Performance of Superplasticized Concretes That Have High Water-to-Cement Ratios

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This study presents results of laboratory investigations into superplasticized concretes that have high water-to-cement (w/c) ratios. Two series of concrete mixes totaling 18 were made at a w/c ratio of 0.65 and a slump of 50 mm (2 in). Various dosages of different superplasticizers were added to the mixes after completion of the initial mixing and then mixed for 2 min. Initial setting times, increases in slump, and subsequent slump loss with time were recorded. A number of test specimens were cast to determine mechanical strength and freeze-thaw durability. The incorporation of superplasticizers in concrete did not significantly affect initial setting time. The large increases in the slump of superplasticized concrete and its loss with time were found to be functions of the dosage rate of the superplasticizer used. At the recommended dosage rates, the 28-day compressive strengths of the test specimens cast with and without vibration were comparable to or greater than those of the control. In spite of the increased bubble spacing, the freeze-thaw durability of test prisms cast from the air-entrained superplasticized concretes at the end of 300 freeze-thaw cycles compared favorably with those cast from the air-entrained control mix.

Superplasticizers, although relatively new, are finding increasing acceptance in the concrete industry in North America and offer considerable potential for energy saving in the precast-concrete industry and for the use of margin aggregate in construction (1, 2).

In 1976, the Canada Centre for Mineral and Energy Technology (CanMET) initiated laboratory investigations to determine the effects of superplasticizers on the mechanical properties and freeze-thaw durability of concrete. Earlier reports had discussed the use of superplasticizers in high-strength concrete with a water-cement (w/c) ratio of 0.42 and the effect of repeated dosages of superplasticizers on the workability, strength, and durability of concrete (3-5). This study deals with performance of superplasticizers in concretes having a w/c ratio of 0.65.

SCOPE OF INVESTIGATION

In this study, two series of concrete mixes were made with a w/c ratio of 0.65 and a cement content of 246 kg/m³ (415 lb/yd³). Four commonly available superplasticizers were incorporated into the mixes at dosages varying from 0.5 to 3.0 percent by weight of cement. The properties of the fresh concrete were determined. For mixes of series A, a number of 100x200-mm (4x8-in) cylinders were cast with and without vibration for compression testing at 28 days. Test prisms were also cast for determining flexural strength and resistance to freeze-thaw cycles. Air-void parameters of the hardened concrete were determined. For mixes of series B a large number of 200x300-mm (6x12-in) cylinders were cast to establish strength-versus-age relationships.

CONCRETE MIXES

The mixes were made in the CanMET laboratory during April and May 1977. Initial mixing time for each batch was 6 min. The properties of the fresh concretes were determined immediately following mixing, after which the required dosage of the superplasticizer was added and the concrete was mixed for 2 min.

Normal portland cement ASTM type I was used. It had a fineness of 373 m²/kg, sulfate content of 3.24 percent, and C₃A content of 8.27 percent. Minus 19-mm (0.75-in) crushed limestone was used as the coarse aggregate and local sand as the fine aggregate. To keep the grading uniform for each mix, the sand was separated into different size fractions that were combined to a specified grading. A sulfonated-hydrocarbon air-entraining agent was used in all the concrete mixes except the non-air-entrained control mix.

Superplasticizers

The following three types of superplasticizers were used in the concrete mixes:

1. Sulfonated naphthalene formaldehyde condensates: Superplasticizers A and C fall in this category. Superplasticizer A is of U.S. origin. It is usually available as a soluble powder or as a 34 percent aqueous solution with a density of 1200 kg/m³ (74.9 lb/ft³) and is dark brown. The chloride content is negligible. Superplasticizer C is of Japanese origin. It is usually available as a 42 percent aqueous solution that also has a density of
1200 kg/m³ and is dark brown. The chloride content is also negligible.

2. Sulfonated melamine formaldehyde condensates: Superplasticizer B belongs to this category and is of German origin. It is usually available as a 20 percent aqueous solution with a density of 1000 kg/m³ (62.4 lb/ft³) and is limpid (clear) to slightly turbid (milky) in appearance. The chloride content is 0.005 percent.

