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PLACED, CURED, AND TESTED IN THE DEEP OCEAN

author: Harvey H. Haynes and Larry D. Underbakke

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Freshly mixed concrete, of low- and high-strength mix designs, was placed in the Pacific Ocean in 6 x 12-inch (152 x 305-mm) cylindrical molds to attain initial and final set and cure at a depth of 1,830 feet (560 m). At age 11 months, the concrete specimens were retrieved and subsequently tested under uniaxial compression in a pressure vessel that simulated the ocean depth. The compressive strengths of the deep-ocean concrete specimens were compared with those of controlled concrete specimens cured in a fog room and also in a tank containing continuously circulating seawater.

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INTRODUCTION

Previous work (Ref 1) involved the feasibility of placing freshly mixed concrete at deep ocean depths. The Navy has an interest in such capability relative to building in-situ structures and foundations. The investigation (Ref 1) determined that the task would be feasible using a drillpipe suspended from a surface platform to convey the concrete by gravity force to the seafloor. Flow control would be maintained by frictional forces between the pipe and concrete. The technology appeared to be state-of-the-art for the hardware and ocean engineering systems, but tests were recommended on the concrete materials.

This study pertains to one aspect of the concrete behavior -- its compressive strength after being placed on the seafloor and allowed to set and cure. The main question is: If freshly mixed concrete is placed on the seafloor for structural purposes, what will be the resulting in-situ compressive strength? A test plan was formulated to determine whether a long-term (up to 2 years) strength-change occurred because of the effect of the deep ocean environment on the concrete.

TESTING PROGRAM

The concrete placement procedure for deep depths should follow the basic method for that of tremie-placed concrete. This method has the end of a pipe submerged in the deposited concrete so that the mass of deposited concrete grows from within; in this manner, there is minimum mixing between seawater and concrete, and few cement fines wash away.

For this testing program, freshly mixed concrete was placed in the ocean by confining the material in 6 x 12-inch (152 x 305-mm) cylindrical plastic molds. The concrete was exposed to the pressure environment and to the seawater by providing two 1/8-inch (3-mm) diam holes in the lids to the molds. The lids prevented the cement fines from washing away. The procedure simulated the tremie placement condition of freshly mixed concrete being exposed to seawater under hydrostatic pressure.

Speed of concrete placement was another important consideration because the concrete should be workable when it reaches the seafloor. It was conceivable that hydrostatic pressure could compact the concrete. For two principal reasons, namely, the quantity of specimens to be cast and cost constraints, the concrete test specimens were made ashore, transported immediately after casting to the oceanic site by helicopter, and allowed to freefall to the seafloor. Because of this approach, the individual specimens were confined within a framework that could be transported inside a military helicopter, and could freefall through water in a stable manner. Freefalling was risky because the seafloor has rock outcrops that could cause the framework to overturn; hence, it was necessary to use two frameworks to increase the odds of attaining an upright landing.

One of the frameworks was outfitted with rope, buoy, and acoustical release. The acoustical release could be actuated from the surface so that the buoy would bring one end of the rope to the surface. This framework could be retrieved when desired. The second framework had no ropes attached so that a manned submersible could approach without concern of entanglement.

Low- and high-strength concretes were tested. The effects of the deep ocean environment could be different on either low- or high-strength concretes as a result of the different pore size distribution that develops within the concretes. Applications for freshly mixed concrete on the seafloor include: (a) for low-strength concrete, seafloor stabilization and object encapsulation; (b) for high-strength concrete, in-situ construction of pressure-resistant structures.

CONCRETE MIXES

The concrete mixes were designed to use locally available materials from a ready-mix plant and at the same time be representative of those mixes used for deep-ocean placement. The aggregate proportions (selected for pumpable concrete) were: 43% by volume of the total aggregate was sand, 10% by volume was 3/8-inch (9-mm) pea gravel, and 47% by volume was coarse aggregate of maximum 1-inch (25-mm) size. Type II portland cement was used in conjunction with a water-reducing and retardant admixture (Pozzolith 300-R at a rate of 5 fl oz/100 lb of cement).

