High-Performance Concrete for a Floating Bridge

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A high-performance concrete mix was developed for the construction of the new I-90 Lacey V. Murrow Floating Bridge (LVM Bridge) on Lake Washington in Seattle, Washington. The LVM Bridge is 2013 m (6,600 ft) long, consisting of 20 prestressed concrete pontoons rigidly connected to form a continuous structure. A typical pontoon measures 110 m (360 ft) long, 18.3 m (60 ft) wide, and 5.4 m (17.85 ft) deep. About 38,000 m^3 (49,600 yd^3) of high-performance concrete went into the construction of the pontoons. The high-performance concrete contains silica fume and fly ash, and its average 28-day compressive strength is more than 69 MPa (10,000 psi). The high-performance concrete has low permeability and low shrinkage. The contractor learns to work with the high-performance concrete by constructing test sections. The lessons from the test sections are put into practice, resulting in improved placement, finishing, and curing procedures. The construction of the LVM Bridge has shown that it is feasible and cost-effective to use high-performance concrete in highway structures for which high strength, impermeability, and durability are of prime importance.

Washington State has been building concrete floating bridges since 1938 (*1,2*). Floating bridges form major transportation links in the state and Interstate highway systems. The first concrete floating bridge was opened to traffic in July 1940 (*1*). The concrete strength for this bridge ranged from 21 to 24 MPa (3,000 to 3,500 psi). In the early 1960s (*3*), the strength of concrete for floating bridges ranged from 24 to 31 MPa (3,500 to 4,500 psi). Concrete pontoons built in the 1980s (*4*) had concrete strength ranging from 28 to 45 MPa (4,000 to 6,500 psi).

In the early 1990s, there was a need to build another concrete floating bridge across Lake Washington, Seattle (*5*). The new bridge is known as the Lacey V. Murrow Floating Bridge (LVM Bridge). The LVM Bridge is 2013 m (6,600 ft) long, consisting of 20 prestressed concrete pontoons connected to form a continuous structure. Figure 1 shows the layout of the new LVM Bridge. A typical pontoon measures 110 m (360 ft) long, 18.3 m (60 ft) wide, and 5.4 m (17.85 ft) deep. Figure 2 shows a typical cross section of the pontoons. In planning the new bridge, it was again recognized that watertightness and durability were of prime importance for long-term performance of a floating structure, because of the exposure to water and severe environmental conditions. The concrete must be extremely dense and impermeable to water, highly resistant to abrasion due to wave action, and relatively crack free. As the design was progressing, an effort was launched to research and develop a concrete mix that would give the above properties. Additionally, the concrete must be readily available locally, have good workability, have low demand on labor skills, and require no special equipment.