3. Modified lignosulfonates: Superplasticizer D falls in this category. It is of French origin but is now being manufactured in Montreal. It is usually available as a 20 percent aqueous solution, has a density of 1100 kg/m³ (68.6 lb/ft³), and is light brown in appearance. It contains no chlorides.

**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 h. 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 h.

A standard mix with a w/c ratio of 0.65, aggregate-to-cement (a/c) ratio of 7.76, and cement content of 246 kg/m³ (15 lb/ft³) was used. The dosage of the air-entraining agent was kept constant, but the type and dosage of superplasticizers were varied.

**Properties of Fresh Concrete**

The properties of the fresh concrete—temperature, slump, unit weight, and air content—were determined after the initial mixing time of 6 min and again after addition of the superplasticizers and further mixing for 2 min (Table 1). Also, measurements were taken frequently to determine the rate of slump loss.

**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) for the time of setting of concrete mixtures by penetration resistance.

**PREPARATION AND CASTING OF TEST SPECIMENS**

**Series A: Concrete Mixes 1-14**

Nine 100x200-mm (4x8-in) cylinders and six 90x100x400-mm (3.5x4x16-in) prisms were cast from each mix. The only exception was the non-air-entrained control mix, for which only three cylinders and five prisms were cast. All test specimens except the control mixes 1 and 2 were cast after adding superplasticizers. Three cylinders were compacted by using a vibrating table; three cylinders were not subjected to any vibration; and the remaining three cylinders were cast (compacted on a vibrating table) after the slump had turned to its original value. The prisms were cast by filling brass molds and compacting them on a vibrating table. After casting, all the molded specimens were covered with water-saturated burlap and left in the casting room at 24 ± 1°C (75 ± 2°F) and 50 percent relative humidity for 24 h. They were then unmolded and transferred to the moist-curing room until they were required for testing.

**Series B: Concrete Mixes 15-18**

Ten 200x300-mm (6x12-in) cylinders were cast from each of the four mixes. All cylinders except that for control mix 15 were cast after superplasticizers were added. The cylinders were compacted by using an internal vibrator. After casting, all the molded specimens were covered with water-saturated burlap and left in the casting room at 24 ± 1°C (75 ± 2°F) and 50 percent relative humidity for 24 h. They were then unmolded and transferred to the moist-curing room until required for testing.

**TESTING OF SPECIMENS**

**Series A: Concrete Mixes 1-14**

The test cylinders from control mix 1 were tested at 28 days only, whereas the cylinders from control mix 2 were tested at both 7 and 28 days. All cylinders of mixes

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Table 1. Properties of fresh concrete.

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Type</th>
<th>Superplasticizer</th>
<th>Dosage ($)</th>
<th>After Initial 6-Min Mixing</th>
<th>After Addition of Superplasticizer and 2-Min Mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Temperature (°C)</td>
<td>Slump (mm)</td>
</tr>
<tr>
<td>1</td>
<td>Control without AEA</td>
<td>1.0</td>
<td>23</td>
<td>50</td>
<td>2371</td>
</tr>
<tr>
<td>2</td>
<td>Control with AEA</td>
<td>1.0</td>
<td>21</td>
<td>50</td>
<td>2333</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>1.0</td>
<td>20</td>
<td>50</td>
<td>2290</td>
</tr>
<tr>
<td>4</td>
<td>A</td>
<td>1.5</td>
<td>17</td>
<td>50</td>
<td>2270</td>
</tr>
<tr>
<td>5</td>
<td>A</td>
<td>2.0</td>
<td>19</td>
<td>100</td>
<td>2270</td>
</tr>
<tr>
<td>6</td>
<td>A</td>
<td>2.0</td>
<td>21</td>
<td>50</td>
<td>2340</td>
</tr>
<tr>
<td>7</td>
<td>B</td>
<td>2.0</td>
<td>21</td>
<td>50</td>
<td>2310</td>
</tr>
<tr>
<td>8</td>
<td>B</td>
<td>3.0</td>
<td>21</td>
<td>70</td>
<td>2340</td>
</tr>
<tr>
<td>9</td>
<td>C</td>
<td>0.5</td>
<td>25</td>
<td>50</td>
<td>2320</td>
</tr>
<tr>
<td>10</td>
<td>D</td>
<td>1.0</td>
<td>23</td>
<td>50</td>
<td>2320</td>
</tr>
<tr>
<td>11</td>
<td>D</td>
<td>1.5</td>
<td>24</td>
<td>50</td>
<td>2310</td>
</tr>
<tr>
<td>12</td>
<td>D</td>
<td>2.0</td>
<td>23</td>
<td>50</td>
<td>2330</td>
</tr>
<tr>
<td>13</td>
<td>D</td>
<td>3.0</td>
<td>23</td>
<td>50</td>
<td>2330</td>
</tr>
<tr>
<td>14</td>
<td>Control with AEA</td>
<td>1.0</td>
<td>24</td>
<td>70</td>
<td>2310</td>
</tr>
<tr>
<td>15</td>
<td>Control with AEA</td>
<td>2.0</td>
<td>22</td>
<td>50</td>
<td>2330</td>
</tr>
<tr>
<td>16</td>
<td>C</td>
<td>1.0</td>
<td>22</td>
<td>50</td>
<td>2320</td>
</tr>
<tr>
<td>17</td>
<td>B</td>
<td>2.0</td>
<td>23</td>
<td>50</td>
<td>2220</td>
</tr>
</tbody>
</table>

