton, des accroissements des hauteurs d'affaissement et de leur perte subséquente avec le temps. On a coulé un certain nombre de cylindres et de prismes d'essais en vue de déterminer la résistance mécanique et la durabilité face au gel-dégel.

L'incorporation de super-plastifiants retarde la prise initiale du béton, dépendemment du type et de la quantité utilisées. On a confirmé des accroissements importants dans l'affaissement du béton super-plastifié; cependant, la malléabilité accrue et sa perte avec le temps dépendent du genre de super-plastifiant utilisé.

La résistance à la compression et à la flexion des échantillons d'essai coulés de bétons super-plastifiés est comparable ou supérieure à celle des échantillons de contrôle. Les échantillons d'essai coulés sans revibration ont une résistance comparable à ceux qui ont subi une revibration.

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Dans le béton super-plastifié à l'étude, le coefficient d'espacement des bulles varie entre 0,006 et 0,01 en comparaison de 0,006 dans le cas du béton de référence. Malgré cet espacement accru des bulles, la durabilité des prismes d'essai en béton super-plastifié n'est pas réduite lorsque ce dernier est exposé à des cycles répétés de gel à l'air et de dégel dans l'eau.

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INTRODUCTION

Superplasticizers are new types of admixtures that have only recently been introduced into North America, although they have been in use in Japan since the late 1960's, and in Europe since 1972[1-6]. Also known as high-range water reducers, they may be defined as chemical admixtures which, when added to normal portland cement concrete, can enormously increase its workability or make possible reductions in its water content. These admixtures are generally sold as solutions but can be obtained as solids. To achieve the results claimed by the manufacturers, large dosages are needed, usually between 1 and 2% by weight of cement, depending on the property required. Compared with conventional water-reducing admixtures, these superplasticizers are expensive.

This report briefly describes the main types available in Canada and gives the results of a laboratory investigation to determine their effect on concrete.

SCOPE OF INVESTIGATION

In this study, a non-air-entrained control mix and 14 air-entrained concrete mixes were made using a water-cement ratio of 0.42 and a cement content of 639 lb/yd^3 (379 kg/m^3). Mixes of 2.2 ft^3 (0.062 m^3) were made in a laboratory counter-current mixer. Three commonly available superplasticizers were incorporated into the mixes with dosages varying from 0.5 to 3 per cent by weight of cement, except in one case, in which 10 per cent by weight of cement was used. The properties of fresh concrete and the initial setting times were determined. A number of 4 x 8-in. (102 x 203-mm) cylinders were cast from each mix with and without vibration, for compression testing at 28 days. Test prisms, 3.5 x 4 x 16 in. (89 x 102 x 406 mm), were also cast for determining flexural strength and resistance to freeze-thaw cycling. Air void parameters of the hardened concrete were determined.

CONCRETE MIXES

The mixes were made in the CANMET laboratory between January and March, 1977. Initial mixing time for each batch was 6 minutes. Properties of the fresh concrete were determined immediately after mixing, following which the required dosage of superplasticizer was added to the mixer and the concrete was mixed for 2 more minutes.

Materials

Cement

Normal portland cement, CSA Type 10 (ASTM Type 1), was used. Its physical properties and chemical analysis are given in Table 1.

Aggregates

Minus ¾-in. (19-mm) crushed limestone was used as the coarse aggregate and local sand as fine aggregate. To keep the grading uniform for each mix, the sand was separated into different size fractions which were then combined to a specified grading. The grading and physical properties of the coarse and fine aggregates are given in Tables 2 and 3.

Air-Entraining Agent

A sulphonated hydrocarbon type air-entraining agent was used in all the mixes except the non air-entrained control mix.

Superplasticizers

The following three types of superplasticizers were used.

Sulphonated Melamine Formaldehyde Condensates

Melment L10 belongs to this category. Of German origin, it is marketed in Canada by Sternson Limited, Brantford, Ontario. It is usually available as a 20% aqueous solution with a density of 68.6 lb/ft^3 (1,100 kg/m^3) and is limpid to slightly turbid or milky in appearance. The chloride content is 0.005%.

Sulphonated Naphthalene Formaldehyde Condensates

Mighty 150 falls into this category. Of Japanese origin, it is distributed in Canada by Atlas Chemical Industries Canada Ltd, Brantford, Ontario. It is usually available as a 42% aqueous solution with a density of 74.9 lb/ft^3 (1200 kg/m^3) and is dark brown in colour. The chloride content is negligible.

Modified Lignosulphonates

Mulcoplast CF is in this category. It is of French origin but is now manufactured in Montreal by Mulco Inc., St. Hubert, P.Q. It is usually available as a 20% aqueous solution with a density of 68.6 lb/ft^3 (1100 kg/m^3) and is light brown in appearance. It contains no chlorides.

All the above superplasticizers are made from organic sulphonates of the type RSO_3^- where R is a complex organic group frequently of high molecular weight (Figure 1).

Mix Proportioning

The graded coarse and fine aggregates were weighed in the room-dry condition. The coarse aggregate was then immersed in water for 24 hours: the excess water was decanted and the water retained by the aggregate was determined by weight difference. A predetermined amount of water was added to the fine aggregate, which was then allowed to stand for 24 hours.

A standard mix with water-cement ratio of 0.42, aggregate-cement ratio of 4.77 and cement content of 639 lb/yd^3 (379 kg/m^3) was used. The dosage of air-entrained agent was constant but the type and dosage of superplasticizers were varied as shown in Table 4.

Properties of Fresh Concrete

The properties of the fresh concrete, i.e., temperature, slump, unit weight and air content, were determined after the initial mixing time of 6 minutes, and again after addition of the superplasticizers and further mixing for 2 minutes (Table 4). Also, measurements were taken frequently to determine the rate of loss of slump.

Initial Time of Set of Fresh Concrete

To determine whether the superplasticizers retarded the set of the concrete, initial times of set were determined in accordance with ASTM Standard C403-70 (1976): "Time of Setting of Concrete Mixtures by Penetration Resistance".

PREPARATION AND CASTING OF TEST SPECIMENS

Concrete Mixes No. 1 to 12

Six 4 x 8-in. (102 x 203-mm) cylinders and six 3.5 x 4 x 16-in. (89 x 102 x 406-mm) prisms were cast from each mix. All test specimens were cast after adding superplasticizers except for mixes 1 and 2, which were control mixes. Three cylinders were compacted using a vibrating table; the remaining three cylinders were not subjected to any vibration. The prisms were cast by filling brass moulds and compacting the moulds on a vibrating table. After casting, all the moulded specimens were covered with water-saturated burlap, and were left in the casting room at 75 ± 3°F (24 ± 1.3°C) and 50% relative humidity for 24 hours. They were then demoulded and transferred to the moist-curing room until required for testing.

Concrete Mixes No. 13 to 15

Six 4 x 8-in. (102 x 203-mm) cylinders were cast from each of the three mixes: two cylinders were cast immediately after completion of initial mixing; two cylinders were cast after adding the superplasticizers and further mixing for two minutes; the remaining two cylinders were cast after the concrete had been allowed to stand in the mixer for 120 minutes. The cylinders were cast by filling steel moulds in two approximately equal layers, each compacted on a vibrating table.

TESTING OF SPECIMENS

Concrete Mixes No. 1 to 12

At 14 days, two prisms were removed from the moist-curing room and tested in flexure according to ASTM Standard C78-75, using a third point loading. At 28 days, both vibrated and non-vibrated cylinders from each mix were removed from the moist-curing room, capped with a sulphur and flint mixture and tested in compression on a 600,000-lb (272,160-kg) testing machine.

Concrete Mixes No. 13 to 15

At 28 days, the three sets of cylinders from each mix were removed from the moist-curing room, capped with a sulphur and flint mixture, and tested in compression.

DURABILITY STUDIES

Although durability cannot be measured directly, prolonged exposure of concrete to repeated cycles of freezing and thawing produces measurable changes in test specimens that may indicate deterioration. Measurements made on the test specimens after freeze-thaw cycling provide data that can be used to evaluate the relative frost resistance or durability.

In this investigation, test prisms were exposed to repeated cycles of freezing in air and thawing in water according to ASTM Standard C666-75. The automatic freeze-thaw unit* can perform eight cycles per day. One complete cycle from 40 ± 3°F to 0 ± 3°F (4.4 ± 1.7°C to -17.8 ± 1.7°C) and back to 40 ± 3°F (4.4 ± 1.7°C) requires about 3 hours. During this investigation the freeze-thaw unit did not fully meet the above temperature requirements, fluctuating between 5 and 11°F (-15 and -11.7°C) during freeze cycles.

At the end of the initial moist-curing period of 14 days, the temperature of each set of prisms was reduced to a uniform 40 ± 3°F (4.4 ± 1.7°C) by placing in the freeze-thaw cabinet at the thawing phase for one hour. The initial and all subsequent measurements of the freeze-thaw and reference test specimens were made at this temperature. After initial measurements of the test prisms were taken, two test prisms were placed in the freeze-thaw cabinet and the two companion prisms placed in the moist-curing room for reference purposes.

