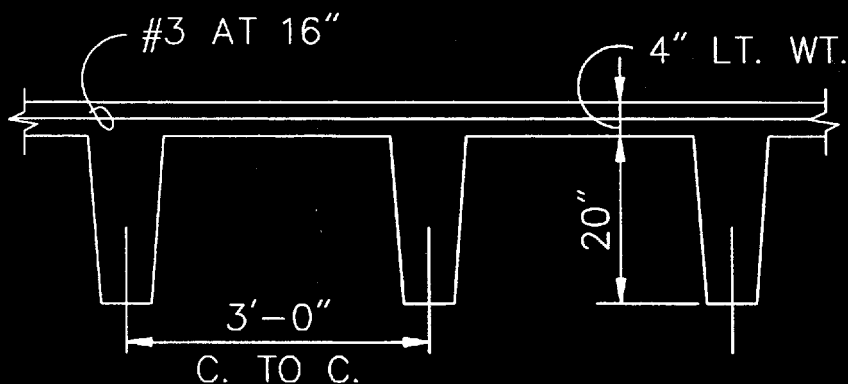
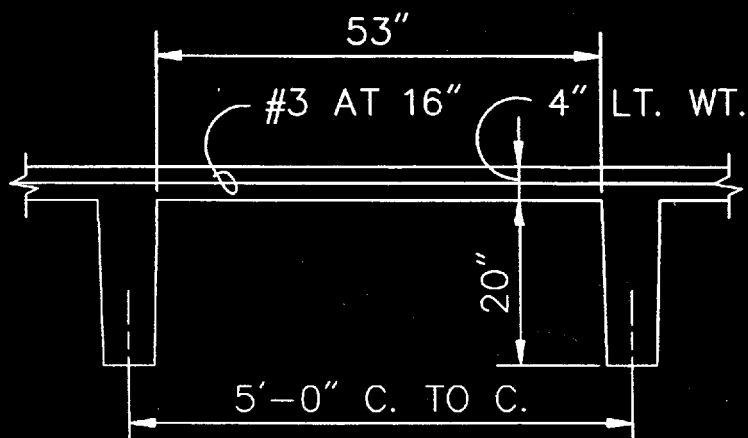


Structural Lightweight Aggregate Concrete Performance



Thomas A. Holm
Alexander M. Vaysburd
Editors

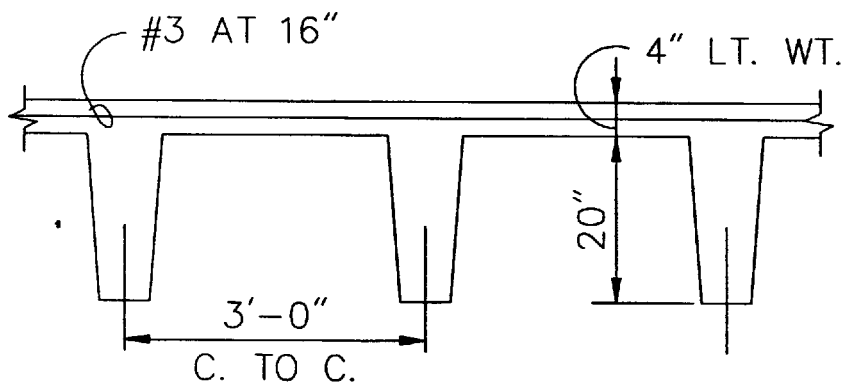
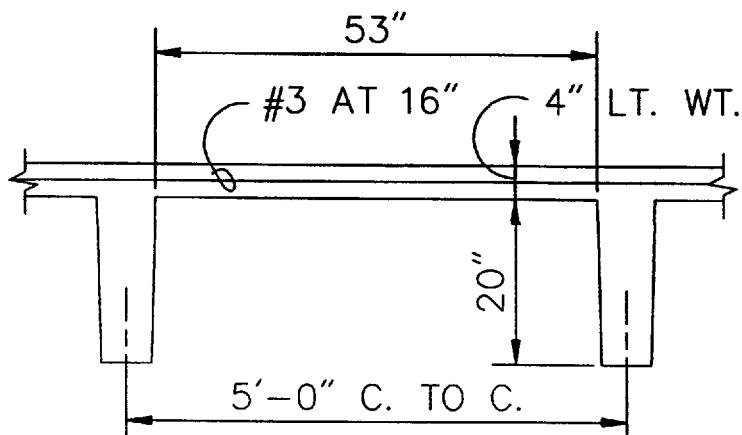


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Structural Lightweight Aggregate Concrete Performance



Thomas A. Holm
Alexander M. Vaysburd
Editors



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PREFACE

This volume is a compilation of papers addressing the "Performance of Structural Lightweight Concrete" presented at the November 14, 1991 technical session of the American Concrete Institute fall convention in Dallas, Texas. Planning for this symposium, sponsored by ACI Committee 213, "Structural Lightweight Aggregate," was in response to construction industry and engineering community interest in using structural lightweight concrete in severe environment applications. The immediate need for disseminating state-of-the-art information motivated the development of this two session symposium.

The speakers addressed topics ranging from fundamental laboratory studies to case histories of concrete performance. The papers include application of lightweight concrete for bridges, arctic structures, buildings and parking structures, aspects of structural design, production and durability of lightweight concrete structures.

We thank the authors for sharing their knowledge, and Messrs. John P. Ries and Dr. Theodore W. Bremner for serving as session co-chairmen. A special note of appreciation is directed towards the many session paper reviewers and to the support and constructive suggestions offered by the 213 committee members and their chairman, David Akers.

Thomas A. Holm
Alexander M. Vaysburd
Session Chairmen

ACI Committee 213
 LIGHTWEIGHT AGGREGATES AND
 LIGHTWEIGHT AGGREGATE CONCRETE

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SP 136-1

High Strength Lightweight Aggregate Concrete for Arctic Applications—Part 1

by G.C. Hoff

Synopsis: This paper is Part 1 of a three part paper which presents the results of a Joint Industry Project to develop high strength lightweight aggregate concretes for use in the Arctic. Described in Part 1 are the lightweight aggregate selection tests, high strength mixture development with the selected aggregates, batching procedures, unhardened properties of the 110 batches made during the program, and the temperature development of the mixtures in large sections of concrete. Both crushed and pelletized lightweight aggregates were used with supplementary cementing materials and high-range water reducers to produce concretes with compressive strengths from 8,000 psi (55 MPa) to 11,000 psi (76 MPa). Also evaluated was the influence of pumping on the aggregate moisture content, slump, unit weight, air content, and concrete strength. The effects of the air void system in the hardened pumped concrete with respect to freezing and thawing durability and the drying behavior of a large section of concrete were also evaluated.

Keywords: Air entrainment; arctic concrete; blast furnace slag; cold weather construction; compressive strength; drying; fly ash; freeze thaw durability; harbor structures; high strength concretes; lightweight aggregates; marine atmospheres; offshore structures; pumped concrete; silica fume; slump; temperature; tensile strength; unit weight

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INTRODUCTION

The study of the use of high-strength lightweight aggregate concrete for Arctic applications was a 3-1/2 year, 3 Phase effort conducted as a joint-industry project involving 11 companies (See ACKNOWLEDGMENTS). The complete results of the study can be found in (1, 2, and 3). A summary of results are presented in 3 parts in the Proceedings of this Symposium.

Part 1, described herein, presents the study rationale, materials selection, mixture development, and unhardened concrete properties including temperature development and pumping considerations. Part 2 (4) presents the test results from the mechanical testing of the hardened concretes described in Part 1. These include strength and modulus, creep and shrinkage, permeability and absorption, thermal characteristics, ice bond development strength, and durability observations. Part 3 (5) presents the results from more complex structural parameter determinations to include stress versus strain behavior, multiaxial stress behavior, beam shear strength, bearing strength, shear-friction capacity, and reinforcement development length.

The study also evaluated the effectiveness of coatings in reducing both the friction coefficient at the ice/structure interface of an offshore Arctic structure. As the coating study was not directly evaluating the high-strength lightweight aggregate concrete but only the coatings, it is not included in this 3 Part summary. The complete results of the coating study can be found in (3).

This Part of the 3 Part summary presents the target concrete properties used throughout the program, the selection process for the lightweight aggregates, mixture development to meet the target properties, and the unhardened properties of the 110 batches of the concrete made over the duration of the program. The hardened properties from those batches are described in Parts 2 and 3 (4,5) of this paper. Once the final mixtures were selected for the program, the heat

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development that each would produce in large sections of concrete was evaluated along with the effects of that heat on the compressive strength of the in-situ concrete. One mixture was selected for use in a field pumping tests using actual field pumping equipment. This test was used to evaluate the effects of pumping on the moisture content of the lightweight aggregate, the effects on slump, unit weight, and air content in the unhardened concrete, and the effects on both the compressive strength and air void system in the pumped concrete after it had hardened. A large section of concrete was also produced and evaluated with respect to rates of drying of the concrete.

CONSIDERATIONS IN THE USE OF CONCRETE IN OFFSHORE ARCTIC STRUCTURES

Concrete has been proven as a durable, efficient, cost-effective construction material for offshore and marine structures in temperate and sub-arctic locations. It has also been seriously considered for developments in the Arctic because of its well-established record of providing adequate structural performance at extremely low temperatures. Two offshore exploration structures (6 and 7) for Arctic use have been built with lightweight aggregate concrete and successfully used in the arctic environment. The exploration and production structures being considered for Arctic applications are usually bottomed-founded gravity base structures which function as a floating vessel until they are permanently installed. For more information on these types of structures, the reader is referred to a detailed report (8) prepared by ACI Committee 357, Offshore and Marine Concretes.