Notes: AEA = air-entraining agent; °C = °F - 32/1.8; 1 mm = 0.039 in; 1 kg/m³ = 0.06 lb/ft³.

*Slumps were read nearest to 10 mm for cases when slump was below 150 mm; they were read to nearest 20 mm when they were greater than 150 mm.
3–14 were tested at 28 days only. Before testing, the cylinders were removed from the moist-curing room and capped with a sulfur and flint mixture. A 272 160-kg (600 000-lb) capacity machine was used for compression testing.

Two test prisms from each of the 14 mixes were removed from the moist-curing room after 14 days and tested in flexure according to ASTM standard C78-75 by using a third-point loading.

Series B: Concrete Mixes 15–18

The test cylinders from each mix of series B were tested at 1, 7, 28, and 91 days. As in series A, the cylinders were removed from the moist-curing room immediately before testing and were capped with a sulfur and flint mixture before testing.

DURABILITY STUDIES

In this investigation, test prisms were exposed to repeated cycles of freezing in air and thawing in water according to ASTM standard C666-75. During this investigation the freeze-thaw unit did not fully meet the temperature requirements of the ASTM standard and fluctuated between -15 and -11.7°C (5 and 11°F) during freeze cycles.

The freeze-thaw test specimens were visually ex-

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Table 2. Summary of compressive strengths after 7 and 28 days.

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Superplasticizer Type</th>
<th>Dosage (%)</th>
<th>7 Days, Vibrated (MPa)</th>
<th>7 Days, Not Vibrated (MPa)</th>
<th>28 Days, Vibrated (MPa)</th>
<th>28 Days, Vibrated* (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Control without AEA</td>
<td>-</td>
<td>-</td>
<td>26.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Control with AEA</td>
<td>-</td>
<td>-</td>
<td>24.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>1.0</td>
<td>-</td>
<td>24.8</td>
<td>23.6</td>
<td>25.8</td>
</tr>
<tr>
<td>4</td>
<td>A</td>
<td>1.5</td>
<td>-</td>
<td>18.6</td>
<td>20.3</td>
<td>25.9</td>
</tr>
<tr>
<td>5</td>
<td>A</td>
<td>2.0</td>
<td>-</td>
<td>11.7</td>
<td>12.1</td>
<td>27.4</td>
</tr>
<tr>
<td>6</td>
<td>B</td>
<td>1.0</td>
<td>-</td>
<td>25.4</td>
<td>26.9</td>
<td>26.8</td>
</tr>
<tr>
<td>7</td>
<td>B</td>
<td>2.0</td>
<td>-</td>
<td>25.5</td>
<td>27.9</td>
<td>27.2</td>
</tr>
<tr>
<td>8</td>
<td>B</td>
<td>3.0</td>
<td>-</td>
<td>25.5</td>
<td>23.8</td>
<td>27.1</td>
</tr>
<tr>
<td>9</td>
<td>C</td>
<td>0.5</td>
<td>-</td>
<td>24.1</td>
<td>26.5</td>
<td>24.9</td>
</tr>
<tr>
<td>10</td>
<td>C</td>
<td>1.0</td>
<td>-</td>
<td>24.2</td>
<td>27.1</td>
<td>25.3</td>
</tr>
<tr>
<td>11</td>
<td>C</td>
<td>1.5</td>
<td>-</td>
<td>24.0</td>
<td>27.0</td>
<td>27.2</td>
</tr>
<tr>
<td>12</td>
<td>D</td>
<td>1.0</td>
<td>-</td>
<td>25.8</td>
<td>25.0</td>
<td>26.5</td>
</tr>
<tr>
<td>13</td>
<td>D</td>
<td>2.0</td>
<td>-</td>
<td>24.0</td>
<td>23.0</td>
<td>24.6</td>
</tr>
<tr>
<td>14</td>
<td>D</td>
<td>3.0</td>
<td>-</td>
<td>24.4</td>
<td>22.9</td>
<td>24.6</td>
</tr>
</tbody>
</table>

