Performance of Structural Lightweight Concrete in a Marine Environment.

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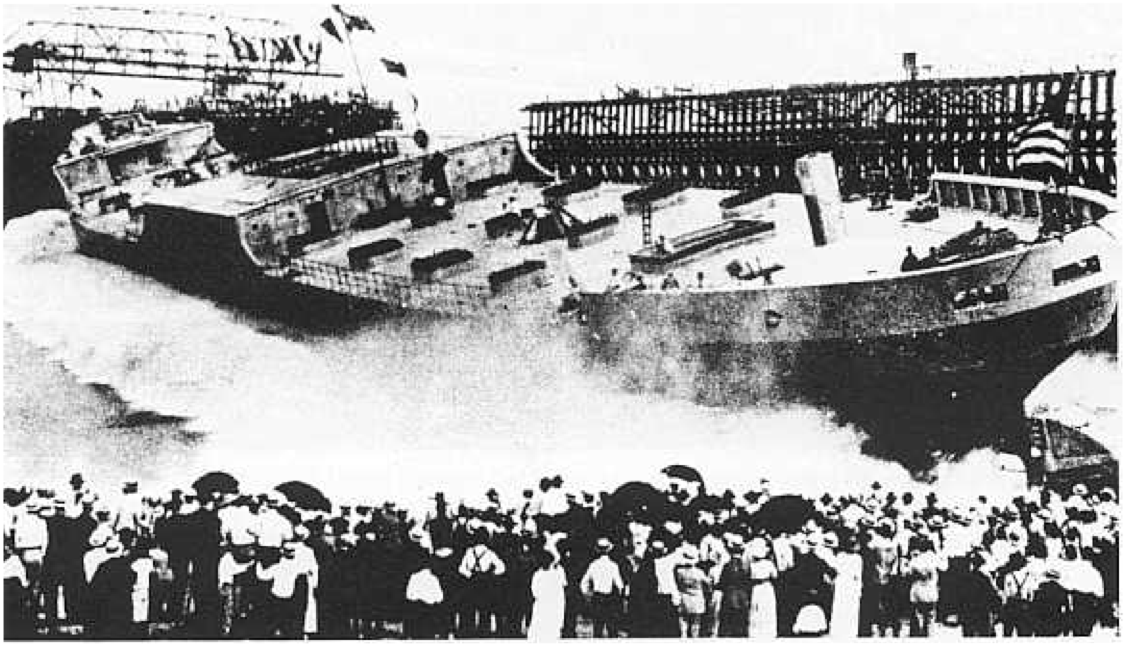

Synopsis

The performance of structural lightweight concrete in a marine environment is reviewed beginning with the construction of concrete ships in World War I. Major laboratory programs, utilizing different methods of evaluating the durability characteristics of structural lightweight concretes are described. Physical properties that influence the weathering characteristics of structural lightweight concrete, that differ significantly from corresponding properties of normal weight concretes are reported. Long term field exposure of lightweight concrete structures, including a 60 year old ship and a 25 year old bridge deck are reported. Criteria for the construction of durable lightweight concrete structures exposed to marine conditions are recommended.

Keywords

Bridge decks; compressive strength; concrete construction; cores; field tests; freeze-thaw durability; *lightweight aggregate concretes; marine atmospheres;* modulus of elasticity; *performance;* physical properties; ships; weathering.

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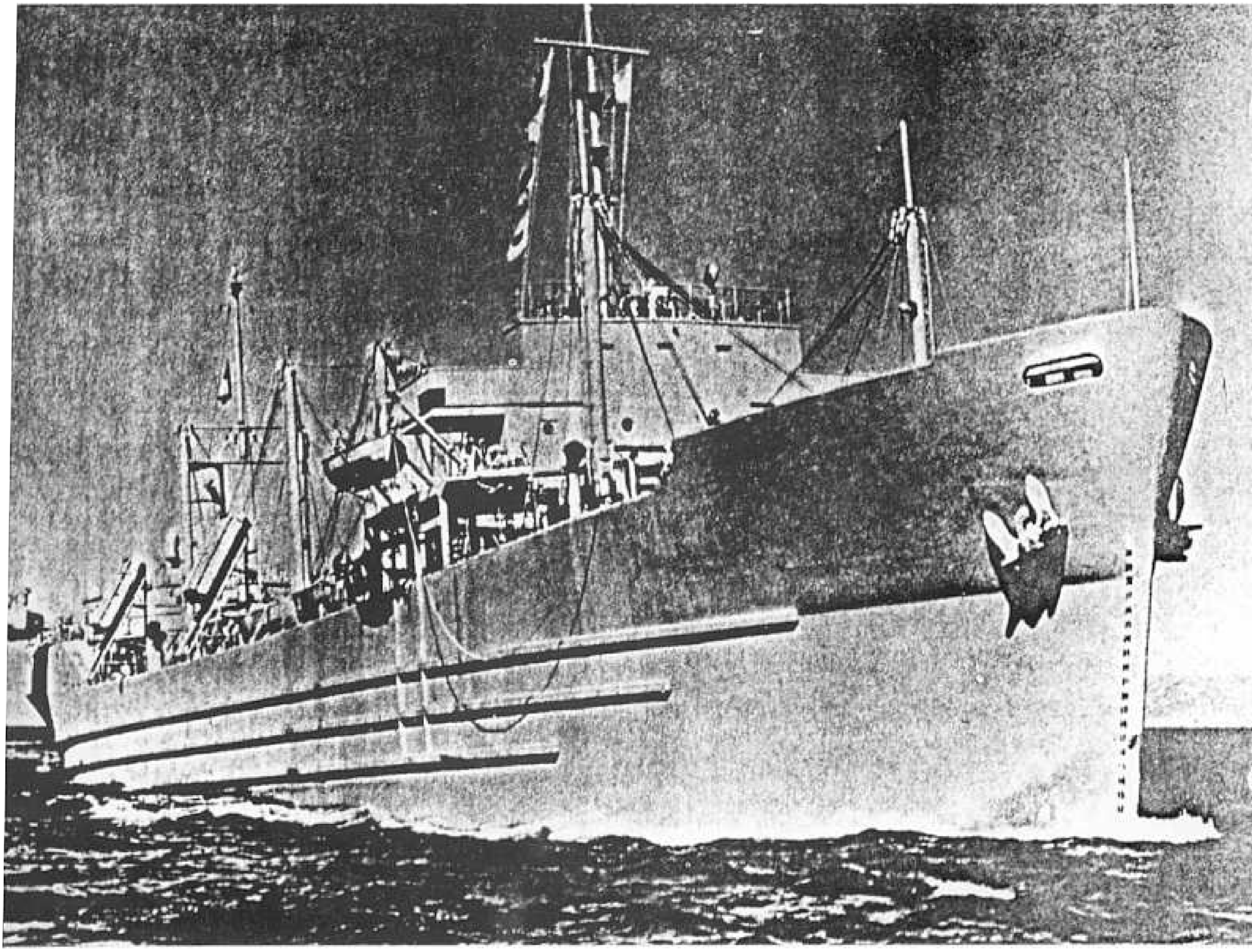