The freeze-thaw test specimens were visually examined at the end of every 50-cycle interval. Their lengths were measured and they were weighed and tested by resonant frequency, and by the ultrasonic pulse method at approximately every 100-cycle interval. The freeze-thaw test was terminated at the end

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*Manufactured by the Canadian Ice Machine Company Ltd., Toronto, Ontario.

of 700 cycles in each case, when both the freeze-thaw and reference prisms were tested in flexure.

Another useful index to determine the durability of concrete exposed to freeze-thaw cycling is the bubble spacing factor, an index related to the maximum distance in inches of any point in the cement paste from the periphery of an air void. The spacing factor for concrete under investigation was determined in accordance with ASTM Standard C457-71 using the modified point count method.

TEST RESULTS AND THEIR ANALYSIS

Ninety cylinders and seventy-two prisms were tested in this investigation. The densities of all specimens were taken at one day as shown in Table 5. The setting times of the concretes are shown in Figure 2 and the loss of slump with time is shown in Figures 3 to 7, with a view of a typical flowing concrete in Figure 8. A summary of the compressive and flexural strengths is given in Tables 6 to 8 and the data are illustrated in Figures 9 to 13, with Figure 10 showing a comparison of test cylinders cast without compaction with those cast using external vibration. The ratio of flexural to compressive strength for the test data is shown in Figure 14.

Changes in weight, length, pulse velocity and resonant frequencies on reference prisms and prisms subjected to freeze-thaw cycling are shown in Tables 9 to 12. Photographs of typical test prisms before and after freeze-thaw cycling are shown in Figure 15.

Results of the air-void analyses of the hardened concrete test specimens are given in Table 13.

DISCUSSION

Superplasticizers - Is this the correct term?

Since their introduction into North America the new admixtures have been variously called "superplasticizers", "super water reducers", "high-range water reducers", and "super fluidifiers". In Germany, they are called "superverflüssiger"[1,2], the literal English translation of which is superfluidifiers. Before the technical literature becomes cluttered with these different names, it is important that a consensus be reached on the correct name.

Mode of Action of Superplasticizing Admixtures

Superplasticizing admixtures act by causing the cement agglomerates to disperse. According to a report by the Cement and Concrete Association, London, their mode of action is best described as follows[3]:

> "These admixtures are thought to be adsorbed onto cement particles, causing them to become mutually repulsive as a result of the anionic nature of superplasticizers, which causes the cement particles to become negatively charged. In principle, this adsorption and dispersing effect is similar to that found for normal anionic plasticizers".

Initial Time of Set of Concrete

All superplasticizers investigated had a retarding effect on the time of initial set of concrete as measured by ASTM Standard C403-70. At the recommended dosage rates* of the superplasticizers, the time of initial set was least affected by the Melment L10, followed in turn by Mighty 150 and Mulcoplast CF (Figure 2). At higher dosages Mulcoplast CF retarded the initial set by about four hours, with the initial set of the reference concrete occurring at 3 hours and 50 minutes. This was probably so because Mulcoplast CF is a lignin-based water reducer. The set retarding property of the superplasticizers can be either beneficial or detrimental, depending on the job application.

Segregation of Superplasticized Concrete

When examined visually, the superplasticized concretes did not show significant segregation even when used at the maximum recommended dosage. When Mighty 150 was used at 10% by weight of cement, there was complete segregation of coarse aggregate from the cement matrix, accompanied by a foaming action. The concrete also failed to set for a number of hours. Of all the superplasticizers investigated, concrete superplasticized with Mulcoplast CF appeared to be more cohesive. If superplasticized concrete is placed by buckets, segregation of concrete should pose no serious problems. However, if placed using a

*Melment L10 - 2% by weight of cement
Mighty 150 - 1% by weight of cement
Mulcoplast CF - 2% by weight of cement

conveyor belt system, segregation may have to be watched closely.

Increases in Slump and Its Loss with Time

Superplasticized concretes exhibited very large increases in slump at the recommended dosages. The slumps reached 8 in. (206 mm) or more within minutes of adding the superplasticizers and the low-slump concretes became flowing concretes (Figures 3 to 8). Even at these high slumps there were no signs of serious segregation. The concretes maintained high slumps for the initial 5 to 10 minutes, following which there was rapid loss in slump. Concrete superplasticized with Melment L10 lost slump more rapidly than concrete with either of the other two agents tested. At recommended dosages, superplasticized concretes reverted to the original slump of about 2 in. (50 mm) in less than 90 minutes under laboratory temperature and humidity conditions. The rate of course varied with the dosage. At maximum recommended dosages*, the superplasticized concrete lost slump at a slower rate; at the elapsed time of two hours, the concretes superplasticized with Melment L10, Mighty 150 and Mulcoplast CF had residual slumps of 1½, 2, and 5½ in. (38,50 and 140 mm) respectively.

To take advantage of these large increases in slump, concrete must be transported and placed quickly. This can easily be achieved in precast concrete plants but may create problems for cast-in-place concrete. In spite of these diffi-

*Melment L10 - 3% by weight of cement
Mighty 150 - 1.5% by weight of cement
Mulcoplast CF - 3% by weight of cement

culties, superplasticizers offer opportunities for placing high-strength concrete in heavily reinforced sections without incurring segregation or honeycombing. This appears to be their principal advantage.

Compressive Strength Development

Concrete Superplasticized with Melment L10

At the dosage rates investigated, the 28-day compressive strengths of cylinders compacted by vibration were about 10% higher than the strengths of cylinders cast from the air-entrained control mix (Figure 9). This was also true for test cylinders that were not vibrated, except that for dosages of 2.0 and 3.0% the difference was only about 5%. For 1.0% dosage, honeycombing caused the strengths of non-vibrated cylinders to be substantially lower than those of the control cylinders (Figure 10).

Concrete Superplasticized with Mighty 150

At the dosages investigated, with the exception of 10%, the compressive strengths of cylinders cast from the superplasticized concrete were equal to or higher than the strengths of cylinders cast from the air-entrained control mix (Figure 11). This was true for both vibrated and non-vibrated cylinders. At 0.5 and 1.0% dosage rates, the difference in strength was slightly more than 10%; at the 1.5% dosage rate, strength of the cylinders cast from the air-entrained control mix were equal to that of the superplasticized concrete.

Concrete Superplasticized with Mulcoplast CF

At dosage rates of 1 and 2%, the compressive strengths of cylinders were equal to or only slightly higher than the strengths of cylinders cast from the air-entrained control mix (Figure 12). However, at the 3% dosage rate, the strengths of cylinders were substantially lower than those of cylinders from the control mix. The difference was 680 psi (4.69 MPa) for cylinders cast without compaction by vibration, the compressive strength of the control cylinders being 5550 psi (38.27 MPa). The concrete mix superplasticized with Mulcoplast CF had entrained higher amounts of air than the control mix; this probably explains why the strengths of cylinders cast from the superplasticized mix failed to show any improvement compared with those of control cylinders, contrary to results using Melment L10 and Mighty 150.

At the 3% dosage rate, the higher strengths of non-vibrated cylinders compared with vibrated cylinders are unexplained.

Concrete Mixes No. 13 to 15

The test cylinders cast immediately before adding superplasticizers showed no significant difference in strength from those cast immediately after mixing in the additives for 2 minutes (Table 7). However, test cylinders cast 120 minutes after the addition of superplasticizers showed significantly higher strengths.

Flexural Strengths

In general, at the recommended dosage rates, the 14-day flexural strengths of test prisms cast from the superplasticized concretes showed no significant change from the strengths of control prisms except for concretes superplasticized with Mulcoplast CF, in which case the strengths dropped by about 10% (Figure 13).

The prism specimens cast from concrete superplasticized with Melment L10 showed a steady increase in strength with increased dosage rate. At the 3% dosage rate, the flexural strength of the test prisms was 1050 psi (7.24 MPa) compared with 1000 psi (6.89 MPa) for the test prisms cast from the air-entrained control mix.

The prisms cast from concrete superplasticized with Mighty 150 showed slight increases in strength over those of the control prisms at dosage rates of 0.5 and 1.0%; at the 3% dosage rate the strength dropped, reaching a value of 970 psi (6.69 MPa) compared with 1000 psi (6.89 MPa) for the control prisms. This is not considered significant.

The prism specimens cast from concrete superplasticized with Mulcoplast CF showed slight increases in strength at a dosage rate of 1.0%, compared with the strengths of the control prisms. At 2 and 3% dosage rates, the strengths of the prisms dropped sharply. A value of 920 psi (6.34 MPa) was reached at 2%; this drop is unexplained because the compressive strengths of companion cylinders did not drop.

Durability of Concrete Prisms Exposed to Repeated Cycles of Freezing and Thawing

Durability of concrete prisms exposed to repeated cycles of freezing and thawing was determined by measuring weight, length, resonant frequency and pulse velocity of test prisms before and after exposure to freeze-thaw cycling and comparing these with corresponding values of reference prisms.