Notes: 1 mm = 0.039 in; 1 MPa = 145 lbf/in².

*Compressive strength of control mix with AEA at 28 days is the average of six test results; the remainder are averages of three test results.

*These cylinders were cast after the slump had reverted to the original value.
Table 3. Summary of compressive strengths after 1, 7, 28, and 91 days.

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Superplasticizer Type</th>
<th>Dosage (%)</th>
<th>After 1 Day (MPa)</th>
<th>After 7 Days (MPa)</th>
<th>After 28 Days (MPa)</th>
<th>After 91 Days (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Control with AEA</td>
<td></td>
<td>8.8</td>
<td>18.8</td>
<td>22.5</td>
<td>24.6</td>
</tr>
<tr>
<td>16</td>
<td>B</td>
<td>2</td>
<td>8.9</td>
<td>16.3</td>
<td>23.4</td>
<td>25.4</td>
</tr>
<tr>
<td>17</td>
<td>C</td>
<td>1</td>
<td>8.3</td>
<td>-</td>
<td>21.2</td>
<td>24.1</td>
</tr>
<tr>
<td>18</td>
<td>D</td>
<td>2</td>
<td>7.6</td>
<td>16.0</td>
<td>20.3</td>
<td>22.0</td>
</tr>
</tbody>
</table>

Notes: 1 mm = 0.039 in; 1 MPa = 145 lbf/in².

*Compressive strength of test specimens of control mix with AEA is the average of three test results. Compressive strength of test specimens of other mixes at 1, 7, 28, and 91 days are the averages of three, two, three, and two results, respectively.

Table 4. Summary of flexural strength test results.

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Superplasticizer Type</th>
<th>Dosage (%)</th>
<th>Strength of Moist-Cured Prisms After 14 Days (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Control without AEA</td>
<td></td>
<td>5.8</td>
</tr>
<tr>
<td>2</td>
<td>Control with AEA</td>
<td></td>
<td>5.2</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>1.0</td>
<td>5.4</td>
</tr>
<tr>
<td>4</td>
<td>A</td>
<td>1.5</td>
<td>4.3</td>
</tr>
<tr>
<td>5</td>
<td>A</td>
<td>2.0</td>
<td>3.3</td>
</tr>
<tr>
<td>6</td>
<td>B</td>
<td>1.0</td>
<td>5.1</td>
</tr>
<tr>
<td>7</td>
<td>B</td>
<td>2.0</td>
<td>4.9</td>
</tr>
<tr>
<td>8</td>
<td>B</td>
<td>3.0</td>
<td>4.9</td>
</tr>
<tr>
<td>9</td>
<td>C</td>
<td>0.5</td>
<td>5.4</td>
</tr>
<tr>
<td>10</td>
<td>C</td>
<td>1.0</td>
<td>5.1</td>
</tr>
<tr>
<td>11</td>
<td>C</td>
<td>1.5</td>
<td>4.8</td>
</tr>
<tr>
<td>12</td>
<td>D</td>
<td>1.0</td>
<td>5.1</td>
</tr>
<tr>
<td>13</td>
<td>D</td>
<td>2.0</td>
<td>5.1</td>
</tr>
<tr>
<td>14</td>
<td>D</td>
<td>3.0</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Note: 1 MPa = 145 lbf/in².