Figure # 1 —General view—Dry cargo lightweight concrete ship, World War II

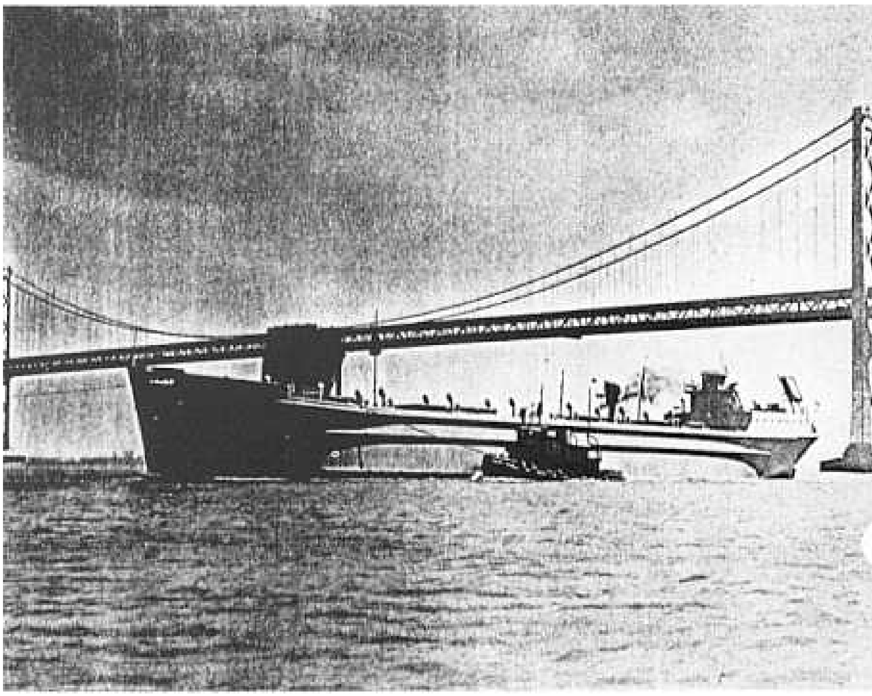

Figure # 2—Lightweight concrete barge passing under lightweight concrete bridge deck—World War II

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History of Structural Lightweight Concrete in a Marine Environment

The use of lightweight concrete in a marine environment is hardly a novel concept. Indeed, the origin of the lightweight aggregate industry as we know it today is to a large degree due to the collaboration in 1918 of American shipbuilding authorities with Stephen J. Hayde's development of a strong, inert, durable, lightweight aggregate produced from a shale, clay or slate in a rotary kiln. Feasibility studies by marine engineers at that time indicated that a concrete ship would be practical if the concrete used could meet the requirements of strengths exceeding 35 MPa (5 ksi) at a density less than 1760 Kg/M³ (110 pcf) (1). Extensive investigations revealed that while naturally occurring lightweight aggregates could not meet these conditions, rotary kiln produced expanded shale could exceed the requirements. On a practical basis the first commercial production of aggregate was conducted in a brick plant near Birmingham, Alabama with enough aggregate produced to supply concrete for the 3000 ton Atlantus launched in December 1918 (2). Again in 1941, with the advent of World War II, immediate consideration was given to the use of lightweight aggregate instead of natural sand and gravel for the concretes to be used in the shipbuilding program. The same type of lightweight aggregate successfully used in the World War I program was recommended for the construction of the second concrete fleet. Samples from several commercial rotary kiln lightweight aggregate production plants were sent to the laboratory of the Public Roads Administration for tests and, after comprehensive investigations, the rotary kiln lightweight aggregates proposed for use were deemed satisfactory (3,4). In all, 104 ships were constructed at five separate shipyards, with several different designs, with follow-up reports indicating the hulls to be watertight and having good riding qualities with little vibration *(Figures 1, 2, 3)*.

After World War II there was a rapid development in the production capacity of the lightweight aggregate industry in North America, in order to meet the growing demands for the use of lightweight concrete masonry units. There was also the emerging use of structural lightweight concrete in all forms of standard construction, principally in urban areas for high rise concrete structures. At about the same time lightweight concrete was incorporated into precast/prestressed plants where the strength levels were considerably higher than the requirements of cast-in-place structures. This widespread construction use of rotary kiln produced expanded shale concretes was accompanied by many technical papers, reports and investigations that are summarized and digested in the "Guide for Structural Lightweight Aggregate Concrete" of the American Concrete Institute Committee 213 (5). At the present time, structural lightweight concrete in North America is not thought of as a fundamental departure from normal weight concrete, but merely a concrete with more efficient physical properties.

It appears that a third major application of concrete in marine environments is presently underway, particularly in the development of ocean resources for our future energy requirements. Mobile floating platforms that could be towed to forward sites to provide operational or strategic functions, as well as massive permanent floating structures housing ocean thermal-energy conversion systems could be effectively produced from structural lightweight aggregate concretes of high specific strength (i.e. ratio of strength to density) (6,7). In several seaboard locations there presently exists the production capacity of existing lightweight aggregate plants necessary to supply the huge demands of such programs. In addition, the ability to produce high quality, high strength-to-weight concretes is currently available. Further improvement over the successful past experience of structural lightweight concrete is also possible through the use of modern techniques involving proportioning concrete mixes with high-range water reducers, the significant advantages of prestressing and post tensioning as well as sophisticated structural design techniques.

This report will deal only with the durability performance of concretes produced with structural lightweight aggregates as well as several significant physical property differences from regular weight concretes that have a direct, phenomenological relationship to resistance to weathering. For physical properties and related aspects that are common to all concretes in a marine environment (admixtures, cement type and chemistry, compaction techniques, steel reinforcement, embedded items, etc.) the reader is referred to the comprehensive presentations provided by Gerwick (8,9).