The mix proportions and freshly mixed concrete properties for the low- and high-strength concretes were:

Low-Strength Concrete

cement content	= 423 lb/yd ³ (251 kg/m ³)
water/cement ratio	= 0.66 (by weight)
sand/cement ratio	= 3.33 (by weight)
aggregate/cement ratio	= 4.43 (by weight)
slump	= 4 in.
air content	= 3.4% (by volume)
unit weight	= 146.2 lb/ft ³ (2.37 Mg/m ³)
setting time (Vicat)	= 4 hrs

High-Strength Concrete

cement content	= 658 lb/yd ³ (391 kg/m ³)
water/cement ratio	= 0.46 (by weight)
sand/cement ratio	= 2.01 (by weight)
aggregate/cement ratio	= 2.68 (by weight)
slump	= 3 in.
air content	= 2.2% (by volume)
unit weight	= 145.8 lb/ft ³ (2.34 Mg/m ³)
setting time (Vicat)	= 3 hr.

A nonstandard test was conducted to obtain an indication of the duration of workability for the concrete mixtures. A handful of freshly mixed concrete was manipulated manually to determine whether the concrete retained plasticity or crumbled. The low-strength mix crumbled 5.5 hours after the start of mixing, and the high-strength concrete, after 4.0 hours.

COMPRESSIVE TESTING PROCEDURE

Of 240 6 x 12-inch (152 x 305-mm) concrete test cylinders, 120 were low-strength concrete and the other 120 were high-strength concrete. Thirty-six low-strength and thirty-six high-strength specimens were placed in the Pacific Ocean at 1,830 feet (560 m) (18 low-strength and 18-high strength specimens in each framework). The temperature at this depth is about 42°F (6°C). The remaining 168 specimens were divided equally so that 84 were cured in a fog room at 73°F (23°C) and 84 cured in a tank of continuously circulating sea water at an average temperature of 66°F (19°C).

At age 28 days, six control specimens from both the fog room and the seawater tank were tested in compression; no deep-ocean specimens were tested at this age. At an age of about 3 months, an attempt was made to retrieve the deep-ocean specimens, but the framework outfitted for surface recovery equipment did not function. Therefore, specimens were not tested at this age. At an age of about 10 months, a manned submersible operation was conducted, and one framework was recovered (Figure 1).

The specimens were transported to CEL and placed in seawater. Since the tops of the specimens were not level, approximately 1 inch (25 mm) of concrete was cut from the top of each specimen after the plastic molds were removed. At this stage all 36 specimens were placed in seawater inside pressure vessels in CEL's Deep Ocean Laboratory and subjected to a hydrostatic head of 1,830 feet (560 m). The specimens were at atmospheric pressure for about 43 hours.

Several pressure vessels were used so that when the pressure was relieved in one vessel all of those specimens could be subsequently tested. In this manner, the deep-ocean specimens underwent two pressure cycles before testing: from the seafloor to the atmosphere, in the pressure vessel for temporary storage, out of the pressure vessel for preparation for compressive load testing and back into the pressure vessel for test. During removal from the ocean, the depressurization rate was about 60 ft/min (0.3 m/s). This rate was used in pressurizing and depressurizing the pressure vessels.

The 18 specimens for each low- and high-strength concrete cured in the ocean were tested as follows:

1. Six specimens each were tested in compression while at a simulated deep-ocean depth of 1,830 feet (560 m). Using three portable compression testers, three specimens at a time were subjected to the deep-ocean environment (Figure 2), allowed to achieve equilibrium with the environment for 3 hours (i.e., allowed the pore pressure within the concrete to become equal to the external pressure), and then subjected

to a uniaxial compression test* to failure. One of the three specimens was instrumented with a compressometer-extensometer (ASTM C469), except that linear position transducers, adapted for underwater application, were used to measure displacements instead of dial gages.