Many unique considerations enter into the design, construction, installation, and operation of a concrete structure for use in the Arctic that normally would not influence the structure if it were used in a more moderate climate. The first of these is that it cannot be economically built close to where it will be used because of the extremely low temperatures that exist in the Region for most of the year. For structures that might be used in the United States and Canadian Arctic or the eastern Arctic of the Soviet Union, they would most likely be built in the Pacific Basin south of the Aleutian Islands and towed to their final location. Anticipated construction locations for those structures have access to lightweight aggregate sources.

The second consideration is that the structure must have as much as possible of its operating equipment and

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consumables on it when it is towed to the Arctic. The ice-free season, when crane barges and supply boats can access the structure at its installed location, is very limited. If possible, the structure should have all of its equipment and at least nine months consumables on it when it is towed. The total weight of these items can easily be between 70,000 to 120,000 tons (64,000 to 109,000 tonnes) depending on the operational requirements of the structure.

The third consideration is the draft at which the fully loaded structure will be towed and installed. Draft limitations exist in the Bering Strait through which the structure must pass on its way to the Arctic. The water depth where the structure will be installed is extremely critical as the structure must be able to float over the final location before it is ballasted down to the sea floor. The large equipment and consumable weight, together with the weight of the structure, displaces very large amounts of water. To accommodate this displacement, the structure must be quite large in base area in order to have an acceptable draft. By using lightweight aggregate concrete in the structure rather than normal weight concrete, for a desired draft, the weight of the structure can be reduced between 20 to 30 percent thus allowing more equipment and consumables weight to be carried for a given size of structure, or the size of the structure can be reduced for a given weight.

The focus of this research program was to examine many of the aspects of arctic environment that might adversely affect the selection of the lightweight aggregate concrete for these structures. Not all lightweight aggregates are suitable for use in that environment so a proper selection process is necessary. The lightweight aggregate concrete will be subjected to unusually severe freezing and thawing exposures, continual saturation in sea water with the potential for chloride ion infiltration, impact and abrasion from floating ice, and the formation of sea ice on surface of the structure. To provide satisfactory performance against most of these demands, the lightweight aggregate concrete needs to have considerably more strength and improved durability than is usually required for lightweight concrete applications.

The performance of the concrete may also be influenced by the construction methods used. A typical construction scenario for these large structures is to use pumping to distribute the concrete to the extensive formwork for the structure. Pumping may introduce excess moisture into lightweight aggregates and thus adversely affect their performance with respect to

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long-term durability. This potential problem is also examined in the program along with other construction related problems such as heat development in large sections of concrete. Most ice-resistant walls of these structures and the base slabs will be, as a minimum, 3 ft (0.9 m) thick or greater.

Design procedures using high-strength lightweight concrete are not well defined. Several Code requirements which are commonly used in the design of offshore structures are examined as to their applicability for use with the concretes developed in this program. Other mechanical properties that also enter into the design process such as modulus of elasticity, splitting tensile strength, multiaxial stress behavior, and thermal properties of the concrete are also developed.

The Joint Industry Project participants in this research program (See ACKNOWLEDGEMENTS) provided input as to observed arctic climate, construction requirements, towing requirements, and desired performance, all of which were used to develop the research program described in this three part paper.

TARGET CONCRETE PROPERTIES

The operational conditions to which an arctic offshore or marine structure will be exposed requires a unique blend of concrete properties. Because the precise location for the use of the structure is not defined at this time, the target concrete properties of this program should be considered only as typical of what might be required. They are reasonable with respect to what can be practically produced with the current generation of concrete materials.

DESIGN COMPRESSIVE STRENGTH AND UNIT WEIGHT

Two target levels of strength and unit weight for the concrete were selected. In general, lightweight aggregate concrete can be made stronger by adding materials which increase the unit weight. These target values were:

$$f'_c = 7000 \text{ psi (48 MPa), minimum}$$

$$\gamma_{\text{sat}} = 120 \text{ lbs/cu ft (1920 kgs/cu m), maximum}$$

for typical concretes who were given designations of LWC. For very high strength lightweight aggregate concrete, the target values were:

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$f'_c = 9000 \text{ psi (62 MPa), minimum}$

$\gamma_{\text{sat}} = 130 \text{ lbs/cu ft (2080 kgs/cu m), maximum}$

and were given the designation of HSLWC. The compressive strength, f'_c , is defined as the minimum specified strength at 90-days age. The unit weight, γ_{sat} , is that of the hardened concrete after curing and after long-term exposure to a 200 ft (61 m) hydrostatic head.

WATER-CEMENT RATIO AND SLUMP

For high strength, high durability marine concretes, the water-cement ratio needs to be as low as practical with respect to the constructability requirements of the structure. For this study, a maximum value of 0.35 by weight was adopted. Considering this value and the need for proper compaction and finishing of the concrete, a slump range of 4 to 6 in. (102 to 152 mm) was also selected. There may be many areas in the arctic marine structures where the reinforcing bar density may become so large that modifications in the water-cement ratio and slump values may be required to facilitate concrete placement. These changes can be handled on an as-needed basis.

AIR CONTENT

The total volume and distribution of entrained air in the concrete has a marked influence on the freezing and thawing performance of the lightweight aggregate concrete. Too much air will adversely affect the concrete strength while too little air will result in early freezing and thawing damage. A compromise between these two requirements resulted in a target range of 4% to 6% entrained air.

STRENGTH GAIN WITH AGE

In an effort to address the constructional and operational scenarios anticipated for typical marine arctic concrete structures, the following minimum requirements for compressive strength at various ages were selected as a guide to mixture design trial batching activities:

$f_c = 3500 \text{ psi (24 MPa) at 24 hours (steam cured)}$

$f_c = 4200 \text{ psi (29 MPa) at 7 days}$

$f'_c = 7000 \text{ psi (48 MPa) at 28 days (LWC)}$

$f'_c = 9000 \text{ psi (62 MPa) at 28 days (HSLWC)}$

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AGGREGATE SELECTION TEST PROGRAM

Based on previous experience with lightweight aggregates and the recommendations of the Expanded Shale, Clay and Slate Institute (USA), a number of lightweight aggregates believed to be capable of meeting the criteria noted above were chosen for screening tests to determine which would be best suited for the entire program. No lightweight aggregates from Europe were considered because of their distance from the Pacific Basin and the anticipated increase in their cost to deliver them to that region. It is known that competent European lightweight aggregates exist and could possibly be used depending on the construction location and project requirements.

Ten lightweight aggregates were evaluated and came from eight different producers. One aggregate was produced in Japan, one in Canada, and seven in the United States. One USA aggregate had two size fractions evaluated thus making the tenth aggregate in the evaluation. Another USA aggregate producer provided aggregates from two different production facilities.

AGGREGATE PROPERTIES

Four screening tests were performed on each aggregate to determine the important properties for the use of that aggregate in concrete. The tests performed were:

- a. As-received moisture content, ASTM C 566
- b. Aggregate gradation, ASTM C 136
- c. Dry, loose unit weight, ASTM C 29
- d. 24-hour absorption, ASTM C 127

The results of these tests are shown in Tables 1 and 2.

The as-received moisture content is generally indicative of what an aggregate supplier will deliver but can vary widely with ambient conditions, method of shipment, and time and location in the manufacturer's stockpile. More important, the moisture content, when compared to the 24-hour absorption, indicates how much water demand the lightweight aggregate will have when initially combined with water in the mixture.

The aggregate gradation indicates whether the individual aggregate fractions will yield minimum voids in the concrete. The USA industry grading requirements are contained in ASTM C 330, "Lightweight Aggregates for Structural Concrete," and are reproduced in Table 3.

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Both the density and the strength of individual particles of lightweight aggregate decrease as the size fraction increases. The smaller size fractions can be expected to produce stronger concrete with a higher unit weight.

ASTM C 330 also has a requirement that the maximum dry loose weight of the coarse aggregate be 55 lbs/cu ft (880 kgs/cu m). By definition, aggregates weighing more than this are not considered lightweight aggregates.

The amount of water that lightweight aggregate will absorb in 24-hours after being initially dry significantly affects the loss of slump in unhardened concrete. Lightweight aggregates with open porous surfaces have high rates and amounts of absorption whereas those who have a protective coating or shell around them formed during the heating and expanding process or those whose pore structure is not significantly interconnected, will have desirable low rates and amounts of absorption. Aggregates with high absorption rates will require substantial pre-wetting to prevent early slump loss. The pre-wetting, however, may raise the moisture level of the aggregate to a level that is unsuitable for resistance to freezing and thawing damage.

INITIAL AGGREGATE TESTS IN CONCRETE

In order to assess the strength characteristics of each aggregate in concrete, each of the ten aggregates was used in an identical concrete mixture whose proportions are shown in Table 4. Proportioning was done by volume and not weight.

The cement was the same Type I/II Portland cement as used in the entire program and is described below. The fine aggregate was a natural sand having an absorption of 1.6%, a specific gravity of 2.67, and a fineness modulus of 2.89. An identical proportion of sand and lightweight aggregate was used in each mixture and was typical of that used in industry.

The target air content was 4% which is typical of what is recommended for high strength concretes. A target slump of 3 in. (76 mm) was selected. It was assumed that higher slumps would be used for the test programs concretes. The unhardened concrete test results are shown in Table 5.

No water-reducing admixtures or supplementary cementing materials were used in the screening tests because it

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was necessary to produce consistent slump and air content in each mixture for aggregate comparisons without them being influenced by the other additions. By not using these additions, the compressive strength levels were not as high as could be obtained although the relative performance of each aggregate appeared to be unaffected.

Both accelerated curing and standard moist curing were used. Compressive strength and splitting tensile tests were performed on 4 by 8 in. (100 by 200 mm) cylinders. The results are shown in Table 6.