Figure # 3—Construction of lightweight concrete ship—World War II

Laboratory Freeze-Thaw Tests on Structural Lightweight Aggregate Concrete

The first major industry-wide laboratory investigation into the freeze-thaw resistance of structural lightweight concretes was conducted by Klieger and Hanson (10) at the Portland Cement Association Laboratory. Concretes incorporating nine lightweight aggregates manufactured by several different processes were tested with the primary variable being strength level, 20 and 31 MPa (3 and 4.5 ksi) with and without air-entrainment. Results were compared with tests on a reference normal weight concrete with a good service record in field performance. After a moist curing period of 14 days, at 23°C (73°F), 100% RH, followed by drying in lab air for 14 days at 23°C (73°F), 50% RH, and then a 3 day immersion in water, concrete prisms were subjected to rapid freeze-thaw in water (formerly ASTM C-290, presently ASTM C-666 Method A). Severe laboratory conditions were imposed on some of the specimens: low cement contents, non-air-entrainment, short drying period, freeze-thaw continuously under water at an early age, and repetitive extreme moisture gradients that are unrepresentative of the weathering of actual structures. It was not surprising to have the authors conclude, "the spread in durability among the concretes made with the different lightweight aggregates appears no greater than might be encountered with normal weight aggregates". High durability (small weight loss, insignificant expansions and almost no decrease in sonic modulus) was demonstrated after 300 cycles of freezing and thawing by the properly proportioned, air-entrained lightweight aggregate concretes. Expanding on the extensive date provided in the first PCA series, Pfeifer (11) continued with durability studies of structural lightweight concretes and included a study of the influence of replacement of a part of all of the lightweight fine aggregate fraction with natural sand.

In an attempt to correlate the good field durability experience of structural lightweight concretes in a number of North American projects, the Expanded Shale Clay and Slate Institute sponsored three comprehensive series of freeze-thaw tests at the University of Toledo (12). In the first series eight rotary kiln produced lightweight aggregates and one reference normal weight aggregate were tested with the main variables being sand replacement of fine aggregate and moisture content of the lightweight aggregate at time of mixing. Rapid freeze-thaw in water procedures were repeated. However, concretes were proportioned in accordance with usual field practice (air contents at 6% and 1%, 100 mm (4") slump and cement contents for all mixes at 360 Kg/M³ (611 pcy). This program demonstrated that structural concretes with high quality mortar fractions and containing rotary kiln produced lightweight aggregates performed satisfactorily for at least 300 cycles of freezing and thawing in water, both with or without sand replacement. Comparing drying times of 14, 28 and 56 days, the results obtained on the 32 concrete mixes tested showed little variation, indicating that a drying period of 14 days prior to the first freeze-thaw cycle was sufficient for concretes mixed with aggregates at usual field moisture contents.

The results of these major programs that include hundreds of laboratory tests may be simplistically summarized by noting that air-entrained lightweight concretes proportioned with a high quality binder provide satisfactory durability results when tested under usual laboratory freeze-thaw programs.

Additionally, freeze-thaw test programs were conducted for analysis by the technical committees of various engineering societies. One series of tests (13) included comparisons of testing environments, (freezing in air or water) as well as attempts to correlate freeze-thaw laboratory concrete tests with more convenient and rapid aggregate soundness tests using cycles of wetting and drying in salt solutions. These tests indicated that, in general, low soundness losses on aggregates correlated with good freeze-thaw laboratory performance of properly proportioned concrete made from the tested aggregates. Suggested soundness and freeze-thaw criteria from these tests were incorporated into the material specifications of some government organizations.

Physical Properties of Structural Lightweight Aggregate Concrete

Axial Compressive Strength

Each particular lightweight aggregate has a limiting strength "ceiling" beyond which there can be no appreciable strength gain despite large increases in cementitious materials. This strength "ceiling" is a function of the strength of the vitreous material and the quantity, size, shape and distribution of the enveloped pores, but the decisive factor is the strength of the largest individual particle. In one high strength lightweight concrete investigation (14), 10 mm (⅜") coarse aggregate top size consistently produced strengths equal to or greater than normal weight concretes with equal binder content. One series of results is shown in *Figure 4.* Long term strength gain of the structural lightweight concrete is generally greater than the companion normal weight concretes, due to the continuous hydration of the binder with the moisture available from the slowly released reservoir of water absorbed within the pores of the lightweight aggregate. This process of "internal curing" is possible when the moisture content of the lightweight aggregate at the time of mixing is at least equal to that achieved by soaking for one day. The effect of "internal curing" is further enhanced if a pozzolan (fly ash or suitable lightweight aggregate fine fraction) is introduced into the mix. It is well known that the pozzolanic reaction of a finely divided alumino-silicate material with calcium hydroxide liberated as cement hydrates is contingent upon the availability of moisture. It should be pointed out that the pozzolanic activity of some lightweight fine aggregates is a dependable, consistent property that is fully exploited as a cement replacement in the high temperature curing of concrete masonry units. In this application however, the pozzolanic behavior should be considered as a desirable, additional virtue, and not for cement reduction.