2. Six specimens each were tested under uniaxial compression while at a pressure head of 6 feet (2 m). None of these specimens was instrumented.

3. Six specimens each were tested under uniaxial compression while at a pressure head of 6 feet (2 m) after the specimens had been exposed to three rapid cycles of pressure to 1,830 feet (560 m) at a rate of 600 ft/min (3 m/s). None of these specimens was instrumented.

A total of 24 control specimens were tested using the same compression testers as the deep-ocean concrete specimens. The fog-cured specimens were tested in the laboratory environment, while the seawater-tank specimens were tested under a pressure head of 6 feet (2 m). One-third of all these specimens were instrumented with the compressometer-extensometer.

RESULTS AND DISCUSSION

Compressive Strength

Low-Strength Concrete. Table 1 shows that there was no significant change in strength between the fog-room cured and seawater-tank-cured concrete. The fog-room concrete had compressive strengths of 3,300 psi (22.8 MPa) at 28 days and 4,220 psi (29.1 MPa) at 10.8 months, an increase of 27.9%, while the seawater-tank concrete had compressive strengths of 3,400 psi (23.4 MPa) at 28 days and 4,220 psi (29.1 MPa) at 10.2 months. The deep-ocean concrete, cured and tested at a pressure head of 1,830 feet (560 m), had a compressive strength of 4,090 psi (28.2 MPa) at an age of 11 months. This strength was essentially the same as that for the 10.8-month fog-cured concrete; the decrease of 3.1% was not statistically significant.

The deep-ocean concrete tested at a pressure head of 6 feet (2 m), and at a pressure head of 6 feet (2 m) after being subjected to three rapid cycles of hydrostatic pressure corresponding to 1,830 feet (560 m), had compressive strengths of 4,320 psi (29.8 MPa) and 4,070 psi (28.1 MPa) respectively. These specimens did not show a statistically significant change in strength compared with that of the deep-ocean concrete tested at a pressure head of 1,830 feet (560 m).

High-Strength Concrete. Table 2 shows there was no statistically significant change in strength between the fog-room-cured and seawater-tank-cured concrete at the age of 28 days, but at about age 10.5 months the seawater-tank-cured concrete showed a decrease in strength of 8.8% compared with that of the fog-room-cured concrete. The fog room concrete had a compressive strength of 6,060 psi (41.8 MPa) at age 28 days and 7,620 psi (52.6 MPa) at age 10.8 months, an increase of 25.7%.

*This test was not a triaxial compression test because no confining stress was imposed by the environmental pressure. The internal pore pressure of the specimen was in equilibrium with the external pressure.

The deep-ocean concrete, cured and tested at a pressure head of 1,830 feet (560 m), had a compressive strength of 6,600 psi (45.5 MPa) at age 11 months; this strength represented a decrease of 13.4% compared with that of the fog-cured concrete at age 10.8 months. The deep-ocean concrete tested at a pressure head of 6 feet (2 m), and at a pressure head of 6 feet (2 m) after being subjected to three rapid cycles of pressure to 1,830 feet (560 m), had compressive strengths of 6,520 psi (45 MPa) and 6,490 psi (4.48 MPa) respectively; these specimens did not show a statistically significant change in strength compared with that of the deep-ocean concrete tested at a pressure head of 1,830 feet (560 m). This finding was the same as that found for the low-strength concrete.

When compared, the compressive strength results for the low- and high-strength concretes showed the following:

1. As the concrete cured in the fog room from ages 28 days to 10.8 months, the strength increased 27.9% and 25.7% for the low- and high-strength concretes respectively.

2. The seawater-tank-cured concrete had strengths essentially the same as that of the fog-cured concrete of equal age. The one exception was the high-strength concrete cured in the seawater tank for 10.2 months; it showed an 8.8% decrease in strength compared with that of the fog-room-cured concrete.

3. At 11.0 months, the deep-ocean, low-strength concrete had a strength essentially the same as that of the fog-cured, low-strength concrete, while the deep-ocean, high-strength concrete showed a strength decrease of 13.4% compared with that of the fog-cured, high-strength concrete.

