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 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 light-weight 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 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 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 psi (48 MPa), minimum

γ_{sat} = 120 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:

f'_c = 9000 psi (62 MPa), minimum

γ_{sat} = 130 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 psi (24 MPa) at 24 hours (steam cured)

f_c = 4200 psi (29 MPa) at 7 days

f'_c = 7000 psi (48 MPa) at 28 days (LWC)

f'_c = 9000 psi (62 MPa) at 28 days (HSLWC)

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.

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 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:

Mixture	Coarse Aggregate	Supplementary Cementing Material
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