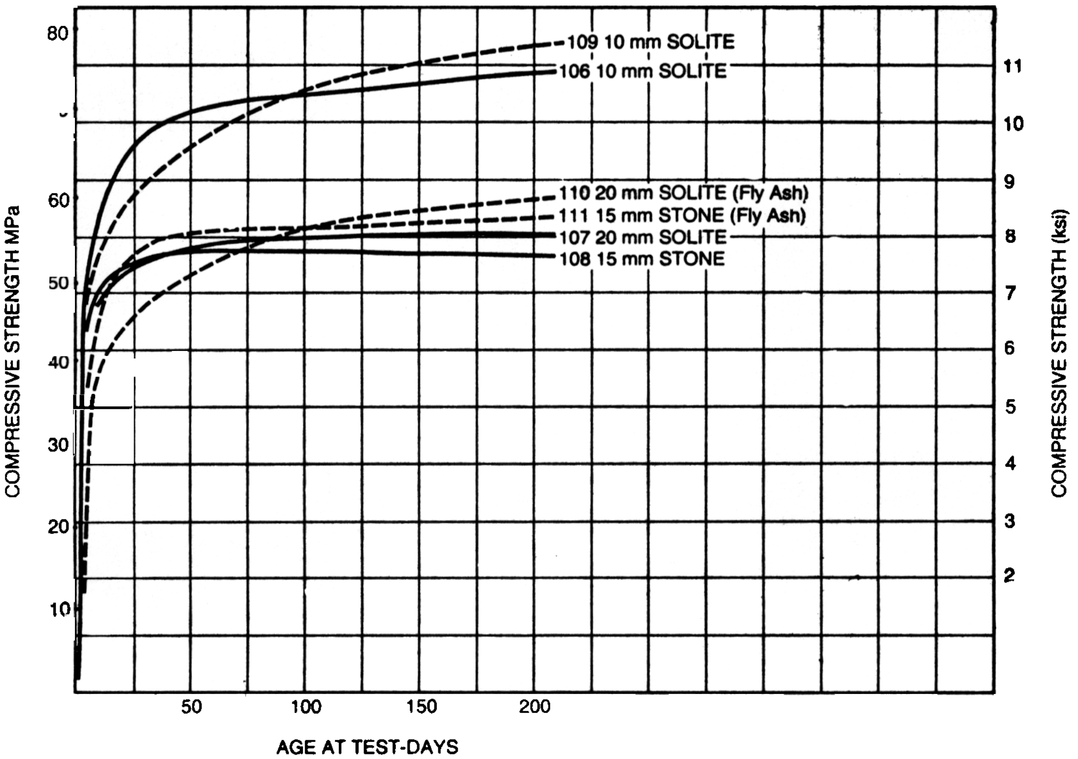
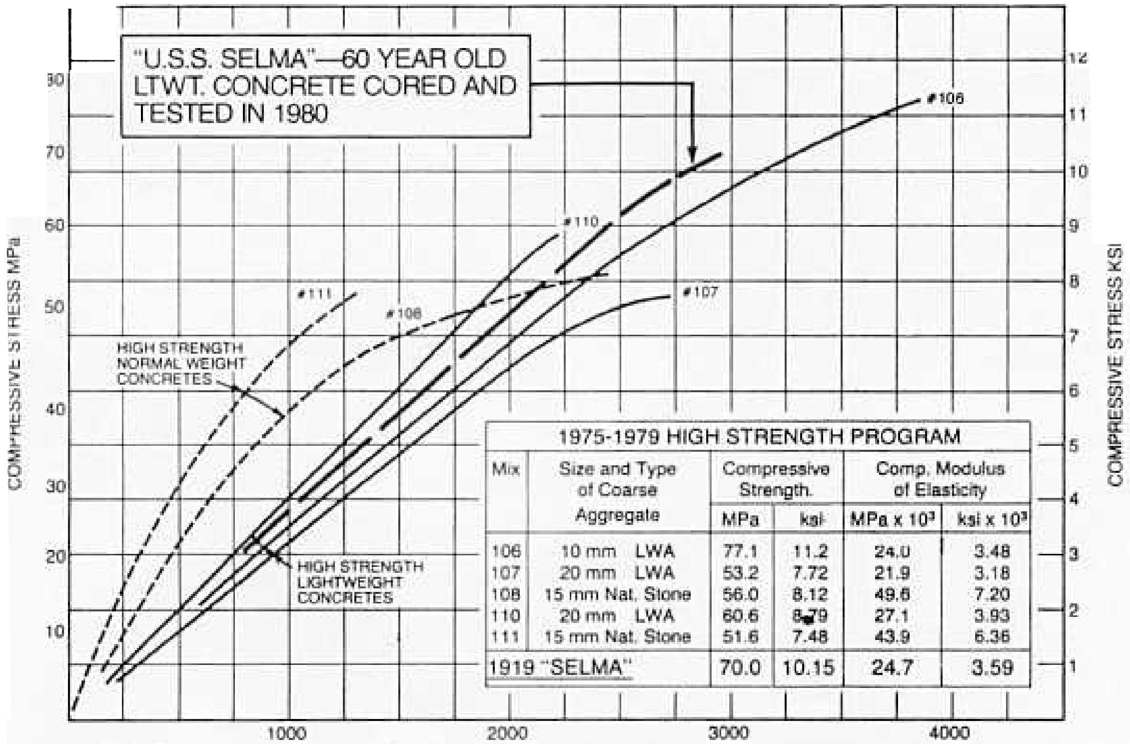


Figure # 4—Compressive strength versus age of lightweight and normal weight concrete (1975-1979 series)



1975-1979 HIGH STRENGTH PROGRAM

Mix	Size and Type of Coarse Aggregate	Compressive Strength.		Comp. Modulus of Elasticity	
		MPa	ksi	MPa x 10³	ksi x 10³
106	10 mm LWA	77.1	11.2	24.0	3.48
107	20 mm LWA	53.2	7.72	21.9	3.18
108	15 mm Nat. Stone	56.0	8.12	49.6	7.20
110	20 mm LWA	60.6	8.79	27.1	3.93
111	15 mm Nat. Stone	51.6	7.48	43.9	6.36
1919 "SELMA"		70.0	10.15	24.7	3.59

Figure # 5—Stress-strain curves for high strength lightweight and normal weight concretes (plus Selma lightweight concrete—60 years old)

It is curious that in the material recommendations of the Federation Internationale de la Precontrainte (15) for the design and construction of concrete sea structures, there is a suggestion for the addition of pozzolanic material for ordinary Portland cements having a C_3A content greater than 8%, while in the aggregate section there is a recommendation against the use of fine aggregates which may react with the cement. Somewhere, within the continuum of gradation, fine lightweight aggregate with the proper physical and chemical characteristics may transcend this arbitrary division of mineral constituents and simultaneously provide roles of aggregate as well as cementitious binder.

Modulus of Elasticity in Compression

One explanation for the excellent durability service record of high strength lightweight concrete may lie in the similarity of the strength and stiffness characteristics of the coarse lightweight aggregate and the remaining "mortar" fraction. It has been reported (14) that the stress-strain curves of high strength lightweight concrete are linear to levels approaching 90% of the failure strength, *(Figure 5)* indicating the relative compatibility of the elastic and strength characteristics of the coarse lightweight aggregate and the mortar component (cement paste and natural sand), that surrounds the large aggregate. "Elastic Matching" of the two components, producing relatively "homogeneous" concrete, will be possible if the coarse aggregate particles have sufficient particle strength to match the strength characteristics of the mortar fraction. This separation of the strength and elastic properties of the two components of a heterogenous concrete system has been thoroughly studied by others (16,17), but generally, in relation to a "stiff" aggregate in a "soft" mortar (high strength normal weight concretes), where $E_M < E_C < E_A$, concretes fail due to bond limitations or microcracking initiated by an extremely rigid coarse aggregate; or a "soft" aggregate in a "stiff" mortar (low density insulating lightweight aggregate concretes), $E_M > E_C > E_A$, where failure is due to crushing of the very light, lightweight aggregate particles. A third situation may exist wherein the coarse aggregate particle strength and elastic characteristics closely match and are securely bonded to a high quality mortar fraction ($E_M \approx E_C \approx E_A$). Analysis of this mechanism is currently underway and will be reported at a later date.

Russian studies, approaching concrete durability from a phenomenological aspect, have also noted the high inner stress conditions due to different deformation responses of the various constituents, ". . . as elasticity modulus decreases . . . the stresses in the conglomerate fall off, it leads . . . to the increase in frost resistance. And really, concrete with keramzite (lightweight) gravel and sand, the elasticity modulus of which is much less than that of volcanic solid rocks possess often greater frost resistance than, for example, concrete made with granitic crushed stone" (18).