AGGREGATE SELECTION

From Table 1, aggregates No. 4, 7, and 10 exhibited the lowest 24-hour absorptions. All three of these aggregates also produced concrete with 28-day compressive strengths (Table 6) in excess of 6000 psi (41 MPa). The unhardened unit weights of concretes made with these aggregates were 113.9, 119.3, and 119.8 lbs/cu ft (1825, 1911, 1919 kgs/cu m), respectively, all of which were below the target unit weight value of 120 lbs/cu ft (1922 kgs/cu m).

Aggregate No. 4 was a pelletized aggregate made in Japan. Aggregate Nos. 7 and 10 were crushed aggregates made in the USA. Of the two USA aggregates, aggregate No. 10 had a demonstrated use in high strength concrete whereas aggregate No. 7 did not. It was therefore decided to complete the remainder of the high strength lightweight aggregate concrete development program with aggregates No. 4 and 10.

MIXTURE OPTIMIZATION

In order to develop the mixtures to meet the target concrete properties, 69 optimization mixtures were made and evaluated. These are not reported in this summary but can be found in (1 and 2). From these optimization mixtures, five lightweight concrete mixtures were selected and used during the study. All the mixtures were made with commercially available materials as described below. Identical cement type, mixing water, air-entraining admixtures, and high-range water reducing admixtures were used in all mixtures. Each of the lightweight concretes contained a supplementary cementing material. The lightweight aggregates used were the crushed aggregate from the USA (Aggregate No. 10) and the pelletized aggregate from Japan (Aggregate No. 4). The various mixtures are identified and characterized as follows:

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<u>Mixture</u>	<u>Coarse Aggregate</u>	<u>Supplementary Cementing Material</u>
LWC1	Crushed Lightweight	Silica Fume
LWC2	Pelletized Lightweight	Silica Fume
LWC3	Pelletized Lightweight	Fly Ash
LWC4	Pelletized Lightweight	Blast Furnace Slag
HSLWC	Pelletized Lightweight	Silica Fume
NWC	Normal Weight	None

A normal density concrete, NWC, was also included in the program for reference purposes, where needed. The proportions of these final mixtures are shown in Table 7.

CONSTITUENT MATERIALS

CEMENT

Type I/II Portland cement from a single source was used throughout the program. Four separate shipments of the cement were received and used over the duration of the study. The chemical and physical properties of each shipment, as listed in silo test certificates, are shown in Table 8. These cements met the requirements of ASTM C 150, "Standard Specification for Portland Cement," for a Type I/II cement. This particular cement has a long history of good performance in marine environments throughout the Northwest Region of the USA and Alaska. It has a low C_3A content (5.2% to 6.4%) which is desirable for cement used in a seawater exposure. The low C_3A also results in reduced water demand in the fresh concrete and this, in turn, leads to improved strength potential.

SUPPLEMENTARY CEMENTING MATERIALS

Silica fume from a single supplier was used in LWC1, LWC2, and HSLWC. Table 9 shows the chemical and physical properties of the silica fume as determined by the manufacturer.

Fly ash from a single supplier was used in LWC3. Table 10 shows the chemical and physical properties of the fly ash as determined by the manufacturer. The fly ash met the requirements of ASTM C 618, "Fly Ash and Raw or Calcined Natural Pozzolan for use as a Mineral

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Admixture in Portland Cement Concrete," for Class F fly ash.

Blast furnace slag from a single supplier was used in LWC4. Table 11 shows the chemical and physical properties of the blast furnace slag as determined by the manufacturer. The blast furnace slag met the requirements of ASTM C 989, "Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars" for a Grade 120 slag.

CHEMICAL ADMIXTURES

Based on optimization tests performed with three different high-range water reducing admixtures (HRWRA), a particular HRWRA which had the best water-reducing and strength-producing characteristic of the three was selected for the remaining mixtures. This HRWRA was a sulphonated naphthalene formaldehyde condensate and met the requirements of ASTM C 494, "Chemical Admixtures for Concrete," for both a Type A water reducing admixture and a Type F high-range water reducing admixture.

The air-entraining admixture (AEA) chosen was a well established neutralized vinsol resin meeting the requirements of ASTM C 260, "Air-Entraining Admixtures for Concrete," and ASTM C 233, "Standard Test Method for Air-Entraining Admixtures for Concrete". It was compatible with the HRWRA that was used.

FINE AGGREGATES

Two fine sands were used during the program. Both were mixtures of carbonates (dolomitic) and siliceous aggregates. Their physical properties were similar and are described in Fig. 1. Mixtures were adjusted to account for the small differences in absorption and specific gravity of the two sands. Any differences between the two sands did not measurably alter the properties of the unhardened or hardened concrete.

COARSE AGGREGATES

The two lightweight aggregates chosen (Nos. 4 and 10) resulted from the screening tests described earlier. The crushed lightweight aggregate is produced in the USA and came from standard production runs of the material. A nominal size of 3/4 in. (19 mm) was selected to optimize the weight/strength performance.

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The pelletized lightweight aggregate is produced in Japan and came from standard production runs of the material. A nominal size of 5/8 in. (16 mm) was selected to optimize the weight/strength performance.

Typical physical properties of both lightweight aggregates and a reference normal weight aggregate are shown in Fig. 1. The normal weight aggregate was a gravel with a 3/4 in. (19 mm) maximum size with a fineness modulus of 6.50.

For field production of the lightweight aggregate concrete, the water absorption characteristics of the aggregate must be known in order to account for the water absorbed by the aggregate during batching and mixing. For the two lightweight aggregates of this study, a number of aggregate samples (approximately 3.3 lb (1500 gm) were oven dried to a constant weight, soaked in water for selected periods of time (15 minutes to 24 hours), brought to a surface-dry condition, weighed and re-dried to determine moisture content. The results are shown in Fig. 2.

The rate of absorption of both aggregates was initially rapid and markedly decreased with the time of soaking. After the initial 30 minutes, absorption appeared to be logarithmically related to time of soaking. After 45 minutes of soaking, both aggregates achieved approximately 50% of their 24-hour absorption values.

BATCHING PROCEDURES

The batching of all the lightweight aggregate concrete was done in a 6 cu ft (0.17 cu m) laboratory pan mixer unless otherwise indicated. Mixing and casting of samples were conducted in rooms with temperatures controlled at $73^{\circ}\text{F} \pm 3^{\circ}\text{F}$ ($22.8^{\circ}\text{C} \pm 1.7^{\circ}\text{C}$) and relative humidity controlled at $50\% \pm 5\%$. During the mixture optimization work, the following batching sequence was found to work best with the materials and proportions of this study:

- a. Add the fine and coarse aggregate.
- b. Start the mixer.
- c. Mix to a uniform distribution. (The amount of mixing time was dependent on the batch size but was generally 2 to 3 minutes for 6 cu ft (0.17 cu m) batches.)
- d. Add approximately 50% of the batch water.
- e. Add the cement and supplementary cementing materials.

- f. Add the remainder of the batch water.
- g. Add approximately 50% to 75% of the high-range water reducer. The actual amount added will depend on experience since it is a function of batch size and moisture content of the aggregate (percentage above SSD). At the end of this Step, the mixture should be sufficiently workable to permit uniform distribution of the air-entraining admixture.
- h. Add the air-entraining admixture.
- i. Add sufficient high-range water reducer to obtain the desired slump.

In general, the batching required a three minute total mix cycle starting with the addition of the cement.

A preconditioning sequence for the lightweight aggregate was also used. This was necessary so the free water in the mixture could be carefully controlled, thereby permitting the water-cement ratio to be calculated. The sequence consisted of putting the as-received lightweight aggregates in perforated-bottom containers, then saturating them from top to bottom with flowing water, and storing them in a fog room. During storage, the aggregates were rewetted daily with flowing water to ensure that a moisture content above the saturated surface dry condition was achieved. The aggregates were not used until their moisture content had exceeded the 24-hour absorption moisture content. Typically, two days were required to achieve this condition. Aggregates used in this condition would not absorb mixing water but did add a quantifiable amount of mixing water to the mixture. To determine the excess moisture present, aggregate samples were "dried back" and the moisture content calculated prior to each mixture. Corrections were then made to the amount of water added to the mixture at the time of batching.

PROPERTIES OF THE UNHARDENED CONCRETE

In order to establish field control limits, and to aid in the preparation of construction specifications, the measure of variation of the unhardened properties of the concrete should be known. To accomplish this, the properties of the unhardened concrete for every batch of concrete produced during the program were determined. The tests performed were as follows:

- a. Slump: ASTM C 143, "Slump of Portland Cement Concrete."
- b. Air Content: ASTM C 173, "Air Content of Freshly Mixed Concrete by the Volumetric Method."

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- c. Unit Weight: ASTM C 138, "Unit Weight, Yield, and Air Content (Gravimetric) of Concrete."

The performance criteria applied to each batch of concrete was as follows:

- a. Required Slump range: 4 to 6 in. (102 to 152 mm)
- b. Air Content range: 4% to 6%
- c. Unhardened Unit Weight range:
 - 113 to 118 lbs/cu ft (1810 to 1890 kgs/cu m) for LWC1, LWC2, LWC 3, and LWC4.
 - 123 to 127 lbs/cu ft (1970 to 2035 kgs/cu m) for HSLWC.
 - 145 to 155 lbs/cu ft (2323 to 2483 kgs/cu m) for NWC.

In normal practice, any batch which does not satisfy all three criteria, is discarded. During the overall program, judgement was allowed for the acceptance of an occasional batch which did not quite satisfy one of the criterion. In particular, slumps tended to be occasionally higher than anticipated.