In general, there were no significant changes in the condition of the test prisms after about 700 cycles, when the freeze-thaw tests were discontinued (Tables 8-12). The changes in length of the prisms after 300 cycles of freezing and thawing were well within the limit of 0.07% set by Klieger for durable concrete[7]. The only exceptions were the non-air-entrained control prisms and the prisms cast from concrete superplasticized with Mighty 150 at a dosage rate of 10%.

The non air-entrained control prisms had shown a relative length change of 0.36% at 100 freeze-thaw cycles; the relative losses in the longitudinal resonant frequency and the ultrasonic pulse velocity were 35.7 and 27.6% respectively. The prisms were damaged to such an extent at the end of 100 freeze-thaw cycles that no flexural tests were possible.

The prisms cast from concrete superplasticized with Mighty 150 at a dosage rate of 10% had completely disintegrated at the end of 60 freeze-thaw cycles, thus preventing determination of resonant frequency, pulse velocity and relative length changes.

The freeze-thaw tests were performed using ASTM Standard

C666-76 and employing Procedure B, "Rapid Freezing in Air and Thawing in Water". ASTM Standard C494-71, Chemical Admixtures, specifies the use of Procedure A, "Rapid Freezing and Thawing in Water" for evaluating concrete incorporating chemical admixtures. Nevertheless, the reported freeze-thaw data are considered valid because the freeze-thaw test is a comparative test carried out with the specimens cast from the control mixes; for the investigation reported herein, the test prisms cast from the non-air-entrained control mix had disintegrated at 100 freeze-thaw cycles. Limited published data by Mukherjee and Chojnacki indicate that superplasticized concrete prisms perform satisfactorily when exposed to rapid freezing and thawing in water in accordance with Procedure A of ASTM Standard C494-71[8].

Air Void Determination of Hardened Concrete

The microscopical determination of air void content, and parameters of the air void system in hardened concrete, were determined according to ASTM Standard C457-71. It has been found that for satisfactory durability, the cement paste should be protected with air bubbles. Adequate protection requires that the spacing factor, an index related to the maximum distance of any point in the cement paste from the periphery of an air void, not exceed 0.008 in. (0.20 mm)[9]. In the superplasticized concretes under investigation, the bubble spacing factor varies between 0.006 and 0.01 compared with 0.006 for the control air-entrained concrete (Table 13). In spite of the increased bubble spacing in some cases the durability of the concrete test specimens is not impaired. This is of considerable significance and investigations are needed to explain this phenomenon.

Elastic Properties of Superplasticized Concrete

No tests were performed to determine the elastic properties of the superplasticized concretes in this investigation; however, subsequent investigations at CANMET indicate that Young's modulus of elasticity is not affected by the incorporation of superplasticizers[10]. Research is currently underway to determine the long-term creep characteristics of the superplasticized concrete. Limited published data on the subject are inconclusive[3,4]

Superplasticized Concrete and Accelerated Strength Testing

Limited accelerated strength tests performed on test specimens prepared from superplasticized concrete show compressive strength development identical to that of test cylinders prepared from the reference concrete[11]. Additional investigations are being done to cover a wide range of mix proportions and different types of superplasticizers using the modified boiling method.

GENERAL COMMENTS AND CONCLUSIONS

Superplasticized concretes show very large increases in slump with no significant segregation apparent in laboratory investigations. Thus, by incorporating superplasticizers, high-strength concretes can be placed in heavily reinforced and inaccessible areas. Superplasticized concretes do lose slump with time and this is one of the serious limitations of the new water reducers. However, with judicious selection of the dosages and by adding superplasticizers to concrete at a job site the above problems can be considerably reduced, if not eliminated altogether.

All superplasticizers investigated had a retarding effect on the time of initial set. This can be either beneficial or detrimental depending on the nature of the job on which they are used.

When superplasticizers are added to concrete at the manufacturers' recommended dosages, the 28-day compressive strengths of test cylinders cast from the superplasticized concrete are equal to or greater than the corresponding strengths of cylinders cast from the reference mix. This is true for cylinders cast with and without compaction by vibration, implying that high-strength concretes incorporating superplasticizers can be placed in forms without the need for mechanical compaction, which can result in considerable savings of time and money.

Limited available data on the elastic properties of superplasticized concretes indicate that Young's modulus of elasticity is not adversely affected by the use of superplasticizers. Further research is indicated in this direction.

The freeze-thaw durability of test specimens cast from superplasticized concretes compares favourably with those cast from the control mix regardless of the value of the bubble spacing factor in the hardened concrete.

There were some differences in performance of the three superplasticizers with regard to the compressive and flexural strengths of concretes and their loss of slump with time. Because the data are limited, no conclusions can be drawn concerning the relative performance of the three superplasticizers used.

The results presented in this report were obtained for concrete having a water-cement ratio of 0.42 and made with CSA Type 10 (ASTM Type 1) cement. The superplasticizers may or may not perform as reported in concretes made with other water-cement ratios and with different types of cements and aggregates.

Superplasticizers are more expensive than ordinary water reducers and are thus not economical for use in every-day concrete; they are ideal where flowing concretes with very low water-cement ratios are required.

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TABLE 1

Physical Properties and Chemical Analysis of the Cement*

Description of Test	
Physical tests - general	
Time of set (Vicat Needle): Initial..	2 hr 00 min
Final....	3 hr 50 min
Fineness: No. 200 (passing)..........	96.2%
Surface area, Blaine.................	373 m^2/kg
Soundness - Autoclave................	0.04%
Physical tests - mortar strength	
Compressive Strength of 2-in. (51-mm) cubes at: 3-day......................	3540 psi (24.4 MPa)
7-day......................	4290 psi (29.6 MPa)
28-day.....................	5160 psi (35.6 MPa)
Chemical analysis	
Insoluble residue....................	0.28%
Silicon dioxide (SiO_2)...............	21.88%
Aluminum oxide (Al_2O_3)...............	4.50%
Ferric oxide (Fe_2O_3).................	2.16%
Calcium oxide (CaO) total............	62.67%
Magnesium oxide (MgO)................	2.50%
Sulphur trioxide (SO_3)...............	3.24%
Loss on ignition.....................	1.22%
Others...............................	1.55%

*Manufacturer's data.

TABLE 2

Grading of Aggregates

Coarse Aggregate		Fine Aggregate	
Sieve size	Cumulative percentage retained	Sieve size	Cumulative percentage retained
$\frac{3}{4}$ in. (19 mm)	33.4	4 mesh (4.75 mm)	0.0
$\frac{3}{8}$ in. (9.5 mm)	66.6	8 mesh (2.36 mm)	10.0
4 mesh (4.75 mm)	100.0	16 mesh (1.18 mm)	32.5
		30 mesh (1.40 mm)	57.5
		50 mesh (300 μm)	80.0
		100 mesh (150 μm)	94.0
		Pan	100.0

TABLE 3

Physical Properties of Aggregates

	Coarse Aggregate	Fine Aggregate
Specific gravity	2.68	2.70
Absorption, %	0.40	0.50

TABLE 4

Properties of Fresh Concrete

Mix no.	Type of superplasticizer and dosage in per cent by weight of cement	After initial mixing of six minutes							After addition of superplasticizer and additional two minutes of mixing				
		Temperature		Slump		Unit weight		Air content, %	Slump		Unit weight		Air content, %
		°F	°C	in.	mm	lb/ft^3	kg/m^3		in.	mm	lb/ft^3	kg/m^3	
1	Control without AEA*	68	20	2	45	150.8	2417	2.1	-	-	-	-	-
2	Control with AEA	72	22	2	45	146.4	2347	4.8	-	-	-	-	-
3	Melment L10 - 1%	66	19	2	50	146.4	2347	5.2	4	100	146.4	2347	5.2
4	2%	66	19	2	50	146.4	2347	5.5	9	230	146.4	2347	5.2
5	3%	70	21	2	50	146.4	2347	5.0	10	260	146.4	2347	4.8
6	Mighty 150 - 0.5%	71	21.5	2	50	147.2	2359	5.0	3.5	90	146.8	2353	5.0
7	1.0%	73	22.5	2	50	146.4	2347	4.8	10	260	146.8	2353	4.8
8	1.5%	68	20	2	50	146.8	2353	5.0	>10	>260	149.6	2398	3.4
9	10%	66	19	2	50	146.0	2340	5.2	>10	>260	153.6	2461	-
10	Mulcoplast CF - 1%	70	21	2	50	146.4	2347	5.0	4	100	145.6	2334	6.0
11	2%	68	20	2	50	146.4	2347	5.4	8	210	143.6	2302	6.8
12	3%	68	20	2.5	70	146.0	2340	5.4	10	260	143.2	2295	6.0
13	Melment L10 - 3%	70	21	2	50	146.4	2347	5.3	10	260	146.8	2353	4.0
14	Mighty 150 - 1.5%	73	23	2	50	147.2	2359	4.8	10	260	149.2	2391	3.8
15	Mulcoplast CF - 3%	66	19	2	50	147.2	2359	5.0	10	260	146.4	2347	5.0

*Air entraining agent.