*Each result is the mean of tests on two prisms; testing was done at third-point loading.

Figure 5. Compressive strength of test cylinders at 28 days for superplasticizer A.

TEST RESULTS AND ANALYSIS

Altogether 169 cylinders and 83 prisms were tested in this investigation. The loss of slump with time is shown in Figures 1-4. A summary of the compressive and flexural strength is given in Tables 2-4 and the data are illustrated in Figures 5-9. Changes in weight, length, pulse velocity, and resonant frequencies of reference prisms and prisms subjected to freeze-thaw cycles are shown in Table 5. The results of the air-void analyses of the hardened concrete test specimens are given in Table 6.

DISCUSSION OF RESULTS

Initial Time of Set of Concrete

Studies were performed only for superplasticizers B, C, and D, and in each case there was some retarding effect on the time of set. However, this was not significant from a practical point of view because maximum retardation was only 42 min (superplasticizer D). These results are similar to the data for concretes with a w/c ratio of 0.42 reported in 1977.

Segregation of Superplasticized Concrete

When examined visually, the superplasticized concretes did show segregation that ranged from insignificant for concrete incorporating superplasticizer C to considerable for concrete incorporating superplasticizer A. In the latter case there was almost complete separation of the mortar fraction. This degree of segregation is unacceptable for field application.

The excessive segregation problem may be overcome by increasing the amount of fines in the mix, such as fly ash or the amount of 50- to 100-mesh fraction of the fine aggregate.

Slump Increases and Losses with Time

Superplasticized concretes exhibited large increases in slump at the recommended dosages. The slumps reached 175 mm (7 in) or more within minutes of adding the superplasticizers, and 50- to 75-mm (2- to 3-in) slump concretes became flowing concretes. And, except for concrete made with superplasticizer A, even at these high slumps there was no significant segregation. The concretes maintained the initial slump for about 5 min,
after which there was rapid slump loss. Concrete incorporating superplasticizer A lost slump more rapidly than the other concretes.

Generally the concretes had reverted to about 50-mm (2-in) slumps in 40 ± 10 min, under laboratory temperature and humidity conditions. At maximum recommended dosages of superplasticizer A = 2.0 percent, superplasticizer B = 3.0 percent, superplasticizer C = 1.5 percent, and superplasticizer D = 3.0 percent, the superplasticized concrete lost slump at a slower rate. At the elapsed time of about 70 min, concretes incorporating superplasticizers A, B, and C had residual slumps of 50 mm (2 in). The corresponding value for

Table 5. Summary of freeze-thaw test results.

<table>
<thead>
<tr>
<th>Superplasticizer</th>
<th>Dosage ($)</th>
<th>Weight (kg)</th>
<th>Length (mm)</th>
<th>Longitudinal Resonant Frequency (Hz)</th>
<th>Pulse Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control without AEA</td>
<td>8.75</td>
<td>3.48</td>
<td>4950</td>
<td>4661</td>
<td></td>
</tr>
<tr>
<td>Control with AEA</td>
<td>8.46</td>
<td>3.06</td>
<td>4960</td>
<td>4520</td>
<td></td>
</tr>
<tr>
<td>A 1</td>
<td>8.16</td>
<td>3.65</td>
<td>4999</td>
<td>4611</td>
<td></td>
</tr>
<tr>
<td>B 2</td>
<td>8.63</td>
<td>3.67</td>
<td>5030</td>
<td>4530</td>
<td></td>
</tr>
<tr>
<td>C 1</td>
<td>8.71</td>
<td>3.93</td>
<td>5049</td>
<td>4617</td>
<td></td>
</tr>
<tr>
<td>D 2</td>
<td>8.58</td>
<td>2.71</td>
<td>5000</td>
<td>4557</td>
<td></td>
</tr>
</tbody>
</table>

Notes: 1 kg = 2.2 lb; 1 mm = 0.039 in; 1 m/s = 3.28 ft/s.