The results for all five lightweight aggregate mixtures and the one normal weight reference mixture are shown in Table 12. The average, maximum, and minimum values as well as the standard deviation are shown for each property and for each mixture. A total of 110 lightweight aggregate concrete batches were made along with 3 normal weight concrete batches. Some additional lightweight aggregate concrete batches were made in Japan and are described in Part 2 (4) of this paper. Those batches are not included in Table 12 which represents only those batches made in the same USA laboratory under a prescribed set of conditions.

TEMPERATURE DEVELOPMENT

LWC1, LWC3, LWC4, and HSLWC mixtures were evaluated for temperature development in freshly placed concrete. LWC2 was not evaluated because it had identical types and amounts of cementing materials and similar amounts of coarse aggregate to LWC1.

The test specimen for all four mixtures was a 3 ft (0.9 m) cube cast in a form that was insulated on four sides, uninsulated on the top and had a 3/4 in. (19 mm) plywood panel on the bottom. The 2-in. (50 mm)

insulation had an insulating quality comparable to approximately 4 ft (1.2 m) of adjoining concrete.

Twenty-nine thermocouples were arranged on vertical dowels within the test cubes as shown in Fig. 3. An additional thermocouple monitored the room temperature. Data was digitally recorded. In a few instances, thermocouples were damaged during concrete placement and form removal. The temperatures at those damaged locations were interpolated from adjacent functioning thermocouples.

The properties of the concrete used to cast the cubes are shown in Table 13.

Immediately after casting, each cube was covered with a 3/4 in. (19 mm) plywood panel. Data recording was begun at that time. For LWC1 and HSLWC, the top and bottom plywood panels were removed after 95 hours of curing to simulate stripping of the formwork during construction. For LWC3 and LWC4, the removal time was between 4 and 6 days.

The temperature development curves at the midpoint and just below the top surface and the temperature gradients for each cube are shown in Figs. 4 to 7. A summary of the temperature data is included in Table 14.

Cores (4 in. diameter by 8 in. height (100 mm diameter by 200 mm height)) were taken from both the LWC1 and HSLWC cubes (Fig. 8) and evaluated for strength, density, moisture content and a linear traverse for determining void contents. The results, except for the linear traverse, are shown in Table 15.

PUMPING CONSIDERATIONS

The objectives of the pumping evaluations were to determine if the lightweight aggregate concretes of this program could be successfully pumped, and if the pumping would have adverse effects on the properties of the concrete. Emphasis was placed on the freezing and thawing durability of the concrete. A full scale field pumping test was conducted with the concrete being pumped over horizontal and vertical distances that were representative of anticipated prototype construction.

MIXTURE DESIGN

Of the five lightweight aggregate mixtures of this study, four of them used the pelletized aggregate from

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Japan. LWC2 was the most developed of the pelletized aggregate mixtures and hence was selected for the pumping tests.

The manufacturer of the pelletized aggregate recommended that the moisture content of the aggregate should be between 20% and 25% by oven dry weight to be successfully pumped. The pelletized aggregate that had been used for all of the other mixtures of this study had moisture contents from 5% to 8%. A special shipment of the aggregate was obtained from the manufacturer that had an as-received moisture content of approximately 21%. This high moisture content aggregate was used in the pumping tests.

In order to account for the high moisture content of the aggregate, the mixture proportions for LWC2 shown in Table 7 had to be adjusted. Table 16 shows the physical properties of both the normal and high moisture content pelletized aggregate. The higher specific gravity of the high moisture content aggregate would produce a higher unit weight if used as a direct replacement for the relatively dry aggregate. Several trial mixtures were made with the high moisture content aggregate, with adjustments being made to produce the mixture proportions shown in Table 17 which was used in the pumping tests.

AGGREGATE MOISTURE/PRESSURE RELATIONSHIP

Since the pressure used to pump concrete may force water into lightweight aggregate, tests were conducted to determine to what extent moisture could be forced into the pelletized aggregate under the pressures anticipated during concrete pumping. The testing was accomplished by placing samples of both the normal and high moisture content aggregate into a pressure chamber filled with water and then applying selected test pressures for 10 minutes. The test arrangement is shown in Fig. 9.

Each aggregate sample was placed into nylon netting and weighed both in air before testing. It was then placed in the chamber, subjected to the water pressure, removed from the chamber, dried to a surface dry condition, weighed, dried to a constant weight, and again weighed. With this data, it was possible to determine initial moisture content and moisture content after pressurization. The test was conducted over a range of pressures considered representative of pumping operations, and were selected to be 150, 300, and 600 psi (1.0, 2.1, and 4.1 MPa). The results of the testing are shown in Fig. 10.

CONCRETE BATCHING

To provide sufficient concrete for uninterrupted pumping, a minimum of 3 cu yds (2.3 cu m) of the concrete proportions shown in Table 17 was mixed in a transit-mix truck. All materials were preweighed and staged for loading into the truck.

The batching sequence into the truck was as follows:

- a. All of the preweighed lightweight aggregate was placed in the transit truck mixer.
- b. All of the preweighed sand was placed in the transit truck mixer.
- c. Approximately one-half of the required mixing water was added.
- d. All preweighed cement was added to the transit truck mixer.
- e. All preweighed silica fume was added to the transit truck mixer.
- f. The remaining mixture water was added and mixed for 1 minute.
- g. One-half of the high-range water reducer was added while mixing.
- h. All premeasured air-entraining agent was added while mixing.
- i. The remaining high-range water reducer was added.
- j. The batch was mixed for an additional three minutes.
- k. Samples for slump, unit weight, and air content were taken to determine if the fresh properties of the concrete were suitable for pumping.

The initial slump measured was 3.6 in. (91 mm), which was felt to be too stiff for pumping. An additional amount of high-range water reducer was added in an attempt to increase slump and the concrete mixed for an additional 5 minutes. Further sampling of the concrete revealed that the concrete had not been thoroughly mixed. It was very wet at the front of the mixer and very stiff in the rear of the mixer. The temperature of the concrete was also rising very rapidly. The entire batch was discarded and the materials for a second 3 cu yd (2.3 cu m) were preweighed and staged for loading into the transit mix truck.

The second batch was introduced into the transit mixer using a modified batching sequence in which 90% of the mixture water and one-half of the high-range water

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reducer were added to the mixer before any of the other materials. Using this modified sequence, a more thorough mixing was achieved and a suitable mixture consistency produced for the pumping test.

PUMPING EQUIPMENT

The pumping test utilized a mobile concrete pump truck rated at 90 cu yds (69 cu m) per hour. The pump had twin 4 by 7 in. (102 by 178 mm) cylinders and operated at a nominal hydraulic pressure of 200 psi (1.4 MPa) with a maximum hydraulic pressure of 1500 psi (10.3 MPa). The pump manufacturer estimated that the line pressure was one-third of the nominal hydraulic pressure.

For the test, a total of 158 ft (48.2 m) of pump line was used. The pump was equipped with 104 ft (31.7 m) of 5 in. (127 mm) line on the boom, of which 20 ft (6.1 m) was rubber line with the remainder being steel line. A 4 ft (1.2 m) reducer was used from the 5 in. (127 mm) line to a 4 in. (102 mm) diameter line. The 4 in. (102 mm) line consisted of 30 ft (9.1 m) of slick line and 20 ft (6.1 m) of rubber hose. The pump boom was set at an angle of approximately 35 degrees from the horizontal. This produced a vertical pumping height of approximately 40 ft (12.2 m).

TESTING PLAN

Unhardened Concrete Properties: To quantify the effects of pumping on the fresh concrete, samples were obtained from both pre-pumped concrete and concrete after it had been pumped (post-pumped concrete) through the 158 ft (48.2 m) of line. At both locations, samples were obtained after approximately 5 cu ft (0.142 cu m), 1.5 cu yds (1.147 cu m), and 2.5 cu yds (1.192 cu m) were discharged for a total of three sets of samples at each location. Testing included slump, unit weight, air content and temperature. The results are shown in Table 18.

Aggregate Moisture Content: In order to determine if the pumping pressure had forced additional moisture into the lightweight aggregate, a representative sample of concrete was obtained from each of the pre-pumped and post-pumped samples and had the mortar fraction washed over a No. 4 sieve. This left behind a sample of the light-weight aggregate which was towel dried to surface dry condition, weighed, oven dried to a constant weight, and reweighed so that the moisture

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content could be determined. The results are shown in Table 18.

Compressive Strength and Unit Weight: Specimens for tests of hardened concrete were also made from the concrete samples. Tests performed on the hardened concrete included compressive strength, unit weight, air void system, and freezing and thawing durability. The rate of drying of a large concrete section was also performed on some additional concrete as described later. Compressive strengths were determined on 6 by 12 in. (150 by 300 mm) cylinders with two cylinders being tested at both 28- and 90-days age. The unit weight was obtained on each cylinder prior to the compressive strength testing. The compressive strength and unit weight test results are shown in Table 19.

Air Void Determinations: Air void determination tests were done in accordance with ASTM C 457, "Standard Practice for Microscopical Determination of Air-Void Content and the Parameters of the Air Void System in Hardened Concrete". The tests were made on hardened concrete specimens obtained from both the pre-pumped and post-pumped concrete obtained from the concrete samples taken after 1.5 cu yd (1.15 cu m) had been discharged from the truck and pumped, respectively. The results are shown in Table 20.

Freezing and Thawing Behavior: A proper air void system in concrete is necessary to protect the concrete from damage caused by freezing and thawing. Concrete used in arctic applications will most certainly experience freezing and thawing at certain periods during the year. Criteria recommended for air void systems (9,10) has generally been developed for lower strength concretes than those of this study and it is not known how applicable they are to higher strength concretes.