TABLE 5

Densities of Test Cylinders at Various Ages

Mix no.	Type of superplasticizer and dosage in per cent by weight of cement	4 x 8-in. (102 x 203 mm) cylinders									
		1-day				7 days		28 days			
		Cylinders, not vibrated		Cylinders, vibrated		Cylinders, vibrated		Cylinders, not vibrated		Cylinders, vibrated	
		kg/m3	lb/ft3	kg/m3	lb/ft3	kg/m3	lb/ft3	kg/m3	lb/ft3	kg/m3	lb/ft3
1	Control, without AEA*	-	-	2430	151.7	2412	150.6	-	-	2407	150.2
2	Control, with AEA	-	-	2356	147.1	2339	146.0	-	-	2336	145.8
3	Melment L10 - 1%	2345	146.4	2357	147.1	-	-	2321	144.9	2335	145.8
4	2%	2338	145.9	2349	146.6	-	-	2317	144.6	2327	145.3
5	3%	2367	147.8	2383	148.8	-	-	2331	145.5	2361	147.4
6	Mighty 150 - 0.5%	2352	146.8	2356	147.1	-	-	2332	145.6	2336	145.8
7	1.0%	2343	146.3	2367	147.8	-	-	2323	145.0	2348	146.6
8	1.5%	2384	148.8	2415	150.7	-	-	2363	147.5	2393	149.4
9	10.0%	2449	152.9	2440	152.3	-	-	2424	151.3	2420	151.1
10	Mulcoplast CF - 1%	2333	145.6	2349	146.6	-	-	2316	144.6	2333	145.6
11	2%	2300	143.6	2316	144.6	-	-	2280	142.3	2295	143.3
12	3%	2314	144.4	2340	146.1	-	-	2293	143.1	2320	144.8

*Air-entraining agent.

Notes:

1. One-day densities are the average of 6 test results.
2. Densities of test specimens of control mixes 1 and 2 at 7 and 28 days are the average of three results.
3. Densities of test specimens of superplasticized mixes 3 to 12 are the average of three test results.

TABLE 6

Summary of Compressive Strengths for 7-Day and 28-Day Old Concrete - Mixes No. 1 to 12

Mix no.	Type of superplasticizer and dosage in per cent by weight of cement	Water-cement ratio (by weight)	Compressive strength* of 4 x 8 in. (102 x 203-mm) cylinders					
			Compressive strength after 7 days		Compressive strength after 28 days			
					Not vibrated		Vibrated	
			psi	MPa	psi	MPa	psi	MPa
1	Control without AEA	0.42	5700	39.3	-	-	7050	48.6
2	Control with AEA	0.42	4730	32.6	-	-	5550	38.3
3	Melment L10 - 1%	0.42	-	-	4690	32.3	6150	42.4
4	2%	0.42	-	-	5830	40.2	6080	41.9
5	3%	0.42	-	-	5920	40.8	6090	42.0
6	Mighty 150 - 0.5%	0.42	-	-	6100	42.1	6070	41.9
7	1.0%	0.42	-	-	5870	40.5	6130	42.3
8	1.5%	0.42	-	-	5580	38.5	5540	38.2
9	10.0%	0.42	-	-	3320	22.9	3570	24.6
10	Mulcoplast CF - 1%	0.42	-	-	5720	39.4	5750	39.6
11	2%	0.42	-	-	5580	38.5	5580	38.5
12	3%	0.42	-	-	5290	36.5	4870	38.6

*Each result is a mean of tests on three cylinders.

TABLE 7

Summary of Compressive Strength Test Results - Mixes No. 13 to 15

Mix no.	Type of superplasticizer and dosage in per cent by weight of cement	28 day compressive strength* of 4 x 8-in. (102 x 203-mm) cylinders						
		Water-cement ratio (by weight)	Control - cylinders cast before superplasticizer added		Cylinders cast immediately after superplasticizer added		Cylinders cast 120 minutes after superplasticizer added	
			psi	MPa	psi	MPa	psi	MPa
13	Melment L10 - 3%	0.42	5255	36.2	5990	41.3	6150	42.4
14	Mighty 150 - 1.5%	0.42	6360	43.9	6050	41.7	6270	43.3
15	Mulcoplast CF - 3%	0.42	5380	37.1	5450	37.6	6000	41.4

*Each result is a mean of tests on two cylinders.

TABLE 8

Summary of Flexural Strength Test Results at 14 Days and at End of Freeze-Thaw Cycling

Mix no.	Type of superplasticizer and dosage in per cent by weight of cement	Water-cement ratio (by weight)	Flexural Strength*: Moist cured prisms: Strength after 14 days, psi	Moist cured prisms: Strength after 14 days, MPa	Moist cured prisms: At end of freeze-thaw cycling, psi	Moist cured prisms: At end of freeze-thaw cycling, MPa	Prisms after exposure to freeze-thaw cycling: Number of freeze-thaw cycles**	Prisms after exposure to freeze-thaw cycling: Age at end of freeze-thaw cycling, days	Prisms after exposure to freeze-thaw cycling: Strength of prisms, psi	Prisms after exposure to freeze-thaw cycling: Strength of prisms, MPa	Residual strength per cent
1	Control, without AEA	0.42	1120	7.72	1230	8.48	100	Prisms completely disintegrated			-
2	Control, with AEA	0.42	1000	6.89	1170	8.07	700	113	1070	7.38	91.5
3	Melment L10 - 1%	0.42	1010	6.96	1140	7.86	700	113	1020	7.03	89.5
4	2%	0.42	1040	7.17	1060	7.31	700	113	980	6.76	92.5
5	3%	0.42	1050	7.24	1110	7.65	700	113	1140	7.86	103.0
6	Mighty 150 - 0.5%	0.42	1020	7.03	1130	7.79	700	113	1100	7.58	97.5
7	1.0%	0.42	1010	6.96	1130	7.79	700	113	1080	7.45	95.5
8	1.5%	0.42	970	6.69	1170	8.07	700	113	1070	7.38	91.5
9	10.0%	0.42	740	5.10	829	5.72	50	Prisms completely disintegrated			-
10	Mulcoplast CF - 1%	0.42	1030	7.10	1170	8.07	700	113	1160	8.00	99.0
11	2%	0.42	920	6.34	1160	8.00	700	113	1015	7.00	87.5
12	3%	0.42	930	6.41	1140	7.86	700	113	970	6.69	85.0

* Each result is a mean of tests on two prisms, with testing being done at third point loading.

**Tests were terminated at 700 ± 15 freeze-thaw cycles.

TABLE 9

Changes in Weight of Test Prisms during Freeze-Thaw Cycling

Mix no.	Type of superplasticizer and dosage in per cent by weight of cement	Weight* of prisms, lb (kg)												Relative loss, per cent
		Reference prisms						Freeze-thaw prisms**						
		W_{14} †	W_{26}	W_{62}	W_{84}	W_{113}	Per cent gain	W^1_0	W^1_{100} ††	W^1_{300}	W^1_{500}	W^1_{700}	Per cent loss	
1	Control, without AEA	19.473 (8.83)	19.506 (8.85)	-	-	-	0.17	19.357 (8.78)	19.328 (8.77)	-	-	-	0.15	0.32
2	Control, with AEA	19.015 (8.63	19.046 (8.64)	19.051 (8.64)	19.060 (8.65)	19.075 (8.65)	0.32	18.775 (8.52)	-	18.769 (8.51)	18.761 (8.51)	18.756 (8.51)	0.10	0.42
3	Melment L10 - 1%	19.278 (8.74)	19.295 (8.75)	19.310 (8.76)	19.321 (8.76)	19.325 (8.77)	0.24	18.896 (8.57)	18.875 (8.56)	18.867 (8.56)	18.858 (8.55)	18.857 (8.55)	0.21	0.45
4	2%	19.095 (8.66)	19.118 (8.67)	19.120 (8.67)	19.140 (8.68)	19.143 (8.68)	0.25	18.811 (8.53)	18.795 (8.53)	18.781 (8.52)	18.781 (8.52)	18.780 (8.52)	0.16	0.41
5	3%	19.232 (8.72)	19.255 (8.73)	19.266 (8.74)	19.281 (8.75)	19.285 (8.75)	0.28	19.170 (8.70)	19.158 (8.69)	19.153 (8.69)	19.160 (8.69)	19.137 (8.68)	0.17	0.45
6	Mighty 150 - 0.5%	19.067 (8.65)	19.097 (8.66)	19.105 (8.67)	19.112 (8.67)	19.121 (8.67)	0.28	19.045 (8.64)	19.028 (8.63)	19.023 (8.63)	19.016 (8.63)	19.017 (8.63)	0.15	0.43
7	1.0%	19.001 (8.62)	19.021 (8.63)	19.036 (8.63)	19.046 (8.64)	19.059 (8.65)	0.31	19.035 (8.63)	19.020 (8.63)	19.010 (8.62)	19.020 (8.63)	19.008 (8.62)	0.14	0.45
8	1.5%	19.482 (8.84)	19.501 (8.85)	19.551 (8.87)	19.517 (8.85)	19.549 (8.87)	0.35	19.421 (8.81)	19.392 (8.80)	19.386 (8.79)	19.381 (8.79)	19.384 (8.79)	0.19	0.54
9	10.0%	19.566 (8.88)	19.575 (8.88)	-	-	-	0.05	19.627 (8.90)	18.645 (8.46)	-	-	-	5.00	5.05
10	Mulcoplast CF - 1%	19.015 (8.63)	19.024 (8.63)	19.034 (8.63)	19.051 (8.64)	19.064 (8.65)	0.26	18.815 (8.53)	18.769 (8.51)	18.771 (8.51)	18.765 (8.51)	18.779 (8.52)	0.19	0.45
11	2%	18.681 (8.47)	18.700 (8.48)	18.709 (8.49)	18.715 (8.49)	18.736 (8.50)	0.29	18.557 (8.42)	18.547 (8.41)	18.540 (8.41)	18.536 (8.41)	18.542 (8.41)	0.08	0.37
12	3%	18.761 (8.51)	18.779 (8.52)	18.895 (8.57)	18.792 (8.52)	18.809 (8.53)	0.26	18.818 (8.54)	18.790 (8.52)	18.788 (8.52)	18.769 (8.51)	18.792 (8.52)	0.14	0.40