*Gauge length = 345 mm.
and in Figures 5-8. The following general observations
placing flowing concretes in basement walls and other
be superplasticized, which offers opportunities for

- Calculated from mix proportions.
- Compressive Strength at 28 Days
- Compressive Strength Development

<table>
<thead>
<tr>
<th>Type</th>
<th>Dosage ($)</th>
<th>Paste Content ($)</th>
<th>Voids in Concrete ($)</th>
<th>Void-Spacing Factor (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control without AEA</td>
<td>27.9</td>
<td>2.2</td>
<td>1.27</td>
<td></td>
</tr>
<tr>
<td>Control with AEA</td>
<td>24.0</td>
<td>6.5</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>B 1.0</td>
<td>24.0</td>
<td>5.2</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>B 2.0</td>
<td>24.0</td>
<td>4.9</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>B 3.0</td>
<td>24.0</td>
<td>3.8</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td>C 0.5</td>
<td>24.0</td>
<td>4.8</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>C 1.0</td>
<td>24.0</td>
<td>3.0</td>
<td>0.41</td>
<td></td>
</tr>
<tr>
<td>C 1.5</td>
<td>24.0</td>
<td>3.3</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>D 1.0</td>
<td>24.0</td>
<td>5.6</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>D 2.0</td>
<td>24.0</td>
<td>4.8</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>D 3.0</td>
<td>24.0</td>
<td>5.0</td>
<td>0.31</td>
<td></td>
</tr>
</tbody>
</table>

Note: 1 mm = 0.039 in.

concrete incorporating superplasticizer D was 85 mm
(3.5 in).

It appears that concretes having high w/c ratios can
be superplasticized, which offers opportunities for
placing flowing concretes in basement walls and other
similar structures. The principal advantage of the
superplasticizers under these conditions would be the
savings from reduced labor needs for handling, placing,
and compacting of concrete.

Compressive Strength Development

Compressive Strength at 28 Days

The compressive strength results are shown in Table 2
and in Figures 5-8. The following general observations
can be made.

1. At the recommended dosage rates
a. The compressive strength of cylinders cast
by vibration was between 2 and 10 percent
higher than the strength of cylinders cast
from the air-entrained control mix (the only
exception was concrete incorporating super-
plasticizer A, where there was a very slight
decrease in the strength that is of little prac-
tical significance);

b. The compressive strength of cylinders cast
without vibration was comparable to that
of the cylinders cast from the air-entrained
control mix; and

c. The compressive strength of cylinders cast
with vibration from concrete after it had re-
verted to the original slump was between 2
and 10 percent higher than the strength of
cylinders cast from the air-entrained control
mix. This is even true for concrete incor-
porating superplasticizer A.

2. At the maximum recommended dosage rates
a. The compressive strengths of superplasticized
cylinders, cast with and without vibration,
were comparable to strengths of cylinders
cast from the air-entrained control mix, al-
though there were exceptions: The cylinders
cast from concrete incorporating superplas-
ticizer A showed about 50 percent loss in
strength compared to the control cylinders,
which was probably due to the excessive seg-
regation of the mix, while the strength of
cylinders cast from concrete incorporating
superplasticizer C was about 11 percent
higher than the strength of the control cy-
linders;

b. The strengths of the superplasticized cy-
linders cast from cements after the slump
had returned to the original value of about 50
mm (2 in) were comparable to or about 11
percent higher than the strength of the control
cylinders. This is probably due to the loss
of moisture from the fresh concrete.

Compressive Strength Versus Age

The compressive-strength-versus-age test results are
shown in Table 3 and Figure 9.

It will be seen from the data that, at the recommended
dosage rates, the compressive strengths of cylinders
cast from concrete incorporating superplasticizers B
and C were comparable to the strength of the control
cylinders at all ages. However, the compressive
strength of cylinders cast from concrete incorporating
superplasticizer D was consistently lower than the
strength of the control cylinders at all ages. At 91 days
the difference was about 9 percent. The lower strengths
were probably due to the high amounts of entrained air
retained by the concrete after the superplasticizer had
been added. These results agree with data reported
earlier for low w/c ratio concrete (3).