Cement paste is normally protected against the effects of freezing and thawing if the spacing factor is 0.008 in. (0.20 mm) or less (9) as determined by ASTM C 457. Canadian Standards (10) allow a spacing factor of 0.23 mm (0.009 in.) or less with no individual value to exceed 0.26 mm (0.010 in.). Additional requirements are that the specific surface of the air voids be greater than 600 in.²/in.³ (23.6 mm²/mm³) of air void volume and that the number of air voids per inch (25 mm) of traverse be significantly greater (e.g., 1.5 times greater) than the numerical value of the percentage of air in the concrete (11).

The spacing factors (Table 20) observed for the pre-pumped and post-pumped concrete were unacceptable

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being 0.017 in. (0.43 mm) and 0.011 (0.28 mm), respectively. The specific surface is an indicator of air void size. For a given air content, the smaller the air bubble, the larger the value of specific surface. The specific surface value (Table 20) for the pre-pumped concrete (441 cu in./sq in. (1120 cu cm/sq cm)) was unacceptable for the pre-pumped concrete but managed to become acceptable (650 cu in./sq in. (1651 cu cm/sq cm)) after pumping. In general, the air void system apparently was not damaged by the pumping operations and in fact was somewhat improved.

Because of the poor air void system in the pumped concrete, the freezing and thawing specimens made from the pumped concrete were not evaluated. It was decided that because the pumping test did not increase the moisture content of the aggregate, which is a critical factor in the freezing behavior of the concrete, it would be more economical to recast the freezing and thawing specimens from concrete having a proper air void system but with aggregates having high moisture contents such as those witnessed in the pumping tests, rather than to run another pumping test.

A concrete mixture simulating the pumped concrete was made in the laboratory for recasting the freezing and thawing specimens. It had identical proportions to that described in Table 17 except the chemical admixture amounts were adjusted slightly to increase the air content. The test specimens were cast as 3 by 3 by 11 1/4 in. (76 by 76 by 286 mm) prisms. Table 21 shows the properties of both the fresh and hardened concrete for the simulated pumped concrete.

The prisms were moist cured for 28-days at $73^{\circ}\text{F} \pm 3^{\circ}\text{F}$ ($22.7^{\circ}\text{C} \pm 1.7^{\circ}\text{C}$). They were then subjected to conditioning to obtain nominal moisture contents of 100%, 90%, 80%, and 60%. Six specimens were cast for each of these conditions. The specimens were dried in an oven at $120^{\circ}\text{F} \pm 2^{\circ}\text{F}$ ($48.9^{\circ}\text{C} \pm 1.1^{\circ}\text{C}$) until the approximate nominal moisture levels were reached as shown in Table 22. Estimates of the drying time required to reach these levels had been obtained by drying the freezing and thawing specimens from the initial pumped concrete that was not evaluated. At the appropriate time, all six specimens were removed from the oven, placed in plastic bags, and allowed to equilibrate in sealed containers for one week. At this point, three specimens were removed from the bags and dried to a constant weight at $221^{\circ}\text{F} \pm 3.6^{\circ}\text{F}$ ($105^{\circ}\text{C} \pm 2^{\circ}\text{C}$). Their moisture contents were calculated on an oven-dry basis and are also shown in Table 22.

The remaining three specimens at each nominal moisture content were removed from their plastic bags and subjected to the spectral freezing and thawing procedures described in Part 2 (4) of this paper. The temperature cycling of the spectral cycle are shown in Fig. 11. The effects of the spectral cycles on the relative dynamic modulus of the concrete are shown in Fig. 12.

Drying Characteristics: In addition to the moisture content specimens associated with the freezing and thawing tests, a 3 by 3 by 3 ft (0.9 by 0.9 by 0.9 m) cube was cast from the same simulated pumped concrete mixture to evaluate the natural drying characteristics of a large section of concrete. This required six 6-cu ft (0.17 cu m) batches of concrete which were made in the manner described earlier in this paper for laboratory mixed concrete. The 3 ft (0.91 m) cube was left in the form for four days with the top surface covered with polyethylene sheets. The form was then removed and the four sides of the cube coated with a moisture-impermeable epoxy. Drying could only then occur from the top and bottom of the cube, thus representing drying conditions in a prototype structure. The cube was stored at approximately 50% relative humidity and $73^{\circ}\text{F} \pm 3^{\circ}\text{F}$ ($22.7^{\circ}\text{C} \pm 1.7^{\circ}\text{C}$).

Samples to evaluate the moisture content in the cube were taken from the cube at various times during its drying period. They were obtained using a 1 in. (25 mm) carbide-tip rotary impact hammer at locations shown in Fig. 13. In addition, the cube was weighed periodically using load cells in order to obtain a weight loss that could be used to calculate an overall moisture content. Initial moisture content was assumed to be equal to the moisture content of the "100% level" prisms used as companions in the freezing and thawing tests.

DISCUSSION

PROPERTIES OF THE UNHARDENED CONCRETE

Properties of the unhardened concrete are needed to provide an early technical evaluation of the adequacy and reproducibility of batched concrete. It is expensive and time-consuming to correct deficiencies once the concrete has hardened in the structure. An understanding of the relationship between the unhardened concrete properties and the mechanical properties of the same concrete (Part 2 (4) of paper) is essential. The properties of the unhardened concrete

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are also indicators of the ease of construction with that concrete. In offshore and marine structures, the average reinforcing bar densities routinely vary from 465 to 675 lbs/cu yd (275 to 400 kgs/cu m) and can be as great as 1850 lbs/cu yd (1100 kgs/cu m) in some areas of the structure. High reinforcing bar densities can be expected in the ice-resisting outer walls of an arctic structure. The slump of the concrete is a measure of workability and an indicator of whether the concrete will be able to be satisfactorily placed around these large amounts of reinforcing bars. Concrete consistency may be indicative of achievable surface finish quality and may dictate the method of concrete forming such as slipforming or jump-forming.

Unit Weight

The average unit weights (Table 12) for the five lightweight aggregate concrete mixtures evaluated are as follows:

<u>Mixture</u>	<u>Unhardened Unit Weight,</u>	
	<u>lbs/cu ft</u>	<u>(kgs/cu m)</u>
LWC1	115.8	(1855)
LWC2	113.9	(1825)
LWC3	115.0	(1842)
LWC4	113.1	(1812)
HSLWC	126.4	(2025)

These values need to be combined with the unit weight change during curing, the seawater absorption, and estimates of the amounts of reinforcing, to provide the necessary data for computing the drafts of the structure when it is floating. The unit weight changes for 28 days of moist curing for LWC1, LWC2, LWC3, LWC4, and HSLWC were increases of 1.4, 1.5, 2.6, 1.3, and 2.6 lbs/cu ft (22, 24, 42, 21, and 42 kgs/cu m), respectively (see Tables 2 through 6 of Part 2 (4) of paper). The seawater absorption rates (see Part 2 (4) of paper) for the silica fume containing mixtures (LWC1, LWC2, and HSLWC) were between 3 to 4 lbs/cu ft (48 to 64 kgs/cu m). The absorption rates for LWC3 and LWC4 were influenced more by the initial curing regime and typically lost more moisture during curing than they regained by pressurized absorption. Adding these numbers to the unhardened unit weight numbers above, only LWC1 and HSLWC exceeded the target values of unit weight and this was only by 1% and 2%, respectively, which is acceptable for the purposes of this study.

Slump

There was a tendency for all mixtures to stiffen within 45 minutes after batching. This stiffening, called slump loss, is often encountered when using high-range water reducers. The stiffening was more rapid for those mixtures containing fly ash (LWC3) and blast furnace slag (LWC4). Construction requirements may dictate the use of a retarder or extended-life high-range water reducer to maintain the desired slump necessary for adequate consolidation and uniform placement. The addition of the high-range water reducer may also be staged to eliminate the slump loss or additional dosing may be required. The quality control is generally better if all the admixture dosing is done in the batching plant rather than in the field and is the preferred method of construction.

It was difficult to perform classical slump determinations on some of the batches containing fly ash (LWC3) and blast furnace slag (LWC4). A phenomenon called "moving slump" was observed. Upon lifting of the slump cone, the concrete would sag to a level representing approximately 6 in. (152 mm) of slump. Immediately thereafter, the concrete would continue to collapse until a maximum slump was reached. This behavior was not observed for those mixtures containing silica fume (LWC1, LWC2, and HSLWC). It is hypothesized that the finely divided silica fume provides a higher degree of cohesiveness to the mixture than either the fly ash or the blast furnace slag. This cohesiveness reduced the tendency of the concrete to flow after the slump cone was removed. This "moving slump" should have no adverse consequences in the field on concrete quality but does raise the question of the suitability of the slump test for these types of concrete.

Segregation

For the slumps observed during the test program (Table 12), including the "moving slump", no segregation of the lightweight aggregate was observed. This suggests that higher slumps than the target range of 4 to 6 in. (102 to 152 mm) may be possible for use in areas of the structure where reinforcing bars are extremely congested.

Finishing: Finishes of the concrete surfaces associated with test specimen fabrication indicated that all five mixtures provided excellent formed surfaces. It is anticipated that the exterior walls of an arctic structure will require a high-quality finish to reduce the effects of ice-abrasion and ice-adhesion. A

smoother exterior surface also reduces frictional drag during towing. LWC1 and LWC2 were somewhat difficult to trowel and float because of the sticky nature of the silica fume/cement binder. This problem was not as evident for HSLWC. LWC3 and LWC4 were more difficult to hand finish. For LWC3 (fly ash mixture), the paste adhered to the trowels and screeds, thus inhibiting the finishing operation. If finishing is a problem for the arctic structures, it may be possible to adjust the mixture proportions to reduce paste content and increase sand content. Both actions will tend to alleviate the problem.