* Each result is a mean of tests on 2 prisms.

**Tests were terminated at 700 ± 15 freeze-thaw cycles.

† W_{14} - weight of test prisms at 14 days.

†† W^1_{100} - weight of test prisms at the end of 100 freeze-thaw cycles.

TABLE 10

Changes in Length* of Test Prisms during Freeze-Thaw Cycling

Mix no.	Type of superplasticizer and dosage in per cent by weight of cement	Length of prisms** in. (mm)												Relative change, per cent
		Reference prisms						Freeze-thaw prisms***						
		L_{14} †	L_{26}	L_{62}	L_{84}	L_{113}	Per cent gain	L^1_0	L^1_{100} ††	L^1_{300}	L^1_{500}	L^1_{700}	Per cent change	
1	Control, without AEA	0.1110 (2.82)	0.1115 (2.83)	-	-	-	0.0036	0.0981 (2.49)	0.1484 (3.77)	-	-	-	+0.3672	+0.3636
2	Control, with AEA,	0.1064 (2.70)	0.1069 (2.72)	0.1062 (2.70)	0.1066 (2.71)	0.1070 (2.72)	0.0043	0.0978 (2.48)	0.0982 (2.49)	0.0977 (2.48)	0.0971 (2.47)	0.0969 (2.46)	-0.0066	-0.0109
3	Melment L10 - 1%	0.1174 (2.98)	0.1176 (2.99)	0.1169 (2.97)	0.1173 (2.98)	0.1171 (2.97)	-0.0022	0.1162 (2.95)	0.1156 (2.94)	0.1159 (2.94)	0.1157 (2.94)	0.1153 (2.93)	-0.0066	-0.0088
4	2%	0.0986 (2.50)	0.0980 (2.49)	0.0981 (2.49)	0.1006 (2.56)	0.1008 (2.56)	0.0146	0.1156 (2.94)	0.1151 (2.92)	0.1145 (2.91)	0.1141 (2.90	0.1137 (2.89)	-0.0139	-0.0285
5	3%	0.1194 (3.03)	0.1200 (3.05)	0.1199 (3.05)	0.1199 (3.05)	0.1202 (3.05)	0.0058	0.1102 (2.80)	0.1108 (2.81)	0.1108 (2.81)	0.1113 (2.83)	0.1105 (2.81)	+0.0022	-0.0036
6	Mighty 150 - 0.5%	0.1150 (2.92)	0.1157 (2.94)	0.1160 (2.95)	0.1170 (2.97)	0.1170 (2.97)	0.0146	0.1140 (2.90)	0.1146 (2.91)	0.1141 (2.90)	0.1146 (2.91)	0.1142 (2.90)	+0.0015	-0.0131
7	1.0%	0.1122 (2.85)	0.1127 (2.86)	0.1126 (2.86)	0.1130 (2.87)	0.1134 (2.88)	0.0088	0.1205 (3.06)	0.1212 (3.08)	0.1212 (3.08)	0.1210 (3.07)	0.1208 (3.07)	+0.0022	-0.0066
8	1.5%	0.1297 (3.29)	0.1301 (3.30)	0.1300 (3.30)	0.1304 (3.31)	0.1304 (3.31)	0.0051	0.1109 (2.82)	0.1114 (2.83)	0.1111 (2.82)	0.1108 (2.81)	0.1110 (2.82)	+0.0007	-0.0044
9	10.0%	0.1232 (3.13)	0.1241 (3.15)	-	-	-	0.0066	0.0977 (2.48)	0.2017 (5.12)	-	-	-	+0.7593	+0.7527
10	Mulcoplast CF - 1%	0.1128 (2.87)	0.1123 (2.85)	0.1126 (2.86)	0.1127 (2.86)	0.1132 (2.88)	0.0029	0.1179 (2.99)	0.1125 (2.86)	0.1183 (3.00)	0.1191 (3.03)	0.1195 (3.04)	+0.0116	+0.0087
11	2%	0.0253 (0.64)	0.0250 (0.64)	0.0250 (0.64)	0.0251 (0.64)	0.0255 (0.65)	0.0015	0.0172 (0.44)	0.0173 (0.44)	0.0176 (0.45)	0.0172 (0.44)	0.0166 (0.42)	-0.0044	-0.0059
12	3%	0.0988 (2.51)	0.0989 (2.51)	0.0988 (2.51)	0.0996 (2.53)	0.0998 (2.53)	0.0073	0.1154 (2.93)	0.1163 (2.95)	0.1164 (2.96)	0.1160 (2.95)	0.1169 (2.97)	+0.0109	+0.0036

* Each result is a mean of tests on two prisms.

**Gauge length = 13.6 in. (345 mm).

***Tests were terminated at 700 ± 15 freeze-thaw cycles.

† L_{14} - length of test prisms at 14 days.

†† L^1_{100} - length of test prisms at the end of 100 freeze-thaw cycles.

TABLE 11

Changes in Fundamental Longitudinal Resonance Frequency during Freeze-Thaw Cycling

Mix no.	Type of superplasticizer and dosage in per cent by weight of cement	Fundamental longitudinal resonant frequency*, N, cps												Relative loss, per cent
		Reference prisms						Freeze-thaw prisms**						
		$N_{14}^{\dagger}$	N_{26}	N_{62}	N_{84}	N_{113}	Per cent gain	N^1_0	$N^{1\,\dagger\dagger}_{100}$	N^1_{300}	N^1_{500}	N^1_{700}	Per cent change	
1	Control, without AEA	5310	5400	-	-	-	1.7	5300	3500	-	-	-	-34.0	35.7
2	Control, with AEA,	5100	5200	5250	5250	5350	4.9	5130	-	5130	5170	5200	+1.4	3.5
3	Melment L10 - 1%	5180	5270	5310	5340	5400	4.3	5200	5150	5200	5190	5210	+0.3	4.0
	2%	5190	5250	5280	5340	5400	3.9	5200	5190	5200	5230	5210	+0.3	3.6
	3%	5230	5300	5400	5430	5460	4.5	5250	5230	5250	5300	5300	+1.0	3.5
6	Mighty 150 - 0.5%	5200	5280	5340	5400	5400	3.9	5230	5200	5240	5250	5280	+1.0	2.9
	1.0%	5210	5300	5400	5400	5450	4.7	5200	5190	5200	5210	5240	+0.7	4.0
	1.5%	5300	5380	5400	5450	5500	3.8	5330	5310	5380	5390	5400	+1.4	2.4
	10.0%	5260	5330	-	-	-	-	5300	-	-	-	-	-	-
10	Mulcoplast CF - 1%	5150	5230	5250	5310	5360	4.1	5130	5130	5150	5180	5200	+1.5	2.6
	2%	5130	5200	5270	5300	5330	3.9	5060	5100	5100	5130	5180	+2.2	1.7
	3%	5100	5240	5300	5350	5390	5.6	5190	5110	5190	5200	5210	+0.4	5.2

*Each result is a mean of tests on two prisms.

**Tests were terminated at 700 ± 15 freeze-thaw cycles.

† N_{14} - resonant frequency at 14 days.

†† N^1_{100} - resonant frequency at the end of 100 freeze-thaw cycles.