The relatively small decreases in compressive strength for the high-strength concrete may be explained by a physical phenomenon observed previously (Ref 2). Concrete saturated with water (pore volume either completely filled or essentially filled) has been found to have a compressive strength about 10% lower than that for concrete wherein pore volume is not saturated. The reason for this difference in strength may be due to pore-pressure buildup during uniaxial compressive loading for the saturated concrete. A small component of pore pressure acting in the radial direction will help form tensile microcracks that lower the ultimate compressive strength. Concrete that is not saturated would not experience the pore pressure buildup.

It is known that pore water is consumed during cement hydration. The process is called self-desiccation because sufficient water is used during hydration to stop further hydration if an external source of water is not provided. The fog room, seawater tank, and ocean environment were external water sources; however, the fog-room environment was not as efficient in resupplying water to fill the voids as were the other two environments. At age 10.8 months, considerable hydration had occurred in the high-strength concrete, which means that most of the larger capillary voids had been filled with cement hydration products, principally calcium-silicate-hydrate "fibers" (Ref 3). The space between the fibers is the gel void volume through which water molecules move

very slowly. It is probable that the fog-cured concrete was not saturated because of the low permeability of the cement paste. Given additional time (more years), the concrete could become saturated in the fog room (Ref 2). However, at age 10.8 months, the fog-cured concrete may not have been saturated. The deep ocean concrete was saturated and showed 13.4% less strength than that shown by the fog-cured concrete. Also, if the seawater-tank-concrete was saturated, its lower strength of 8.8% could be explained by this phenomenon.

The above discussion to explain strength differences does not apply to the low-strength concrete because, at the age of 10 to 11 months, strength differences did not exist. The high water/cement ratio of 0.66 for this mix indicates that capillary voids would always exist. The capillary volume, formed by the original mixing water, was so large that gel fibers could not fill all the space; hence, permeability of water through the paste was considerably easier. It is possible that the saturated low-strength concretes did not develop pore pressure buildup during compressive testing because the capillary voids vented the pressure. Hence, the saturated concretes (seawater-tank and deep-ocean) behaved similarly to that of the unsaturated fog-room concrete.

4. The deep-ocean concretes, both low- and high-strength, tested at a pressure head of 6 feet (2 m), showed strengths essentially the same as that for the deep-ocean concrete tested at 1,830 feet (560 m). This result implies that the concretes were saturated with water and in equilibrium with the external environment. When this case exists, high-pressure heads have no influence on the concrete strengths.

5. The deep-ocean concretes, both low- and high-strength, tested at a pressure head of 6 feet (2 m) after being subjected to three rapid cycles of pressure head to 1,830 feet (560 m), showed strengths essentially the same as that of the deep-ocean concrete tested at 1,830 feet (560 m). The pressure cycles were imposed on the specimens to determine whether the pore structure was disrupted by any of the pressure cycling that occurred for the deep-ocean concrete. The results indicated that the pressure cycling rate of 600 ft/min (3 m/s) was not harmful, so it is likely that the cycling rate of 60 ft/min (0.3 m/s) when coming out of the ocean was also not harmful.

The difference in pore pressure build-up between rapid pressure cycling and uniaxial loading is difficult to determine. For the rapid pressure cycling of 600 ft/min, the pore pressure changed at a rate of 4.4 psi/sec (30 KPa/sec) (calculated as 1 psi/2.25 ft x 1 min/60 sec x 600 ft/min). The maximum rate of pore pressure build-up within the concrete tested under uniaxial loading would be for the case where all the water was trapped within the concrete. The uniaxial loading rate was 50 psi/sec (345 KPa/sec) which would be the pore pressure build-up rate. This rate is 11 times greater than that from the rapid pressure cycling. However, it is known that all the pore water was not trapped within the concrete during uniaxial test. Bubbles of water formed on the exterior surface as the concrete was loaded uniaxially, so the magnitude of actual pore pressure build-up was unknown, but ranged between 0 and 50 psi/sec (0 and 345 KPa/sec).