Air Content

The target air content of 4% to 6% was achieved by all the mixtures except LWC4 (Table 12). All of the air content values in Table 12 were measured at the mixer. In actual construction, the air contents should be measured at the point of discharge of the concrete because much of the loss of entrained air occurs while the concrete is in transit to the formwork. Some reduction of air content can also be expected during placing and consolidation of the concrete but this is typically a very small amount. Because of the significant durability problems that will exist in arctic concrete structures, it is desirable to be on the high end of any specified range of air contents to ensure that a proper amount of entrained air ends up in the concrete. The results of freezing and thawing tests described in Part 2 (4) of this paper support this position.

TEMPERATURE DEVELOPMENT

Several different methods for predicting the temperature rise were examined for the mixtures used and most under-predicted the measured data. This was not unexpected because most empirical methods were not developed for high cement content, low water-cement ratio concrete. The method described in (12) and shown in Table 14 gave results within ± 15 percent.

It is generally believed that replacements of cement with fly ash or slag in concrete help to reduce the heat development in concrete. For the levels of replacement in LWC3 (fly ash) and LWC4 (slag) and the very high cementitious contents (880 to 956 lbs/cu yd (474 to 566 kg/cu m)) used (Table 7), the only significant effect appears to be a small delay (approximately 4 to 8 hours) in the time when the peak temperature and maximum gradients were reached. The fact that all the mixtures produced similar maximum

temperature may also be a function of the size of specimen used and the manner of insulation. Pure adiabatic conditions would most likely have produced higher maximum temperatures for HSLWC and lower maximum temperatures for LWC3 (fly ash). Mixtures containing slag may or may not produce lower temperatures depending on the composition and fineness of the slag. It is felt that the test specimens used provided a realistic approach to actual thick wall construction.

High temperatures and gradients such as those observed can lead to significant surface cracking although no deleterious effects were observed in the cubes. Cores taken from the LWC1 and HSLWC cubes were tested in compression and demonstrated more than adequate strength (Table 15). Uncontrolled heat development may, however, lead to thermal cracking and consideration should be given to reducing the mixing temperature during batching. With temperatures such as those observed in the test cubes, insulated forms will most likely have to be used to mitigate any thermal cracking damage caused by large gradients. In actual construction, the effects of casting large placements of these types of concretes in insulated forms against adjacent hardened concrete will have to be examined more closely. The thermal strains induced in relatively fixed adjacent members must also be accounted for in design.

PUMPING CONSIDERATIONS

Aggregate Moisture/Pressure Relationship

The aggregate moisture versus simulated pump pressure relationship for the pelletized aggregate of this program is shown in Fig. 10. The moisture content at zero pressure represents the average as-received moisture content of the aggregate. A separate sample was evaluated at each of three test pressures (150, 300, and 600 psi (1.0, 2.1, and 4.1 MPa)). Although the moisture content of each sample did not differ greatly, it was necessary to normalize each to the average as-received moisture content. This was done by adding the measured change in moisture content to the average as-received moisture content. Also shown is a vacuum-saturated moisture content for the high moisture content pelletized aggregate. This, too, was normalized to the average as-received moisture content.

As can be seen from Fig. 10, the stimulated pump pressures applied over a 10 minute period forced a considerable amount of water into the nominally dry pelletized aggregate. The 10 minute period is

typically as long as the concrete might remain in the pump and pump line. When the aggregate had a very high moisture content to begin with, very little additional moisture was forced into the aggregates even at pressures of 600 psi (4.1 MPa). Thus, when using pre-saturated lightweight aggregates, little or no additional water should be expected to enter the aggregate when the concrete is pumped.

Unhardened Concrete Properties

The test results for the unhardened concrete both before and after pumping (Table 18) indicate that the pumping operation did not significantly alter the properties of the unhardened concrete. The one exception was for the slump of the initial post-pumped sample which increased from 2.3 to 6.2 in. (58 to 157 mm). This apparent increase in slump was attributed to mixing of the initial grout mixture used to lubricate the line before pumping with the actual concrete being placed. In an actual construction project, this grout/concrete mixture is usually discarded.

The maximum aggregate moisture content difference between the pre-pumped and post-pumped concrete was 0.6%. This supports the observation of the aggregate moisture versus simulated pump pressure tests (Fig. 10) that little, if any, additional moisture was going to be forced into the high moisture content pelletized aggregate during pumping.

The pumping action caused a slight increase in the air content of the concrete. This is not uncommon when the mixing action applied to the pre-pumped concrete is insufficient or improper for development of the air void system. The fact that none of the pre-pumped concrete air contents reached the target levels (4% to 6%) also supports the position that the truck mixing was not adequate for these tests.

Hardened Concrete Properties

The compressive strength and unit weights of the hardened concrete were determined at both 28- and 90-days age and are shown in Table 19. Figs. 14 and 15 show the relationship of the pre-pumped and post-pumped concrete strengths at each age, respectively. In all cases, the post-pumped concrete had lower compressive strengths than the pre-pumped concrete. This can be explained in part by that fact that the air content increased during the pumping operation. This air content increase can also explain some but not all of the reduction in unit weight that also occurred between the pre-pumped and post-pumped concrete. Other reasons

for the amount of the reduction in both the compressive strength and unit weight could not be quantified.

As noted above, both the spacing factors and specific surface values (Table 20) observed for the pre-pumped and post-pumped concrete were unacceptable. When the mixture was repeated using a laboratory mixer rather than the transit mixer truck, both values became acceptable (Table 21) along with the target value for air content in the freshly mixed concrete. Despite the poor air void parameters obtained using the transit mix truck, the pumping operation did not appear to degrade the air void system.

Freezing and Thawing Durability

A detailed description of the freezing and thawing behavior of all the high strength lightweight aggregates of this Joint Industry Project is contained in Part 2 (4) of this 3 Part paper and includes additional information on the spectral freezing and thawing test applied to the simulated pumped concrete.

The spectral freezing and thawing procedure (Fig. 11) was formulated to approximate climate conditions in the Arctic where concrete would undergo intermittent freezing and thawing during the summer at temperatures somewhat above freezing and then have a single, prolonged freezing in the winter. The method used involved running 6 cycles per day of freezing at 0°F (-18°C) and thawing at 40°F (5°C) for a total of 60 cycles. This was followed by freezing at -20°F (-29°C) for one day and then thawing in a water tank at approximately 70°F (22°C) for a period of 8 hours. All cycling was done while the specimens were inundated in simulated seawater.

After each spectral cycle, the relative dynamic modulus (RDM) of the prisms was measured and compared to the RDM of the prisms before the start of the spectral cycling as shown in Fig. 12. An arbitrary RDM value of 50% was chosen as a failure criterion for the concrete. Those prisms conditioned to an approximate moisture level of 60% performed well for four cycles but became progressively worse with additional cycles. The number of spectral cycles to failure is shown in Fig. 16 with respect to the moisture contents of Table 22. The rate of decay of RDM appears to be proportional to the initial moisture content. Table 23 shows the estimated service life of the concrete based on laboratory tests and comparing this to Fig. 16, it appears that to obtain a service life of 20 years, the moisture content of the aggregate would have to be kept to less than 10%. For service life beyond 20 years, the aggregates

would have to approach the oven-dry condition. From Fig. , it can be seen that for the pelletized aggregate of this study, it is virtually impossible to keep the moisture content below the 10% level when the concrete is pumped.

Techniques are available to apply coatings to pelletized aggregates during their cooling process as they come from the production kiln. These coatings have been observed to reduce the absorption of the aggregates to 1 or 2% even under simulated pump pressures. Aggregates treated in this manner most certainly could be used in pumping operations to construct arctic platforms but would be more expensive.

Drying Characteristics

The average (overall) moisture content of the large cube versus drying time is shown in Fig. 17. There is only a slight decrease in moisture with time, beginning at 13% and dropping to 11.7% at 108 days. There was no change between 76 and 108 days. The moisture gradient through the cross section of the cube after 76 days of drying is shown in Fig. 18. There is no significant moisture gradient with all values ranging between 11% and 13%. When considering that the construction of an arctic structure will typically be done in a high humidity environment, it is doubtful if the concrete will ever dry out to levels where the concrete would not be affected by freezing and thawing.

SUMMARY AND CONCLUSIONS

The study evaluated ten lightweight aggregates as potential candidates to produce high-strength lightweight aggregate concretes for use in offshore and marine structures in the Arctic. Two types of structural lightweight aggregates, crushed and pelletized, were then selected for mixture development. Target concrete densities and compressive strengths were selected which were representative of what may be required for the arctic structures. The target densities were 120 and 130 lbs/cu ft (1922 and 2083 kgs/cu m), maximum, with target strength levels of 7,000 and 9,000 psi (48 and 62 MPa), minimum, respectively. From these requirements, five specific mixtures were developed and evaluated. One mixture was developed for the crushed lightweight aggregate which was produced in the USA and the other four mixtures used a pelletized aggregate produced in Japan. All of the mixtures incorporated a single supplementary cementing material (silica fume, fly ash, or blast

furnace slag). All mixtures also used high-range water reducers and were air entrained.

One-hundred and ten batches of concrete were made over the duration of the program using the mixtures developed. The mechanical properties and structural parameters associated with the concrete produced from these batches are described in Parts 2 and 3 (4,5) of this paper, respectively. The slump, unit weight, and air content of each batch were determined. Large sections of concrete were cast to measure the temperature development for the mixtures. The drying characteristics of a large concrete section made with one of the mixtures were also determined. A field pumping test was performed using one of the mixtures containing pelletized aggregate to determine the influence of the pumping on both the unhardened and hardened properties of the concrete.

Specific conclusions for the effort described in this Part of the three Part paper are as follows:

1. **Aggregate Selection:** Not all lightweight aggregates are suitable for producing high-strength concretes for marine applications in the Arctic. The aggregates need to have a very low absorption and be structurally competent. Suitable aggregates made either by crushing expanded lightweight clinker or by pelletizing the aggregate can meet this criteria and are commercially available.