TABLE 12

Changes in Ultrasonic Pulse Velocity of Test Prisms during Freeze-Thaw Cycling*

Mix no.	Type of superplasticizer and dosage in per cent by weight of cement	Ultrasonic pulse velocity, V, ft/sec (m/sec)												Relative loss, per cent
		Reference prisms						Freeze-thaw beams**						
		V_{14}†	V_{26}	V_{62}	V_{84}	V_{113}	Per cent gain	V^1_{0}	V^1_{100}††	V^1_{300}	V^1_{500}	V^1_{700}	Per cent change	
1	Control, without AEA	16,010 (4,880)	16,112 (4,910)	-	-	-	0.64	15,959 (4,864)	11,658 (3,553)	-	-	-	-26.95	27.59
2	Control with AEA	15,128 (4,611)	15,357 (4,681)	15,545 (4,738)	15,641 (4,767)	15,935 (4,857)	5.33	15,265 (4,653)	-	15,174 (4,625)	15,152 (4,618)	15,267 (4,653)	+0.01	5.32
3	Melment L10 - 1%	15,427 (4,702)	15,568 (4,745)	15,885 (4,842)	15,814 (4,819)	16,089 (4,904)	4.29	15,450 (4,709)	15,287 (4,659)	15,428 (4,703)	15,154 (4,619)	15,595 (4,753)	+0.94	3.35
4	2%	15,210 (4,636)	15,616 (4,760)	15,762 (4,804)	15,691 (4,782)	16,166 (4,927)	6.29	15,311 (4,667)	15,265 (4,653)	15,334 (4,674)	15,222 (4,639)	15,524 (4,732)	+1.39	4.90
5	3%	15,497 (4,723)	15,885 (4,842)	15,985 (4,872)	15,913 (4,850)	16,374 (4,990)	5.66	15,497 (4,723)	15,521 (4,731)	15,451 (4,710)	15,406 (4,696)	15,547 (4,738)	+0.32	5.34
6	Mighty 150 - 0.5%	15,334 (4,674)	15,521 (4,731)	15,811 (4,819)	15,960 (4,864)	16,115 (4,912)	5.09	15,498 (4,724)	15,357 (4,681)	15,310 (4,666)	15,522 (4,731)	15,572 (4,746)	+0.48	4.61
7	1.0%	15,474 (4,716)	15,664 (4,774)	15,762 (4,804)	16,036 (4,888)	16,166 (4,927)	4.47	15,450 (4,709)	15,242 (4,646)	15,265 (4,652)	15,381 (4,688)	15,548 (4,739)	+0.63	3.84
8	1.5%	15,762 (4,804)	15,910 (4,849)	15,935 (4,857)	16,089 (4,904)	16,374 (4,991)	3.88	15,910 (4.849)	15,737 (4,797)	15,664 (4,775)	15,765 (4,805)	15,889 (4,843)	-0.13	4.01
9	10.0%	15,811 (4,819)	-	-	-	-	-	15,835 (4,827)	-	-	-	-	-	-
10	Mulcoplast CF - 1%	15,061 (4,590)	15,689 (4,782)	15,762 (4,804)	16,038 (4,888)	16,034 (4,887)	6.46	15,175 (4,625)	15,264 (4,652)	15,288 (4,660)	15,335 (4,674)	15,428 (4,702)	+1.67	4.79
11	2%	15,084 (4,597)	15,521 (4,731)	15,568 (4,745)	15,691 (4,782)	15,887 (4,842)	5.32	15,061 (4,591)	15,083 (4,597)	15,061 (4,590)	15,245 (4,647)	15,220 (4,639)	+1.06	4.26
12	3%	15,061 (4,590)	15,689 (4,782)	15,640 (4,767)	15,938 (4,858)	15,962 (4,864)	5.98	15,174 (4,625)	15,219 (4,639)	15,174 (4,625)	15,430 (4,703)	15,475 (4,717)	+1.98	4.00

*Each result is a mean of tests on two prisms.

**Tests were terminated at 700 ± 15 freeze-thaw cycles.

† V_{14} - pulse velocity of test prisms at 14 days.

†† V^1_{100} - pulse velocity of test prisms at the end of 100 freeze thaw cycles.

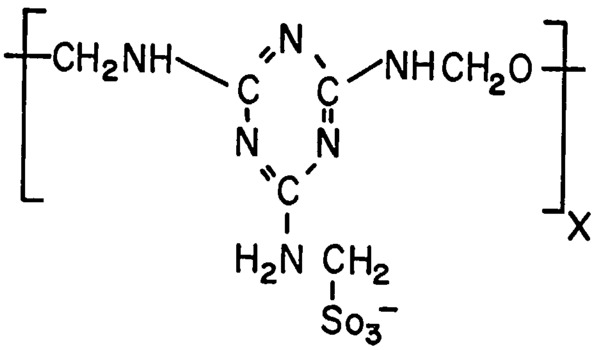
TABLE 13

Summary of Air Void Determination on Hardened Concrete*

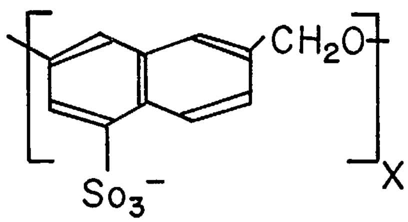
Mix no.	Type of superplasticizer and dosage in per cent by weight of cement	Number of stops	Length of traverse		Paste content**, per cent	Voids in concrete, per cent	Specific surface area (in.$^{-1}$)	Void spacing factor (in.)	
			in.	mm				in.	mm
1	Control, without AEA	-	-	-	-	-	-	-	-
2	Control, with AEA	1600	100	2540	27.9	4.9	861	0.006	0.15
3	Melment L10 - 1%	1600	100	2540	27.7	5.8	624	0.007	0.18
4	2%	1600	100	2540	27.7	4.3	530	0.010	0.25
5	3%	1600	100	2540	27.7	3.5	879	0.006	0.15
6	Mighty 150 - 0.5%	1600	100	2540	27.7	4.4	616	0.008	0.20
7	1.0%	1600	100	2540	27.7	4.1	575	0.009	0.23
8	1.5%	1550	97	2464	27.7	2.8	782	0.008	0.20
9	10.0%	-	-	-	-	-	-	-	-
10	Mulcoplast CF - 1%	1600	100	2540	27.7	4.2	920	0.006	0.15
11	2%	1575	99	2515	27.7	7.1	594	0.007	0.18
12	3%	1575	99	2515	27.7	5.1	788	0.006	0.15

* Air void determinations performed by Ontario Hydro using modified point count method

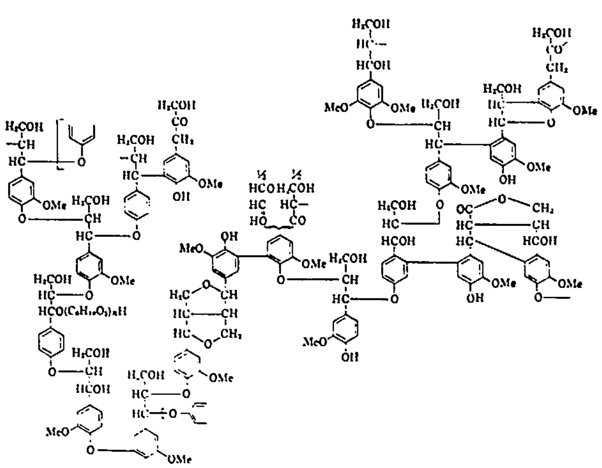
** Calculated from the mix proportions



R = MELAMINE– FORMALDEHYDE



R = NAPHTHALENE–FORMALDEHYDE



LIGNOSULPHONATE R = LIGNIN

Figure 1 - R-Organic group for naphthalene formaldehyde, melamine formaldehyde, and lignosulphonate.

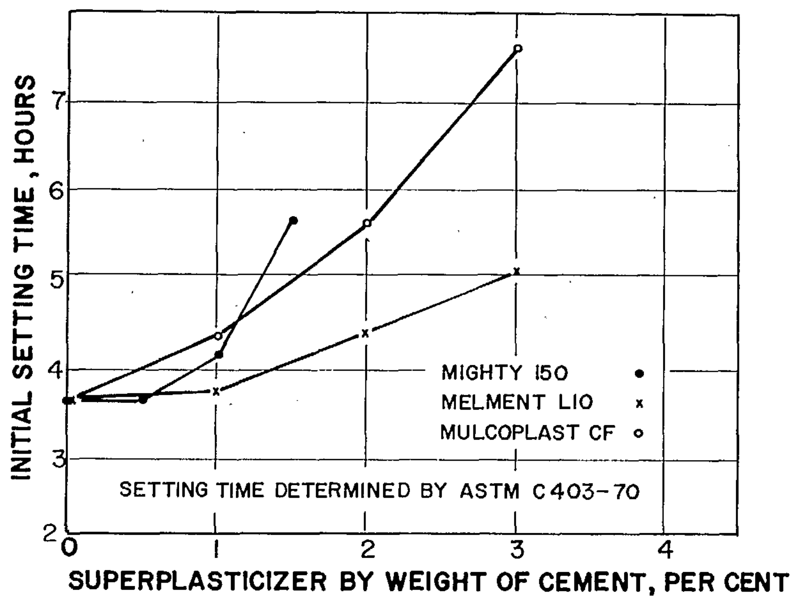


Figure 2 - Effect of superplasticizers on the initial setting time of concrete.