Past Work. Lorman (Ref 4 and 5) conducted compressive strength tests on 3 x 6-inch (76 x 152-mm) concrete specimens that were cured in a simulated ocean environment of 47°F (8°C) and 600-foot (183-m) depth. His interest was in the strength of concrete at early ages, from 1 to 28 days. For control tests, specimens were cured in a fog room at 73°F (23°C); others were cured in a seawater tank at 47°F (8°C) so that the effect of temperature could be observed. Low-slump (3.5-in., 90-mm) and high-slump (7-in., 180-mm) concrete mixes using five different brands of portland cement were investigated.

On the average, Lorman's results showed that for low-slump concrete, which had a 28-day fog-cured compressive strength of 7,350 psi (50.7 MPa), the "ocean"-cured specimens underwent a decrease in strength of 24%, 13%, and 11% at 7, 14, and 28 days respectively, compared with fog-cured concrete at equal ages. For high-slump concrete, which had a 28-day fog-cured strength of 4,950 psi (34.1 MPa), the "ocean"-cured specimens underwent a decrease in strength of 29%, 21%, and 18% at 7, 14, and 28 days respectively, compared with fog-cured concrete at equal ages. In general, the effect of temperature caused about half of the decrease in compressive strength. Also, the data showed that the "ocean"-cured concrete developed strength more slowly than the fog-cured concrete and that the strengths were converging as age increased.

Stress-Strain Behavior

Figures 3 through 7 present the stress-strain behavior for the concretes, and Tables 1 and 2 show the values of Young's modulus and Poisson's ratio.

The stress-strain behavior of the deep-ocean concrete appears to be typical of that of the fog-room and seawater-tank concretes. Values of Poisson's ratio for the deep-ocean concrete are lacking because of problems encountered in using a linear transducer to measure hoop displacement. The Young's moduli and Poisson ratios also appear to be typical of those of the fog-room and seawater-tank concretes.

FINDINGS

1. Low-strength fog-cured concrete having a uniaxial compressive strength of 3,300 psi (22.8 MPa) at age 28 days showed an increase in strength of 27.9%, 27.9%, and 23.9% respectively, after 10.8 months of curing in a fog room, 10.2 months in a seawater tank, and 11 months in a deep-ocean environment at 1,830 feet (560 m). Statistically, the deep-ocean concrete had a strength equivalent to that of the fog-room-cured and seawater-tank-cured concrete.

2. High-strength fog-cured concrete having a uniaxial compressive strength of 6,060 psi (41.8 MPa) at age 28 days showed an increase in strength of 25.7%, 14.7%, and 8.9% respectively, after 10.8 months of curing in a fog room, 10.2 months in a seawater tank, and 11 months in a deep ocean environment of 1,830 feet (560 m). The differences in strength were statistically significant.

3. The low-strength deep-ocean concrete tested at pressure heads of 1,830 feet (560 m) and 6 feet (2 m) had the same compressive strengths. The same was true of the high-strength deep-ocean concrete.
4. The compressive strength of low- and high-strength deep-ocean concretes subjected to three rapid cycles of pressure to 1,830 feet (560 m) at a rate of 600 feet/min (3 m/s) was not affected when compared with that of identical specimens subjected to two cycles of pressure at a rate of 60 feet/min (0.3 m/s).
5. There were no distinguishable differences in the stress-strain behavior of concretes cured in fog, seawater tank, or deep-ocean.

FUTURE WORK

The second framework containing 36 test specimens will be retrieved from the ocean in 1981. The specimens then will be about two years old, and testing similar to that reported herein will be accomplished.