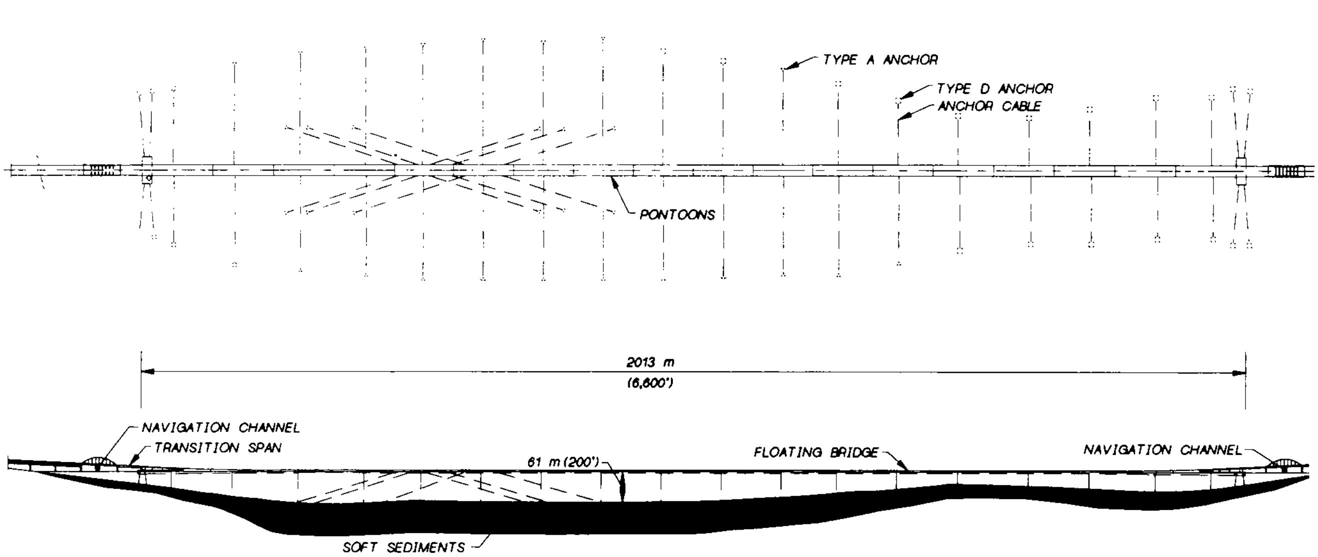

FIGURE 1 Lacey V. Murrow Floating Bridge: ***top***, plan; ***bottom***, elevation.

The objectives of this paper are to describe the procedures used to develop a high-performance concrete mix and the methods for placement, consolidation, and curing of the high-performance concrete.

Concrete Mix Design Development

The concrete mix development program was conducted in three phases. The first phase was to conduct preliminary trial mixes to evaluate cement types, effects of silica fume, fly ash, and admixtures. The trial mixes confirmed the performance characteristics of the material as follows:

1. Silica fume
   –Reduces permeability,
   –Increases early compressive strengths,
   –Reduces bleeding, and
   –Increases heat of hydration.
2. Fly ash
   –Increases workability,
   –Reduces heat of hydration, and
   –Increases ultimate compressive strength.
3. Retarders
   –Increase workability,
   –Extend slump life, and
   –Improve concrete set control.
4. Superplasticizers
   –Increase workability, and
   –Decrease water demand.

The second phase was to provide a design mix that would meet watertightness, durability, constructability,

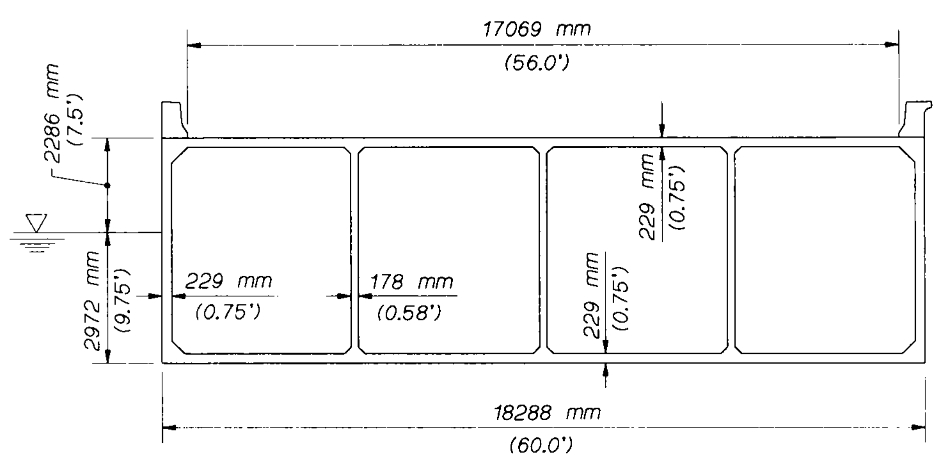

FIGURE 2 Cross section of typical pontoon.

and compressive strength. From the results of the first-phase trial mixes, the final mix was developed with the following proportions per cubic meter (per cubic yard) of concrete:

- Cement Type II: 380 kg (640 lb)
- Silica fume: 38 kg (64 lb)
- Fly ash: 59 kg (100 lb)
- Water: 142 kg (240 lb)
- Coarse aggregate: 1078 kg (1,815 lb)
- Sand: 706 kg (1,189 lb)
- Retarder: 230 mL/59 kg (6 oz/100 lb cementitious materials)
- Superplasticizer
  - –Initial dose: 310 mL/59 kg (8 oz/100 lb cementitious materials)
  - –Final dose: 464 mL/59 kg (12 oz/100 lb cementitious materials)
- Air entrainment: none
- Slump: 210 mm (8.25 in.)

The average compressive strengths of the hardened concrete were as follows:

- 7 days: 54 MPa (7,800 psi)
- 14 days: 72 MPa (10,420 psi)
- 90 days: 86 MPa (12,480 psi)

The third phase was to construct full-size test sections to test the constructability of the mix. The test sections consisted of wall and slab combinations including reinforcing bars and posttensioning conduits. The test sections also provided information on finishability, consolidation, curing requirements, and construction joints. The following observations were made from the tests carried out on the test sections:

- The concrete was easily placed and finished.
- The concrete appeared "sticky;" however, a float finish was achieved easily.
- A light mist helped achieve a smooth and dense surface finish.
- Effort to prepare construction joint was minimal.
- Construction joint had low permeability.
- Retarder applied to the construction joint resulted in an inferior joint.
- Curing compound must be applied immediately after finishing to avoid cracking.
- Wet burlap covered with polyethylene sheeting provided adequate moisture for proper curing.
- External vibration was the most desirable method for consolidation of concrete in the walls.
- Free-fall of concrete did not show sign of segregation.
- Two-hr cold joint could be reconsolidated into concrete of the new lift.
- Walls must be continuously supplied with moisture while forms were in place; otherwise surface crazing would occur.

The information gathered in the three phases of concrete mix development was used in preparing the construction specifications for the project.

Construction Specifications

The Washington State Standard Specifications for Road, Bridge, and Municipal Construction have provisions for contracting agency-provided mix designs for concrete with 28-day strength of up to 34.5 MPa (5,000 psi). For higher-strength concrete, the contractors are required to submit a mix design for the state's approval under the terms of the standard specifications.

The concrete mix for this project was designated as Class LVM with emphasis on watertightness, low permeability, and low shrinkage. The structural designers needed 45 MPa (6,500 psi) at 28 days to satisfy the structural requirements.

Consequently, the contractor was to provide a mix design with a minimum compressive strength of 45 MPa (6,500 psi) at 28 days. Besides meeting the requirements of the standard specifications, the mix per cubic meter (cubic yard) was to meet the following specifications:

1. Minimum portland cement Type II content shall be 370 kg (625 lb).
2. Microsilica shall be used at a rate of not less than 30 kg (50 lb) or more than 40 kg (70 lb).
3. Fly ash shall be used at a minimum content of 59 kg (100 lb).
4. The combined microsilica and fly ash should not exceed 25 percent of total cementitious materials by weight. Total cementitious materials should be defined as the combined weight of cement, microsilica, and fly ash.
5. Aggregate gradation proportions shall be determined by the contractor to be suitable for the placement conditions and methods of placement. Aggregate gradations shall be submitted to the engineer for approval.
6. Water content shall not exceed 166 kg (280 lb). Maximum ratio of water to cementitious materials shall not exceed 0.33 by weight.
7. Both normal and high-range water reducing admixtures shall be used.
8. The contractor shall submit a plan for admixture dosage. The initial application rate shall not exceed that shown in the mix design. A subsequent dosage, prior to

acceptance of the concrete by the engineer, will be permitted but shall not exceed half of the initial dosage.