Flexural Strength

In general, the 14-day flexural strengths of test prisms
(Table 4) cast from the concretes superplasticized at the
recommended dosage rates showed no significant change
from the strengths of the control prisms. The strength
values were of the order of 5 MPa (725 lbf/in²). How-
ever, the prisms cast from concrete incorporating
superplasticizers A, B, and C showed a steady drop in
strength with increased dosage rate. For example, at
the maximum recommended dosage rates the 14-day
strength values were 3.27, 4.92, and 4.76 MPa (475,
715, and 690 lbf/in²), respectively. The prisms cast
from concrete incorporating superplasticizer D, to the
contrary, showed a very slight increase in strength with
increased dosage rates; at the maximum recommended
dosage rate, the 14-day strengths reached a value of
5.24 MPa (760 lbf/in²).

DURABILITY OF CONCRETE PRISMS
EXPOSED TO REPEATED FREEZE-
THAW CYCLES

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
cycles and then comparing these with corresponding
values of the reference prisms. The test prisms had
been cured for 13 days in a moist-curing room before
being subjected to freezing and thawing.

The non-air-entrained control prisms had shown con-
siderable distress after about 30 freeze-thaw cycles.
The tests were discontinued after 45 freeze-thaw cycles,
at the end of which the residual flexural strength of the
prisms was only 3.8 percent.

In general, there were no significant changes in the
test prisms cast from air-entrained superplasticized
concrete at the end of 300 cycles (Table 5). Tests are
being continued and the performance of the prisms up to
the end of 1000 cycles will be reported at a later date.

Test results have indicated that all prisms performed
just about equally well, at least up to 300 cycles. This
was also confirmed by the results of flexural strength tests of the prisms. However, there are indications that test prisms incorporating superplasticizer A may not last much beyond 400 freeze-thaw cycles.

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 that incorporates chemical admixtures. Nevertheless, the reported freeze-thaw data are still considered valid because the freeze-thaw is a comparative test carried out with the specimens cast from the control mixes. For this investigation, the test prisms cast from the non-air-entrained control mix had disintegrated at less than 45 freeze-thaw cycles. Data published by others (7) indicate that superplasticized concrete prisms perform satisfactorily when exposed to rapid freezing and thawing in water in accordance with procedure A.

AIR-VOID DETERMINATION OF HARDENED CONCRETE

The microscopic determination of air-void content and parameters of the air-void system in hardened concrete was made according to ASTM standard C457-71. It has been found that for satisfactory durability the cement paste should be protected with air bubbles (4). Adequate protection required 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 0.20 mm (0.008 in).

In this investigation the air-entrained concrete had a void-spacing factor of 0.254 mm (0.01 in) but performed satisfactorily in freeze-thaw cycling (Table 6). The superplasticized concrete investigated for air-void determination had bubble-spacing factors that ranged from 0.254 to 0.432 mm (0.01 to 0.017 in). In spite of the increased bubble spacing, the durability of concretes incorporating superplasticizers B and D was not impaired. It appears that bubble-spacing factor limitations stipulated for air-entrained concrete may not be valid for concretes incorporating superplasticizers. Further research is needed on how these parameters can be correlated with the performance of concrete under freeze-thaw cycles.

CONCLUSIONS

At the recommended dosage rates there was no significant segregation of concrete except for the mix incorporating one of the naphthalene-based superplasticizers. High dosages of superplasticizers are not recommended because of the tendency of the concrete to segregate. This is particularly true of superplasticizer A.

All superplasticizers investigated had only insignificant retarding effects on the time of initial set of concrete.

When superplasticizers are added to concrete at the manufacturers' recommended dosage rates, the 28-day compressive strengths of test cylinders cast from superplasticized concrete are comparable to or greater than the corresponding strengths of cylinders cast from the reference mix. The strengths are comparable when the cylinders from the superplasticized concrete are cast without compaction by vibration and greater when cast with compaction by vibration.

For recommended dosage rates, the freeze-thaw durability of the test prisms cast from the superplasticized concretes compared favorably with those cast from the air-entrained control mix at the end of 300 freeze-thaw cycles. The nature of the relationship between the durability of superplasticized concrete and the value of its bubble-spacing factor needs further research. Superplasticizers are more expensive than ordinary water-reducing admixtures and therefore may or may not be economical for use in concrete of a high w/c ratio.

This aspect will have to be considered for each job situation.

The results reported here were obtained with concrete of a w/c ratio of 0.65 and made with ASTM type I cement. The superplasticizers may or may not perform as reported in concrete made with other w/c ratios and with different types of cements and aggregates.

REFERENCES