Marine Applications of Structural Lightweight Aggregate Concrete

Concrete Ships

The U.S.S. Selma, a 7500 ton reinforced expanded shale concrete tanker launched in 1919 is perhaps the most vivid testament to the durability in a marine environment of structural lightweight concrete. After several years of service this vessel was purposely sunk in 1922 in Galveston Bay, Texas where it has remained partially submerged ever since. The hull has been in sea water for over 60 years with a band width of approximately 1 meter exposed to wetting and drying in salt air caused by wind and tides. The deck and upper section of the hull have been exposed to salt air and occasionally awash with sea water due to wave action in storms *(Figure 6)*.

A study of the concrete was sponsored by The Expanded Shale Clay and Slate Institute in 1953 and reported in the publication, "Story of the Selma—Expanded Shale Concrete Explores the Ravages of Time" (1). This study reported that cubes and cores taken from the waterline area had compressive strengths of approximately 55 to 75 MPa (8 to 11 ksi) when normalized to 150 × 300 mm (6″ × 12″) cylinders. Modulus of elasticity was reported at 20×10^3 MPa (3×10^6 psi) and a bond strength on plain reinforcing bars of 3.56 MPa (516 psi). Surprisingly little corrosion was noted despite a coverage of only 16 mm (⅝″) *(Figure 7)*.

In 1980 the Selma's performance was reviewed again with cores taken for an up-date on the extensive tests conducted in 1953. Examination of both the submerged and waterline area cores of the sixty year old lightweight concrete revealed little if any deterioration *(Figure 8)*. Form marks on the core's exterior surface were visible and no evidence of microcracking was observed when viewed under a magnifying glass. The concrete was extremely well compacted (the first known application of internal vibration techniques) with only a small number of macroscopic air voids, coarse aggregate (minus ½″) was well bonded to the mortar fraction, uniformly distributed and without any indication of water gain under large aggregate particles indicating a fluid easily placed, but not wet concrete. (An engineer in charge of the Emergency Fleet Corporation in 1919 developed an apparatus to control the workability of the concrete from batch to batch and provided the industry with the initial slump cone test). Particle shape of the aggregate was semi-angular to rounded, typical of modern lightweight aggregates. Visible pore structure of the lightweight aggregate was fine to medium.

Core samples cut through the undeformed steel reinforcing bars showed little evidence of rusting. There was almost no sign of corrosion at the reinforcing bar to concrete interface that could be observed when cut sections of steel were inadvertently separated from broken cores.

Compression strength measured on the concrete cores, normalized to 150 × 300 mm (6″ × 12″) cylinders was 70 MPa (10.2 ksi); the modulus of elasticity in compression was 25×10^3 MPa (3.59×10^6 psi). These values are comparable to the results of the cores and cubes test

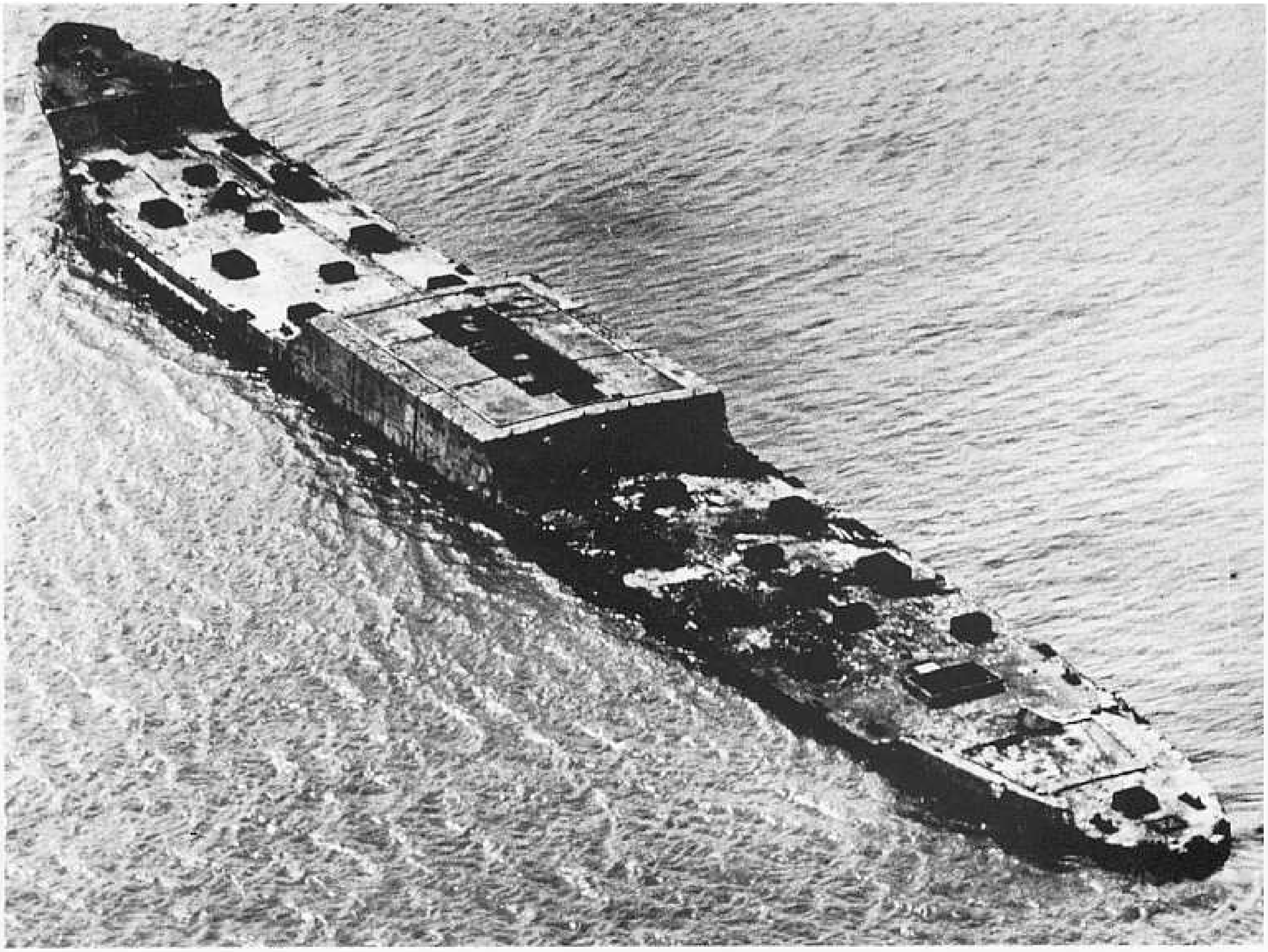


Figure # 6—U.S.S. Selma—Lightweight concrete ship launched in 1919—Photograph taken in 1953