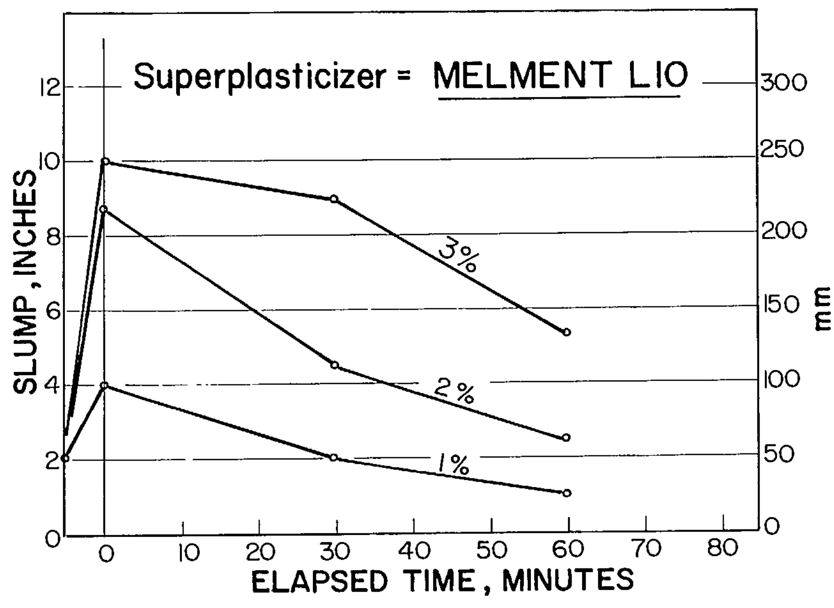


Figure 3 - Loss of slump with time - Melment L10.

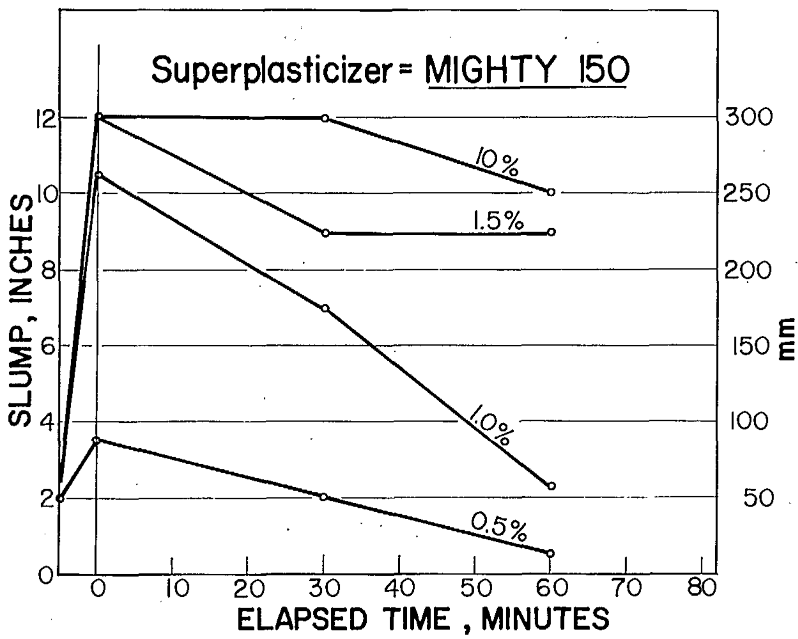


Figure 4 - Loss of slump with time - Mighty 150.

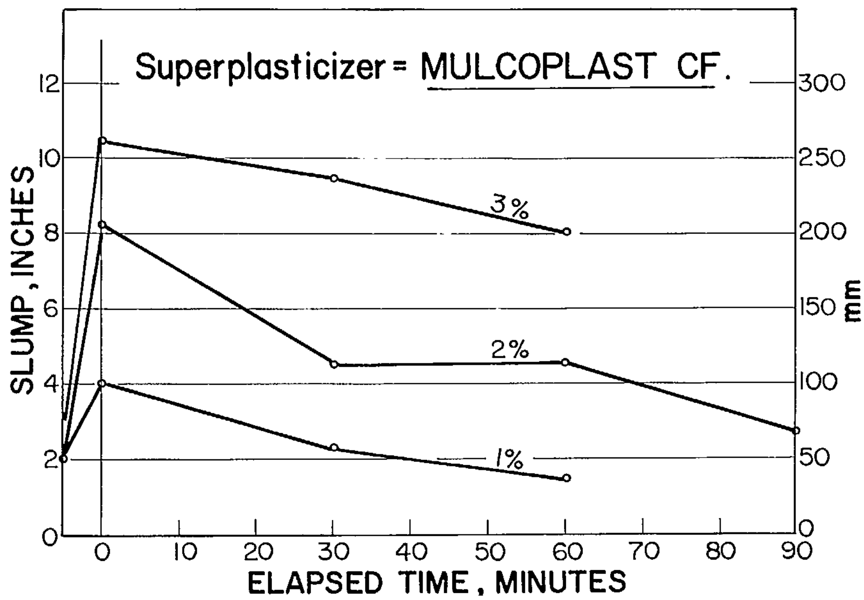


Figure 5 - Loss of slump with time - Mulcoplast CF.

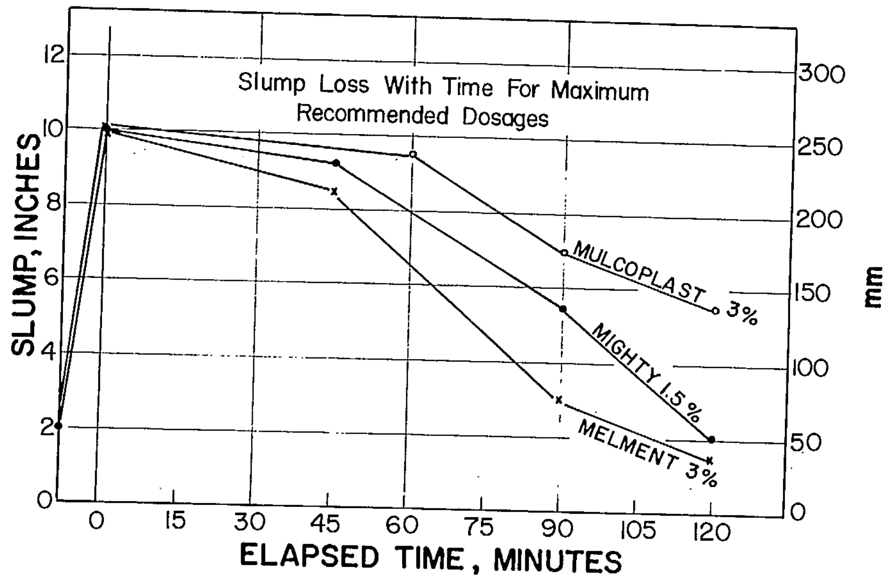


Figure 6 - Loss of slump with time of superplasticized concretes for maximum recommended dosage rates.

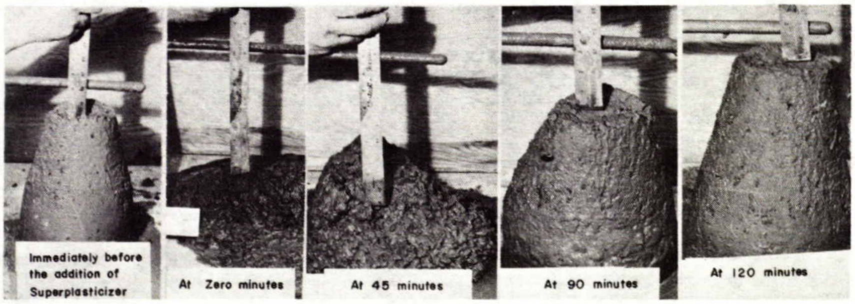


Figure 7 - Slump tests after various intervals of time for concrete incorporating 3 per cent Melment L10 by weight of cement.

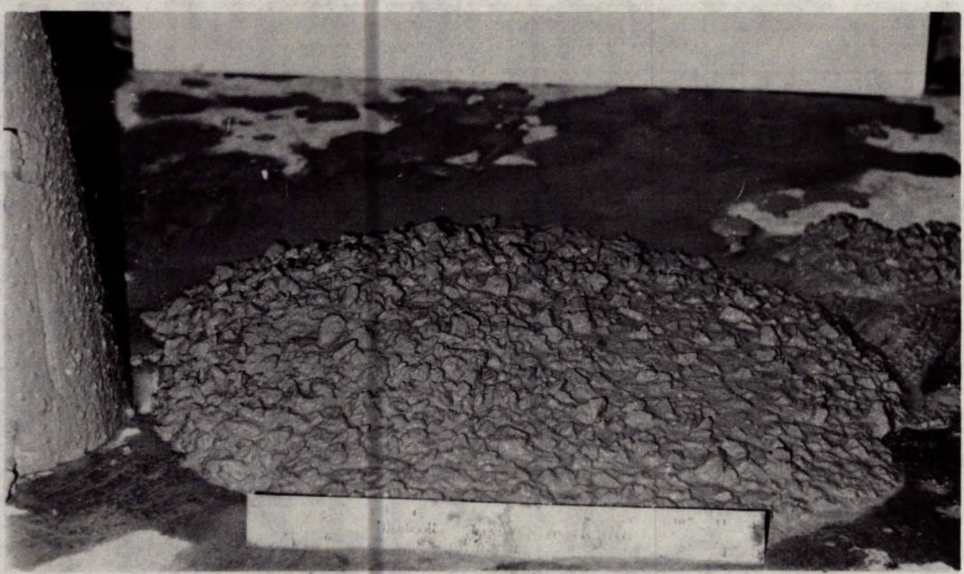


Figure 8 - A view of flowing concrete incorporating 1 per cent Mighty 150 by weight of cement.