2. **Mixture Constituents:** It is doubtful if high strength lightweight aggregate concrete can be produced without the use of supplementary cementing materials (silica fume, fly ash, blast furnace slag) and high-range water reducing admixtures (superplasticizers). Using these materials in combination with competent lightweight aggregates, normal density sand, ordinary Portland cement, and a low water cementitious ratio (less than 0.30 by weight), compressive strengths in excess of 8,000 psi (55 MPa) are practical in suitable for construction quality concrete. Densities associated with this strength level are 115 to 120 lbs/cu ft (1842 to 1922 kgs/cu m) and will increase to approximately 130 lbs/cu ft (2083 kgs/cu m) as the mixture proportions are adjusted to produce concrete of 11,000 psi (76 MPa).

3. **Batching Procedures:** Because of the absorption needs of the lightweight aggregate, the use of finely divided supplementary cementing materials, and the use of high-range water reducers, batching procedures for a high-strength lightweight aggregate concrete must be specifically developed for the actual materials being

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used. This is not a difficult task but is necessary to insure uniformity in the produced concrete.

4. **Unhardened Concrete Properties:** The variation in air content of the laboratory batches was acceptable but was pushing the limits of what might be acceptable for an actual construction project. Variations in unit weight follow those of the air content. This conceivably would be rectified on actual construction project with the continuous batching of the same mixture proportions. The slump determinations were extremely variable. This variation may be due to the constituent materials in the mixture. If this is the cause, the standard slump test may not be appropriate for these types of mixtures.

5. **Temperature Development:** The maximum temperature rise in large sections of concrete made with the high strength lightweight aggregate mixtures varied from 100 to 114 °F (56 to 63 °C). This suggests that the temperature of the freshly mixed concrete may have to be constrained to 60 °F (15 °C) or less to meet most typical construction specifications for maximum temperature in the concrete. Significant thermal gradients are developed in the concrete due to the better insulation characteristics of the lightweight aggregates. These gradients will most likely require the use of insulated forms to mitigate any thermal cracking damage. The use of fly ash and blast furnace slag as a supplementary cementing material did not significantly influence the temperature regime. Peak temperatures were delayed only 4 to 8 hours with these materials. The mixture containing blast furnace slag actually produced the highest peak temperature even though it had the lowest total cementitious content. The high temperatures did not appear to adversely affect the in-situ strength of the concrete as determined by core tests.

6. **Pumping Considerations:** Because of the significant demands put on the concrete to resist the freezing and thawing that occurs in the Arctic, pumping of the lightweight aggregate for placement during construction is not recommended unless the aggregates are specially treated to reduce absorption levels during pumping to only 1 to 2 percent. The total moisture content of the lightweight aggregate delivered to the formwork will have to be less than 10 percent if the concrete is to survive the arctic environment. Normal pumping pressures can, in a very short time, easily force enough moisture into untreated lightweight aggregates so that the 10 percent limit is exceeded. The pumping process does not appear to significantly alter the air void system in the lightweight aggregate

concrete, providing the air void system is acceptable before the concrete is pumped. The compressive strength of the pumped concrete was slightly less than before it was pumped. No good explanation was available for this behavior.

7. **Drying Characteristics:** Large sections of the high strength lightweight aggregate concrete dry very slowly. When considering that the construction of an arctic structure will typically be done in a high humidity environment and the structure will be immersed in sea water, it is doubtful if the concrete will ever significantly dry out.

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TABLE 1—AGGREGATE PROPERTIES FOR SCREENING TESTS

Aggregate Number	Aggregate Lot No.	Dry Loose Unit Weight, lbs/cu ft (kgs/cu m)	As-Received Moisture Content, percent	24-Hour Absorption, percent
1	22012	50.7 (812)	8.9	8.7
2	22017	38.7 (620)	22.7	11.7
3	22013	45.7 (732)	27.0	15.9
4	22019	46.3 (742)	0.8	4.4
5	22021	51.6 (827)	0.2	12.0
6	22027	48.1 (771)	10.3	8.0
7	22015	49.5 (793)	0.9	4.4
8*	22031	41.6 (666)	7.2	11.0
9*	22030	40.8 (654)	6.6	10.2
10	22032	47.1 (755)	1.6	3.6

* Aggregate Nos. 8 and 9 are from the same source. Aggregate No. 8 has a grading from No. 8 (2.36 mm) to 3/8 in. (9.5 mm). Aggregate No. 9 has a grading from No. 4 (4.75 mm) to 3/4 in. (19 mm).

TABLE 2—AGGREGATE GRADATIONS FOR SCREENING TESTS

Aggregate Number	Aggregate Lot No.	Sieve Size, Percent Passing					No. 4 (4.75 mm)	No. 8 (2.36 mm)
		1 in. (25 mm)	3/4 in. (19 mm)	1/2 in. (12.5 mm)	3/8 in. (9.5 mm)			
1	22012	100	100	85	49		1	--
2	22017	100	100	100	74		4	--
3	22013	100	100	90	66		7	--
4	22019	100	100	24	8		0	--
5	22021	100	100	93	57		1	--
6	22027	100	100	32	13		0	--
7	22015	100	100	92	51		8	--
8*	22031	100	100	100	97		11	1
9*	22030	100	100	84	48		20	1
10	22032	100	94	54	28		2	--

* Aggregate Nos. 8 and 9 are from the same source.

TABLE 3—ASTM C 330 — STRUCTURAL LIGHTWEIGHT AGGREGATE GRADING REQUIREMENTS

Size Designation	Percentage (By Weight) Passing Sieves Having Square Openings									
	1 in. (25 mm)	3/4 in. (19 mm)	1/2 in. (12.5 mm)	3/8 in. (9.5 mm)	No. 4 (4.75 mm)	No. 8 (2.36 mm)	No. 16 (1.18 mm)	No. 30 (.60 mm)	No. 60 (.25 mm)	No. 100 (.15 mm)
Fine Aggregate No. 4 to 0	---	---	---	100	85-100	---	40-80	10-35	---	5-25
Coarse Aggregate	95-100	---	25-60	---	0-10	---	---	---	---	---
3/4 in. to No. 4	100	90-100	---	10-50	0-15	---	---	---	---	---
1/2 in. to No. 4	---	100	90-100	40-80	0-20	0-10	---	---	---	---
3/8 in. to No. 8	---	---	100	80-100	5-40	0-20	0-10	---	---	---
Combined Fine and Coarse Aggregate	---	100	95-100	---	50-80	---	---	5-20	2-15	---
1/2 in. to 0	---	---	100	90-100	65-90	35-65	---	10-25	5-15	---

TABLE 4—MIXTURE DESIGN FOR AGGREGATE SCREENING TESTS

Cement Content, lbs/cu yd (kgs/cu m)	752 (446)
Lightweight Aggregate, cu ft (cu m) based on dry loose unit weight	16 (0.45)
Natural Sand, cu ft (cu m) based on absolute volume	7.5 (0.21)
Air Entraining Agent	to obtain 3% to 5% air
Water	to obtain approximately 3 in. (76 mm) slump

TABLE 5—UNHARDENED CONCRETE PROPERTIES FOR
AGGREGATE SCREENING TESTS

Aggregate Number	Aggregate Lot No.	Air Content percent	Unhardened Unit Weight		Slump	
			lbs/cu ft	kgs/cu m	in.	mm
1	22012	4.0	121.4	(1945)	2.7	(69)
2	22017	4.1	117.7	(1886)	3.2	(81)
3	22013	4.3	121.8	(1951)	2.4	(61)
4	22019	3.3	113.9	(1825)	2.9	(74)
5	22021	3.4	124.3	(1991)	3.2	(81)
6	22027	3.8	119.8	(1919)	2.9	(74)
7	22015	4.0	119.3	(1911)	3.5	(89)
8*	22031	6.1	114.1	(1828)	3.4	(86)
9*	22030	3.2	114.4	(1833)	4.1	(104)
10	22032	3.5	119.8	(1919)	3.5	(89)

TABLE 6—HARDENED CONCRETE PROPERTIES FOR AGGREGATE SCREENING TESTS

Aggregate Number	Aggregate Lot No.	Compressive Strength **, psi (MPa)				Splitting Tensile Strength** psi (MPa)	
		Accelerated 1-day	Cured*		Moist Cured 14-days	Moist Cured 28-days	
			7-days	28-days		14-days	28-days
1	22012	3640 (25)	3860 (27)	4760 (33)	5510 (38)	480 (3.3)	590 (4.1)
2	22017	4000 (28)	4780 (33)	4490 (31)	5180 (36)	500 (3.4)	550 (3.8)
3	22013	2920 (20)	3400 (23)	3800 (26)	4580 (32)	440 (3.0)	500 (3.4)
4	22019	4080 (28)	5000 (34)	5000 (34)	5680 (39)	470 (3.2)	540 (3.7)
5	22021	3450 (24)	4070 (28)	4960 (34)	5220 (36)	540 (3.7)	570 (3.9)
6	22027	3040 (21)	4320 (30)	4730 (33)	5310 (37)	470 (3.2)	550 (3.8)
7*	22015	3350 (23)	4140 (28)	4440 (31)	5720 (39)	530 (3.6)	540 (3.7)
8*	22031	2750 (19)	4110 (28)	4080 (28)	4980 (34)	430 (3.0)	490 (3.4)
9*	22030	2790 (19)	3580 (25)	3810 (26)	4410 (30)	560 (3.9)	490 (3.4)
10	22032	3640 (25)	4170 (29)	4880 (34)	5470 (38)	410 (2.8)	540 (3.7)

* 1-day steam cure, 6-days moist cure.