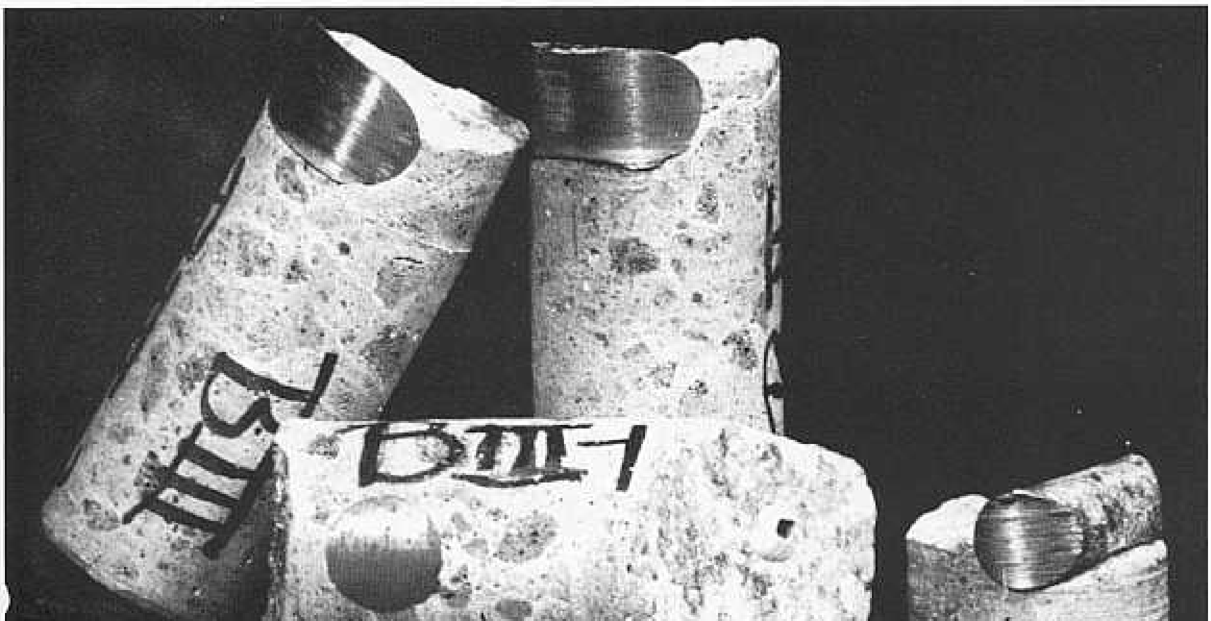


Figure # 7—Cores taken from U.S.S. Selma in 1980 results from the 1953 investigation. In addition, the result of the Selma concrete stress-strain curve is superimposed in *Figure 5* on the results of recently completed high strength lightweight concrete test program (14). The similarity of the data on the concrete specimens, cast almost 60 years apart, is evident.

Explanations of this unusual resistance to weathering and corrosion is difficult to quantify and may include some or all of the following physical and chemical mechanisms:

1. Superior resistance to microcracking due to high bond of aggregate to mortar fraction combined with the reduction of inner stresses due to elastic matching of the coarse aggregate and the mortar phase.
2. High ultimate strain capacity provided by a concrete with a high strength to modulus ratio.
3. A well dispersed void system provided by the fine lightweight aggregate fraction that may serve an absorption function in weathering resistance as well as reducing salt concentration levels in the mortar phase.
4. Long term pozzolanic action provided by lightweight fine aggregate with the proper physical and chemical characteristics that could combine with the calcium hydroxide liberated during cement hydration. This could minimize the leaching of soluble compounds and in addition may reduce the possibility of sulphate salt disruptive behavior.
5. Low mortar permeability provided by the combination of high cement contents and the water available in the lightweight aggregate for internal curing.

Attempts to evaluate the potentially beneficial contribution of these mechanisms will continue in the future.