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Table 1. Results of Low-Strength Concrete

[Specimen size: 6 in. diam x 11 in. long (152 x 280 mm)]

Test	Curing Environment	Testing Environment	Age at Test	Compressive Strength (psi)	Standard Deviation (psi)	Coef. of Variation (%)	Change from 28-Day Fog Strength (%)	Change from 10.8-Mo. Fog Strength (%)	Young's Modulus, E (psi x 10 ⁶)	Poisson's Ratio
Fog	Fog room, 73°F	in laboratory	28 days 10.8 mo	3,300 4,220	90 170	2.7 4.0	-- +27.9	-21.8 --	3.0 (2) ^c 3.2 (2)	0.20 (2) ^c 0.16 (1)
Seawater Tank	in seawater at 6-ft depth, avg 66°F	in seawater at 6-ft depth	28 days 10.2 mo	3,400 4,220	110 110	3.2 2.6	+3.0 +27.9	-19.4 0.0	3.0 (2) 3.5 (1)	0.21 (2) 0.20 (1)
Deep Ocean	in ocean at 1,830-ft depth, avg 42°F	in sea-water at 1,830-ft depth	11.0 mo	4,090	340	8.3	+23.9	-3.1	2.9 (2)	--
		in sea-water at 6-ft depth	11.0	4,320	150	3.5	+30.9	+2.4	--	--
		in sea-water at 6-ft depth after three rapid cycles ^d to 1,830 ft	11.0 mo	4,070	180	4.4	+23.3	-3.6	--	--

^a Average of six specimens.^b [(other - fog)/fog] x 100^c Number in parentheses is number of test specimens.^d Rapid cycle rate was 600 ft/min. During each cycle, a pressure head of 1,830 feet was held for 30 minutes before decreasing the pressure.

Table 2. Results of High-Strength Concrete

[Specimen size: 6 in. diam x 11 in. long (152 x 280 mm)]

Test	Curing Environment	Testing Environment	Age at Test	Compressive Strength ^a (psi)	Standard Deviation (psi)	Coef. of Variation (%)	Change from 28-Day Fog Strength ^b (%)	Change from 10.8-Mo. Fog Strength ^b (%)	Young's Modulus, E (psi x 10 ⁶)	Poisson's Ratio
Fog	Fog room, 73°F	in laboratory	28 days 10.8 mo	6,060 7,620	180 190	3.0 2.5	0.0 +25.7	-20.5 0.0	3.1 (2) ^c 4.3 (2)	0.22 (2) ^c 0.18 (1)
Seawater Tank	in seawater at 6-ft depth, avg 66°F	in seawater at 6-ft depth	28 days 10.2 mo	5,970 6,950	400 420	6.7 6.0	-1.5 +14.7	-21.7 -8.8	2.9 (2) 3.5 (1)	0.19 (2)
Deep Ocean	in ocean at 1,830-ft depth, avg 42°F	in seawater at 1,830-ft depth	11.0 mo	6,600	380	5.8	+8.9	-13.4	3.6 (2)	--
		in seawater at 6-ft depth	11.0	6,520 ^d	730	11.2	+7.6	-14.4	--	--
		in seawater at 6-ft depth after three rapid cycles ^e to 1,830 ft	11.0 mo	6,490	470	7.2	+7.1	-14.8	--	--

^a Average of six specimens.^b [(other - fog)/fog] x 100.^c Number in parentheses is number of test specimens.^d Average of five test specimens.^e Rapid cycle rate was 600 ft/min. During each cycle, a pressure head of 1,830 feet was held for 30 minutes before decreasing the pressure.

Figure 1. Framework with specimens.

Figure 2. Test setup before immersion in pressure vessel.

Figure 3. Uniaxial stress-strain behavior of continuously fog-cured, low-strength concrete tested in laboratory environment.

Figure 4. Uniaxial stress-strain behavior of continuously fog-cured, high-strength concrete tested in laboratory environment.

Figure 5. Uniaxial stress-strain behavior of low-strength concrete cured and tested in seawater at 6-feet pressure head.

Figure 6. Uniaxial stress-strain behavior of high-strength concrete cured and tested in seawater at 6-feet pressure head.

Figure 7. Uniaxial stress-strain behavior of 11-month-old cured concrete and tested in a deep ocean environment (pressure head = 1,830 feet).

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