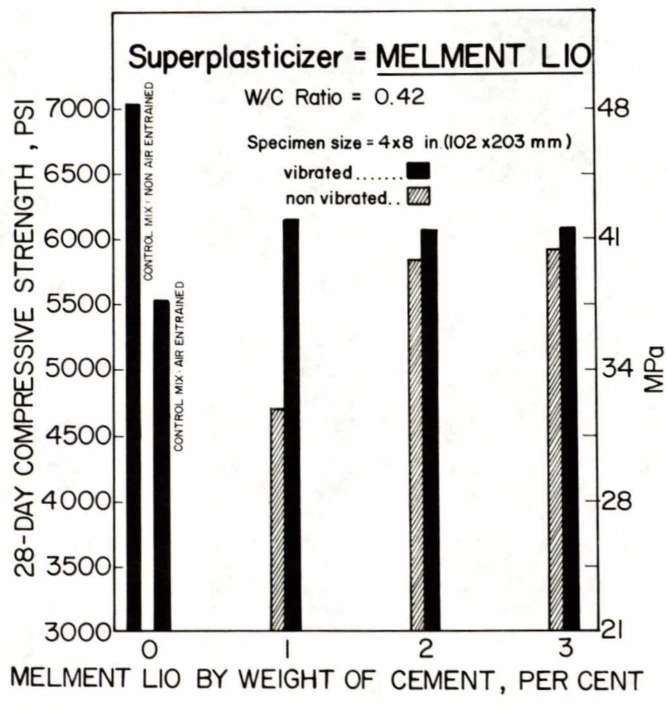


Figure 9 - Compressive strength of test cylinders at 28 days - Melment L10.

(a) (b)

(a) (b)

Figure 10 - Test cylinders cast with and without external vibration.

(a) Non-vibrated

(b) Vibrated

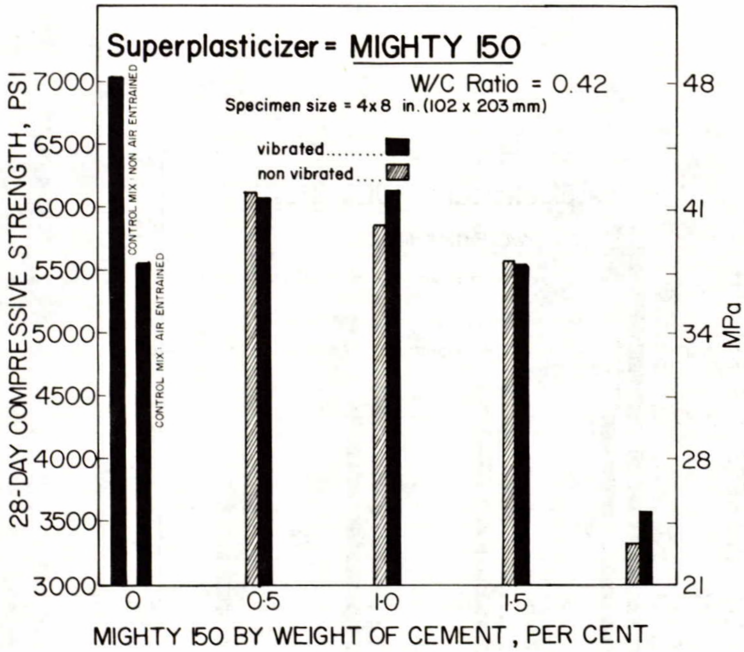


Figure 11 - Compressive strength of test cylinders at 28 days - Mighty 150.

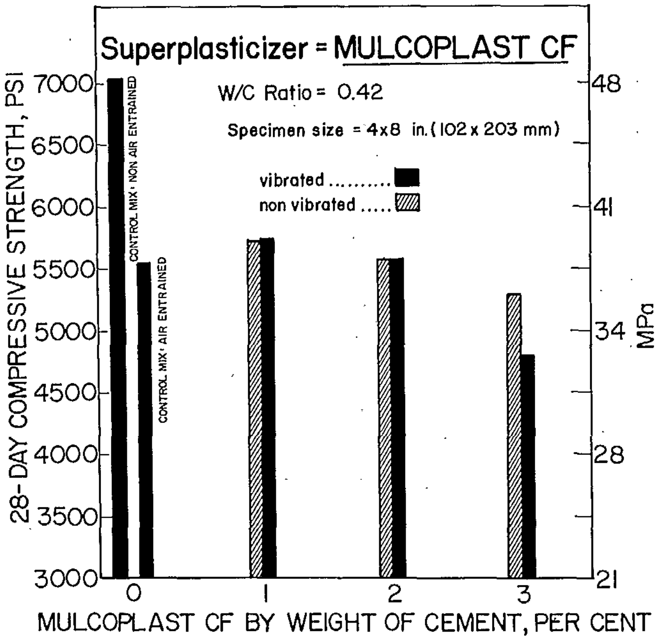


Figure 12 - Compressive strength of test cylinders at 28 days - Mulcoplast CF.

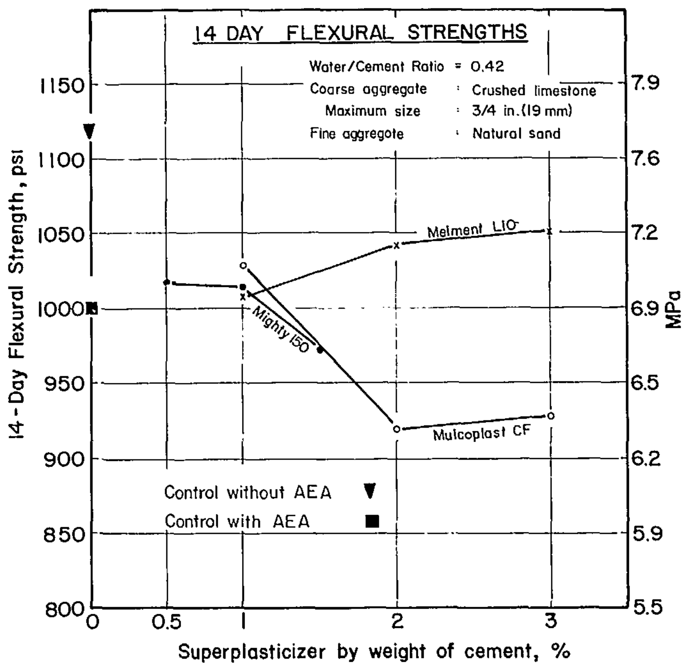


Figure 13 - Flexural strength of test prisms at 14 days.

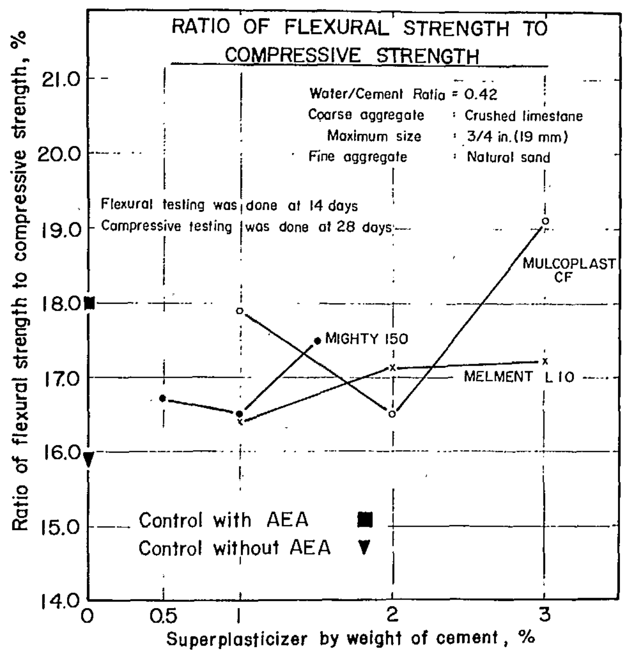


Figure 14 - Ratio of flexural to compressive strength of superplasticized concretes.

(a)

Top: Reference prism.

Bottom: Freeze-thaw prism.

(b)

Top: Reference prism.

Bottom: Freeze-thaw prism.

Figure 15 - Test prisms before and after freeze-thaw cycling.

(a) Prisms incorporating 1 per cent Mulcoplast CF.

(b) Prisms incorporating 2 per cent Mulcoplast CF.

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