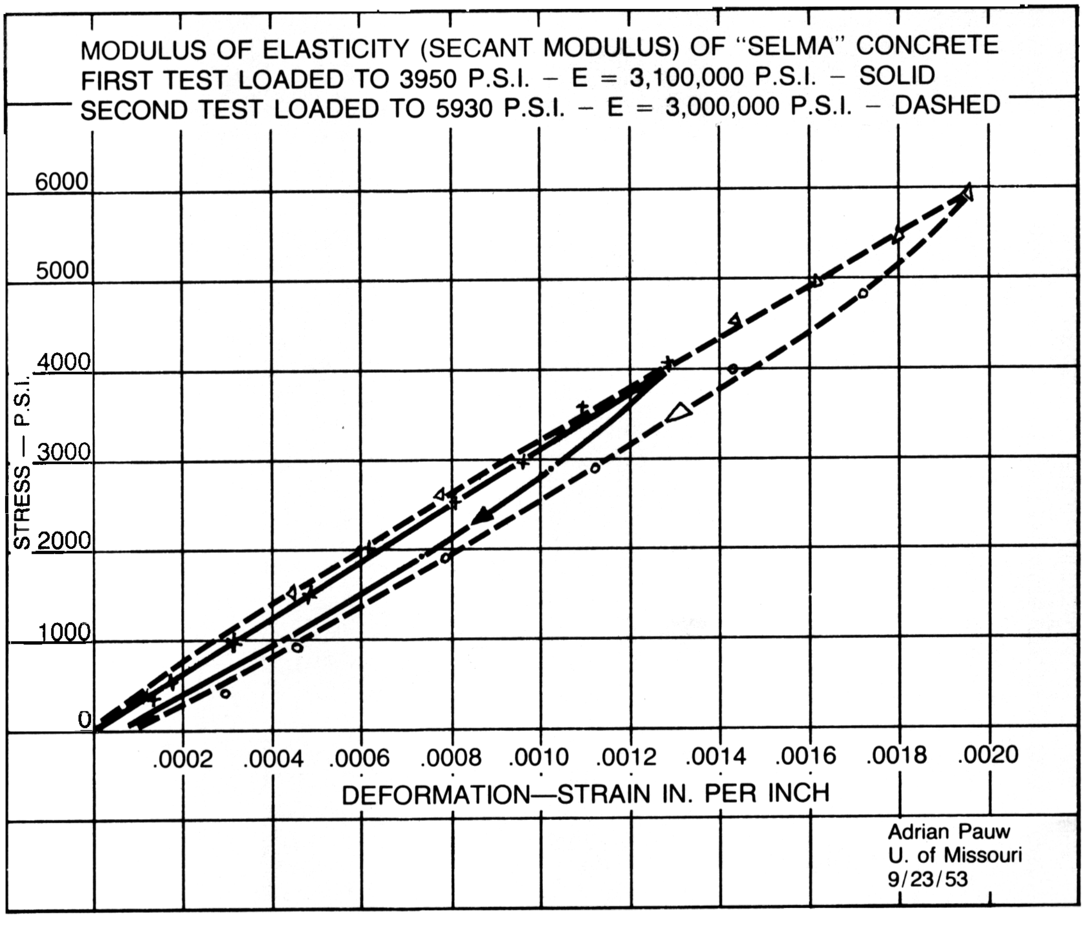
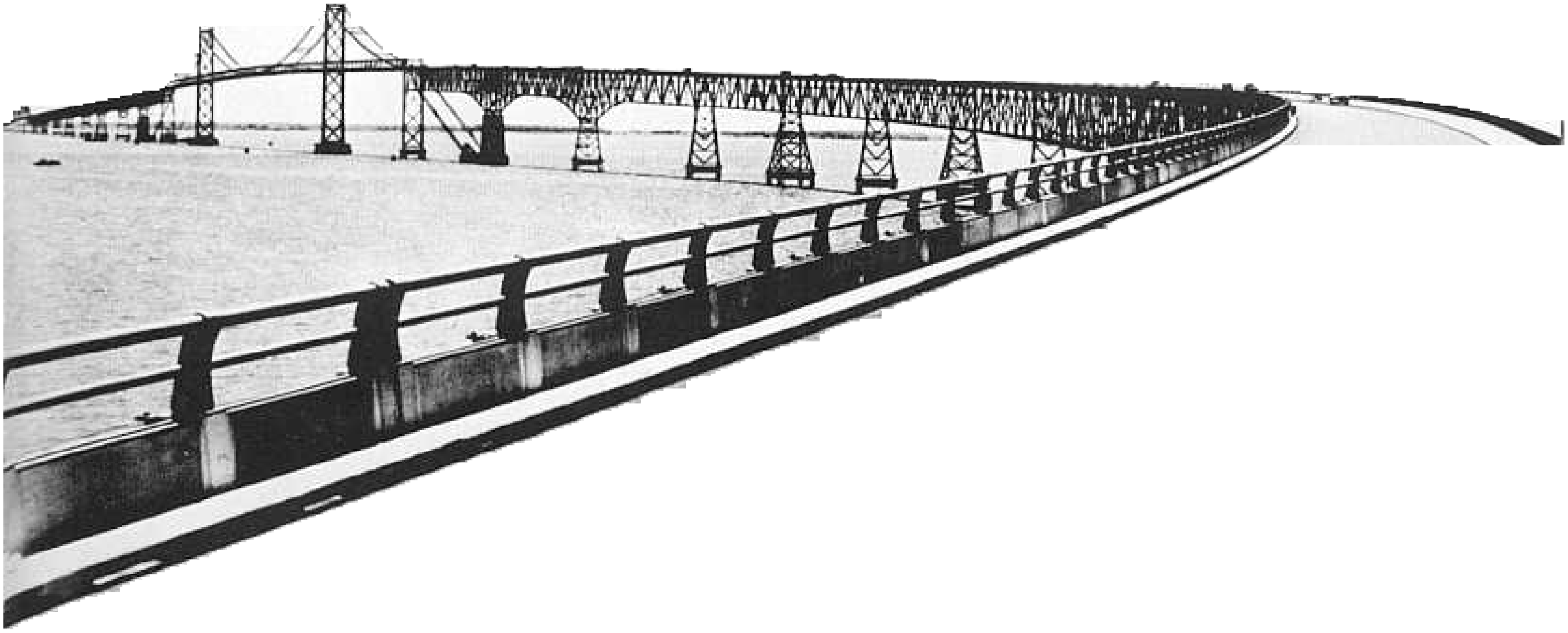


Figure # 8–Stress-strain curve of U.S.S. Selma lightweight concrete from 1953 tests



:igure # 9- -Chesapeake Bay Bridge- Annapolis, Maryland, constructed 1954

Chesapeake Bay Bridge

Many lightweight concrete bridge decks have been constructed in marine environments throughout North America, including major projects such as the 7 km (4.5 miles) Chesapeake Bay Bridge, constructed in 1954 at Annapolis, Maryland with a design strength of 24 MPa (3.5 ksi) and an air dry density of 1680 Kg/Mg^3 (105 pcf) *(Figure 9).* After completion in 1975 of a second parallel crossing to handle the increased traffic load, the asphalt wearing surface of the original bridge was removed and an extensive investigation into the serviceability of the concrete deck conducted by an independent testing laboratory (19). Freezing and thawing combined with rapid temperature cycling, road salt exposure, vibration and stress reversals typical of long span bridges may constitute an environment that is more severe than continuous immersion. Extensive physical tests (core drilling, petrographic and ultrasonic) revealed excellent condition of the non-air-entrained lightweight concrete of the main spans. Deterioration of the non-air-entrained normal weight concrete of the approach spans required a significant amount of concrete removal and repair. After the investigation demonstrated that repair of the lightweight concrete spans was not necessary, a new wearing surface was applied and the bridge put back into service.

It is especially interesting that Fagerlund's extraordinarily comprehensive theoretical and laboratory investigations into the "Frost Resistance of Concretes with Porous Aggregates" (20) suggested extra frost resistance could be available in some lightweight concretes in that, "The reason for this feature could be that lightweight concretes did also contain a lightweight sand fraction. These porous grains could very well have acted as air-entrained pores . . . sand particles of a size smaller than .025 mm (.01 inch) have a spacing that is of the same order of size as air-entrained pores". While the actual in-service experience of the Chesapeake Bay Bridge precisely fulfills Fagerlund's observations, it must be emphasized (as in fact Fagerlund also noted) that appropriate air-entrainment and high quality mortars are essential for maximizing durability as well as minimizing scaling, bleeding and permeability.

Some transportation engineers are now specifying higher concrete strengths for bridge decks in order to develop high quality mortar fractions (high strength with high air content) that will minimize maintenance costs. One state authority has several bridges presently under construction which utilize a lightweight concrete with a target strength of 36 MPa (5.2 ksi) with 6-9% air content. Another highway authority (21) has systematically replaced deteriorating existing normal weight concrete bridge decks with structural lightweight concrete because of demonstrated improvements in durability. A bridge deck survey sponsored by the Expanded Shale Clay and Slate Institute found the vast majority of lightweight concrete bridges providing good service performance (22).