** Average of three 4 by 8 in. (100 by 200 mm) cylinder tests.

TABLE 7—SUMMARY OF HIGH-STRENGTH LIGHTWEIGHT CONCRETE PROPORTIONS

Mixture Number	Quantities, lbs/cu yd (kg/cu m)						
	LMC1	LMC2	HSLWC	LMC3	LMC4	NWC	
Cement (Type I/II)	799 (474)	799 (474)	846 (502)	700 (415)	600 (356)	658 (390)	
Fine Aggregate	1004 (596)	965 (573)	1575 (934)	896 (532)	1004 (596)	1140 (676)	
Coarse Aggregate Crushed Type	1012 (600)	---	---	---	---	---	---
Pelletized Type	---	1022 (606)	613 (364)	924 (548)	920 (546)	---	---
Normal Weight	---	---	---	---	---	1990 (1180)	---
Silica Fume	80 (47)	80 (47)	110 (65)	---	---	---	---
Fly Ash	---	---	---	200 (119)	---	---	---
Slag	---	---	---	---	200 (119)	---	---
High-Range Water Reducer	160 oz (4.7 l)	160 oz (6.2 l)	169 oz (6.5 l)	132 oz (5.0 l)	104 oz (4.0 l)	95.4 oz (3.7 l)	
Air-Entraining Admixture	32.0 oz (1.25 l)	32.0 oz (1.25 l)	16.9 oz (0.66 l)	19.6 oz (0.73 l)	17.4 oz (0.63 l)	55.9 oz (2.15 l)	
Mix Water*	237 (141)	234 (139)	256 (152)	236 (140)	247 (147)	215 (128)	
Water/Cement Ratio	0.30	0.30	0.31	0.34	0.41	0.33	
Water/Cementi- tious Ratio	0.28	0.27	0.28	0.26	0.31	---	---

* Water added in addition to that contained in chemical admixtures.

TABLE 8—SUMMARY OF CEMENT PROPERTIES*

	Shipment Number			
	1	2	3	4
Chemical Composition				
Silicon Dioxide (SiO_2)	21.9	22.2	22.0	22.1
Aluminum Oxide (Al_2O_3)	4.7	4.6	4.5	4.5
Ferric Oxide (Fe_2O_3)	3.6	3.7	4.0	3.8
Calcium Oxide (CaO)	64.5	64.5	64.2	64.3
Magnesium Oxide (MgO)	0.8	1.0	1.0	0.8
Sulfur Trioxide (SO_3)	2.7	2.5	2.5	3.0
Total Alkalies (Na_2O equiv.)	0.41	0.48	0.56	0.60
Loss on Ignition	0.8	0.9	1.0	0.8
Insoluble Residue	0.11	0.28	0.20	0.20
Tricalcium Silicate (C_3S)	51	50	51	50
Dicalcium Silicate (C_2S)	24	26	25	25
Tricalcium Aluminate (C_3A)	6.4	5.8	5.2	5.5
Tetracalcium Aluminoferrite (C_4AF)	11.0	11.4	12.0	11.0
Physical Properties				
Specific Surface, Blaine, cm^2/g	3725	3645	3535	3828
Autoclave Expansion, %	-0.04	-0.02	-0.03	-0.01
Time of Setting,				
Gilmore Initial Set, hrs:mins	5:00	4:20	3:45	--
Gilmore Final Set, hrs:mins	7:15	5:50	6:35	--
Vicat Initial Set, hrs:mins	3:45	3:05	3:10	2:20
Vicat Final Set, hrs:mins	6:15	5:40	5:15	5:10
Compressive Strength,				
1 day, psi (MPa)	1240 (8.5)	1150 (7.9)	1090 (7.5)	--
3 days, psi (MPa)	2860 (19.7)	2830 (19.5)	2540 (17.5)	3180 (21.9)
7 days, psi (MPa)	4260 (29.4)	4270 (29.4)	4010 (27.6)	4470 (30.8)
28 days, psi (MPa)	6010 (41.4)	6190 (42.7)	6230 (43.0)	--
Air Entrainment, % by volume	7.4	7.5	6.8	7.0
False Set,				
Initial Penetration, mm	36	29	30	32
Final Penetration, %	81	66	67	72

* All results are from the cement suppliers silo certificates.

TABLE 9—SILICA FUME PROPERTIES*

<u>Composition</u>	<u>Value</u>
Silica, percent	92 - 93
Carbon, percent	4 - 5
Fe ₂ O ₃ , percent	0.10 - 0.50
CaO, percent	0.10 - 0.15
Al ₂ O ₃ , percent	0.20 - 0.30
MgO, percent	0.10 - 0.20
MnO, percent	0.008
K, percent	0.10
Na, percent	0.10
S, percent	0.10
<u>Typical Properties</u>	
Specific Gravity	2.02**
Bulk Density, lbs/cu ft (kgs/cu m)	20 (320) (approx.)
Average Particle Size, micrometer	0.1
Passing 100 Mesh Screen, percent	99.75
pH (10% Water Slurry)	7.3
Volatiles at 105°C, percent	0.8
Ash at 550°C (db), percent	95.3
Water Extractables, percent	1.3
Color	Grey

* From the Manufacturers' Data Sheet.

** Measured Specific Gravity was 2.07. A Blaine Fineness of 51,145 cm²/gm was also measured.

TABLE 10—FLY ASH PROPERTIES*

<u>Chemical Composition</u>	<u>Value</u>	ASTM C618-89 Requirements for Class F Fly Ash
Loss on Ignition, percent	2.09	6 max.
SO ₃ , percent	0.88	5 max.
SiO ₂ /Al ₂ O ₃ /Fe ₂ O ₃ , percent	52.06/ 24.86/ 13.41	
Total, percent	90.33	70 min.
CaO/MgO, percent	2.44/ 0.78	
K ₂ O/Na ₂ O, percent		
(Total as Na ₂ O), percent	2.21/ 0.25 (1.70)	
<u>Physical Properties</u>		
Pozzolanic Activity with Portland Cement, Strength at 28 days, percent of control	109.7	75 min.
Water Requirement, percent of control	100.0	105 max.
Autoclave Expansion, percent	0.002	0.8 max.
No. 325 Sieve Residue, percent	23.1	34 max.
Variation, percentage points from average.	1.55	5 max.
Specific Gravity	2.44	
Variation from Average, percent	1.01	5 max.

* Furnished by the Fly Ash company.

TABLE 11—BLAST FURNACE SLAG PROPERTIES

<u>Chemical Analysis</u>	<u>Value</u>	<u>ASTM C989-89 Requirements for Grade 120 Blast Furnace Slag</u>
SiO ₂ , percent	35.4	
Al ₂ O ₃ , percent	9.5	
Fe ₂ O ₃ , percent	1.14	
CaO, percent	44.83	
MgO, percent	8.1	
S, percent	1.36	2.5 max.
Na ₂ O, percent	0.09	
K ₂ O, percent	0.30	
GOI, percent (weight gain on ignition)	+1.85	
SO ₃	---	4.0 max.
<u>Physical Tests</u>		
Air, percent	7.3	12 max.
Blaine Fineness, sq. cm/gm	5400	
No. 325 Sieve Residue, percent	1.1	20 max.
Compressive Strength, psi (MPa)		
ASTM C-989		
3 days	2270 (15.6)	
7 days	4230 (29.2)	
28 days	7200 (49.6)	5000 (35) min.
Slag Activity, ASTM C-989		
3 days	65.3	
7 days	103.2	90 min.
28 days	135.2	110 min.

* Furnished by the slag company.

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TABLE 12—SUMMARY OF UNHARDENED CONCRETE PROPERTIES

Mixture	No. of Batches	Value	Air Content percent	Unit Weight, lbs/cu ft (kgs/cu m)		Slump, in. (mm)
LWC1	33	Average	5.4*	115.8	(1855)	5.2 (132)
		Minimum	4.4	114.0	(1826)	3.0 (76)
		Maximum	6.0	118.3	(1895)	6.8 (173)
		Standard Deviation	0.45	1.59	(25)	0.82 (21)
LWC2	31	Average	5.6	113.9	(1825)	5.4 (137)
		Minimum	4.3	111.3	(1783)	3.9 (99)
		Maximum	6.8	118.0	(1890)	8.2 (208)
		Standard Deviation	0.60	1.64	(26)	1.06 (27)
LWC3	11	Average	4.8	115.0	(1842)	7.2 (183)**
		Minimum	3.5	109.1	(1748)	6.4 (163)
		Maximum	6.5	118.1	(1892)	8.0 (203)
		Standard Deviation	0.97	2.88	(46)	0.57 (14)
LWC4	11	Average	6.6	113.1	(1812)	6.4 (163)**
		Minimum	5.0	110.4	(1769)	4.4 (112)
		Maximum	8.3	114.9	(1841)	9.1 (231)
		Standard Deviation	1.21	1.49	(24)	1.74 (44)
HSLWC	24	Average	4.5***	126.4	(2025)	6.1 (155)
		Minimum	3.6	123.4	(1977)	4.8 (122)
		Maximum	6.6	129.0	(2067)	9.7 (246)
		Standard Deviation	0.80	1.60	(26)	1.30 (33)
NWC	3	Average	4.1	152.7	(2446)	3.6 (91)
		Minimum	3.6	152.0	(2435)	3.1 (79)
		Maximum	5.1	153.4	(2457)	4.0 (102)
		Standard Deviation	0.84	0.70	(11)	0.46 (12)

* Average of only 26 batches.

** Average of only 4 and 7 batches for LWC3 and LWC4, respectively. The other batches exhibited approximately 6 in. (152 mm) of slump immediately upon lifting the slump cone and then would continue to slowly collapse until maximum slump was reached.

*** Average of only 20 batches.