Other Applications

Numerous other applications of structural lightweight concretes in marine environments include floating bridges, boat marinas, and large submerged concrete pipe structures (Figure 10). Where available, service records indicate low maintenance costs and insignificant rates of deterioration.

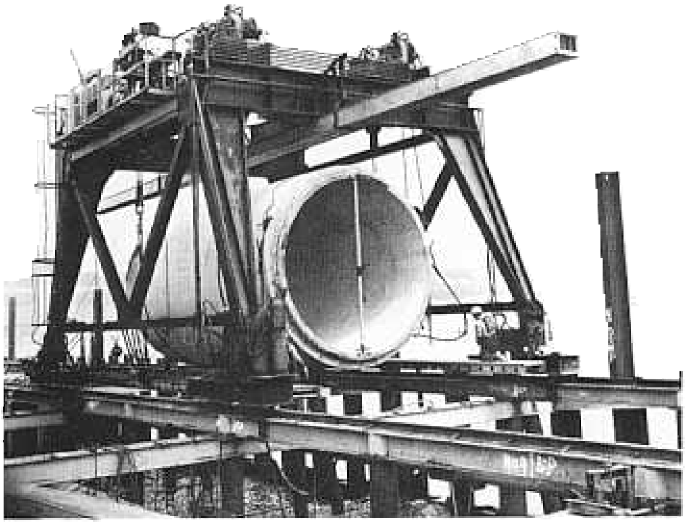


Figure # 10—Lightweight concrete pipe used in Pacific Coast Power Plant water system

Conclusion and Recommendations

Large scale concrete structures in marine environments to assist worldwide energy source development has brought about a re-examination of the durability characteristics of structural lightweight aggregate concrete (23,24).

Extensive laboratory freeze-thaw testing programs have demonstrated that structural lightweight aggregates, in combination with high quality pastes containing the proper spacing and amounts of air, and permitted a drying period of at least 14 days prior to first freezing, will produce adequate laboratory tested concrete durability.

Investigations of a number of in-service lightweight concrete structures in marine environments for up to 60 years verify the laboratory indications of good weathering resistance and suggest the following criteria for future applications:

A. Use high quality structural lightweight aggregate (both coarse and fine) that has a proven record of durable performance in severe weathering exposure.
B. Use a minimum cement content of 360 Kg/M^3 (611 pcy) for structures with moderate exposure (building facades, garages) and 440 Kg/M^3 (748 pcy) for concretes with severe exposure (bridge decks, marine environments).
C. Use air contents suggested by ACI 201 (25) as a minimum starting point, 6% for 20 mm (¾"), 7.5% for 10 mm (⅜") aggregate.
D. Place concretes at reasonable slumps 75 mm (3"), using best recommended practice for compaction, finishing and curing.

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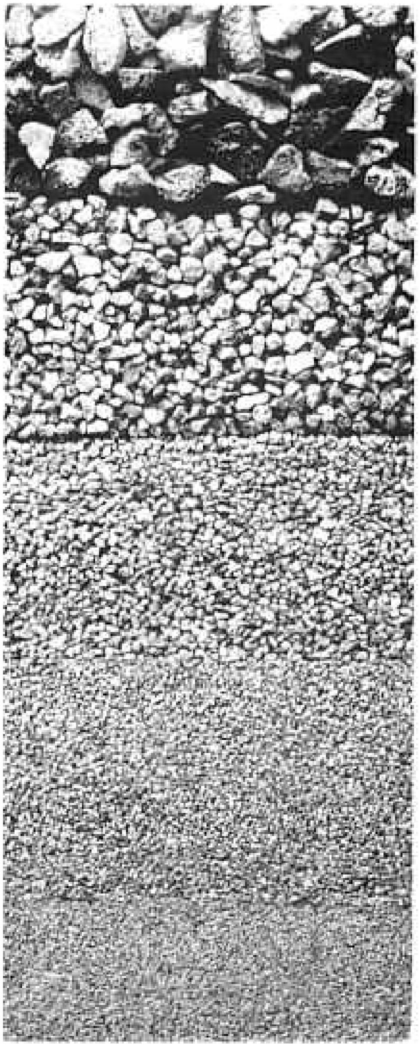
Structural Concrete

High quality structures are produced through a combination of:

A. High quality materials, mixing and transportation techniques;
B. High quality structural design and details;
C. Specifications carefully written and observed;
D. Attentive control and adjustments of field concrete. (Air content, density, yield, slump, temperature, etc.)

SOLITE field service representatives will follow through to see that your job is completed according to specifications. Call for their services when writing your job specs.

Structural Lightweight Aggregate Specifications



All lightweight aggregate shall be produced by the rotary kiln process, and shall be SOLITE or approved substitute, and shall meet all the requirements of ASTM-330 (AASHTO M195). ASTM certification, verified by an independent testing laboratory within 2 years, shall be submitted to the architect/engineer at least 60 days prior to the start of the project. Concrete made from the aggregate with a cement content of 564 pcy (334 kg/m^3) and approximately 6% air content shall have a minimum durability factor of 85% when tested in accordance with ASTM C-666.

Structural Lightweight Concrete

Materials shall be proportioned in accordance with ACI211.2 so as to produce concrete with the properties listed below:

A. 28-day compressive strength	Wet Density ± 3 pcf (50 kg/m^3) (C-138)	Calculated Equilibrium Density ± 3 pcf (50 kg/m^3) (C-567)
3000 psi (21 MPa)		
4000 psi (28 MPa)		
5000 psi (34 MPa)	____________	____________

B. Air content determined in accordance with ASTM C-173 shall be 6-8 percent by volume.

C. Slump shall be as listed below: ____ on slabs
____ on vertical surfaces

D. Concrete cylinders shall be molded and cured in accordance with ASTM C-31 with the following exception: after 7 days of moist curing in the laboratory, the cylinders shall be removed from the moist room and cured at 50% ± 2 relative humidity and 73.4°F ± 2 (23 ± 1.7°C) until time of test.

E. Design data, creep, shrinkage and design coefficients shall be made available to the architect/engineer for prior approval.

F. The lightweight aggregate producer specified for the project shall make available to the architect/engineer tests conducted in accordance with ASTM C-496 indicating tensile splitting strength on concrete composed of coarse lightweight aggregate and natural sand in excess of .85 of the values called for in ACI 318 for the particular compressive strength called for in the specification (.75 for all lightweight concrete).

The aggregate producer shall provide field service for initial placements and upon request shall provide such service to the architect/engineer and ready-mix producer at no cost to the owner.