9. The concrete shall not be air entrained.

The contractor was also required to submit the following test data on permeability and shrinkage with the proposed mix design for approval:

1. Rapid chloride permeability (AASHTO T277): two samples shall be tested from laboratory-cured cylinders at 28 days. The maximum allowable electrical charge passed shall not exceed 1000 coulombs.
2. Length change of hardened concrete (AASHTO T160): the maximum allowable shrinkage shall not exceed 400 millionths at 28 days.

Contractor's Final Mix Design

The approved contractor-provided mix design conformed closely to the project specifications. A 9.5-mm ($^3/_8$-in.) maximum aggregate was used, as was a silica fume in slurry form. The slurry contained about 45 percent silica fume solids, water, and a small amount of high-range water reducer. The proportion of the contractor's final mix design per cubic meter (cubic yard) was as follows:

- Portland cement Type II: 370 kg (624 lb)
- Silica fume (AASHTO M307): 30 kg (50 lb)
- Fly ash (AASHTO M295): 59 kg (100 lb)
- Paving sand: 770 kg (1,295 lb)
- Coarse aggregate: 1050 kg (1,770 lb)
- Water: 150 kg (255 lb)
- Water reducer (ASTM C494): 965 mL (25 oz)
- Superplasticizer (ASTM C494): 5065 mL (131 oz)
- Air entrainment: none
- Water/cementitious materials ratio: 0.33
- Slump: 180 mm (7 in.)

The average 28-day compressive strength of this mix was above 69 MPa (10,000 psi). The average permeability as tested in accordance with AASHTO T-277 was as follows:

- 28 days: 1,198 coulombs (C)
- 56 days: 790 C
- 90 days: 584 C

At 28 days the permeability did not meet specifications. However, at 56 days the permeability was well below 1,000 C, which was considered very low. Future specifications should require that the permeability at 56 days be less than 1,000 coulombs.

Test Section

The contract specifications required that the contractor build a test section of a cell of a typical pontoon before pontoon construction began. The test section was to include the reinforcement, posttensioning ducts, and anchorages. Tests were conducted to evaluate the concrete mix, forms, concrete placement method, consolidation technique, and curing method proposed for the pontoon construction. The test demonstrated the necessity for adequate external vibration and strict quality control in mixing, placing, vibrating, and curing of the concrete.

Additionally, the contractor conducted several tests of the concrete mix and placement procedure for two walls 6 m (20 ft) high. The tests were performed to measure form pressures, evaluate vibration methods, and measure form deformation. The form pressures at the bottom of the wall were between 48 and 58 kPa (1,000 and 1,200 lbf/ft^2) and about 31 kPa (650 lbf/ft^2) near the top. The information gathered from these tests was valuable to the contractor in designing forms, estimating rate of slump loss, and planning quality-control procedures.

Concrete Placement

The workability of the concrete was good. A slump of 180 to 230 mm (7 to 9 in.) allowed the concrete to be pumped without difficulty. A set time of 6 to 8 hr was achieved during construction. However, once the mix started to set, it set very rapidly. The longer set time was important for casting and finishing the flatwork such as the bottom and top slabs of the pontoons. Figure 3 shows the initial strength gain of the LVM concrete mix as compared with the normal concrete mix. The normal concrete mix has a compressive strength of 28 MPa (4,000 psi) and no silica fume. Concrete was placed in the walls in multiple lifts. The long set time allowed internal vibration full height of the walls. The concrete mix was very cohesive and resistant to segregation.

A modified structural tube attached to the concrete pump hose was used as a tremie to place concrete in the tall walls. The tremie was lowered to the bottom of the wall and slowly raised as the level of concrete rose. The tremie was inserted at 3.7 to 4.3 m (12 to 14 ft) centers for depositing concrete. The concrete flowed 1.8 to 2.4 m (6 to 8 ft) laterally from the point of deposit through the heavily reinforced wall. The upper lifts of concrete were placed from the top of the wall without the tremie.

Figure 4 shows that the bottom slab of a pontoon had been completed and that wall forms were being erected. Figure 5 shows that a pair of pontoons was

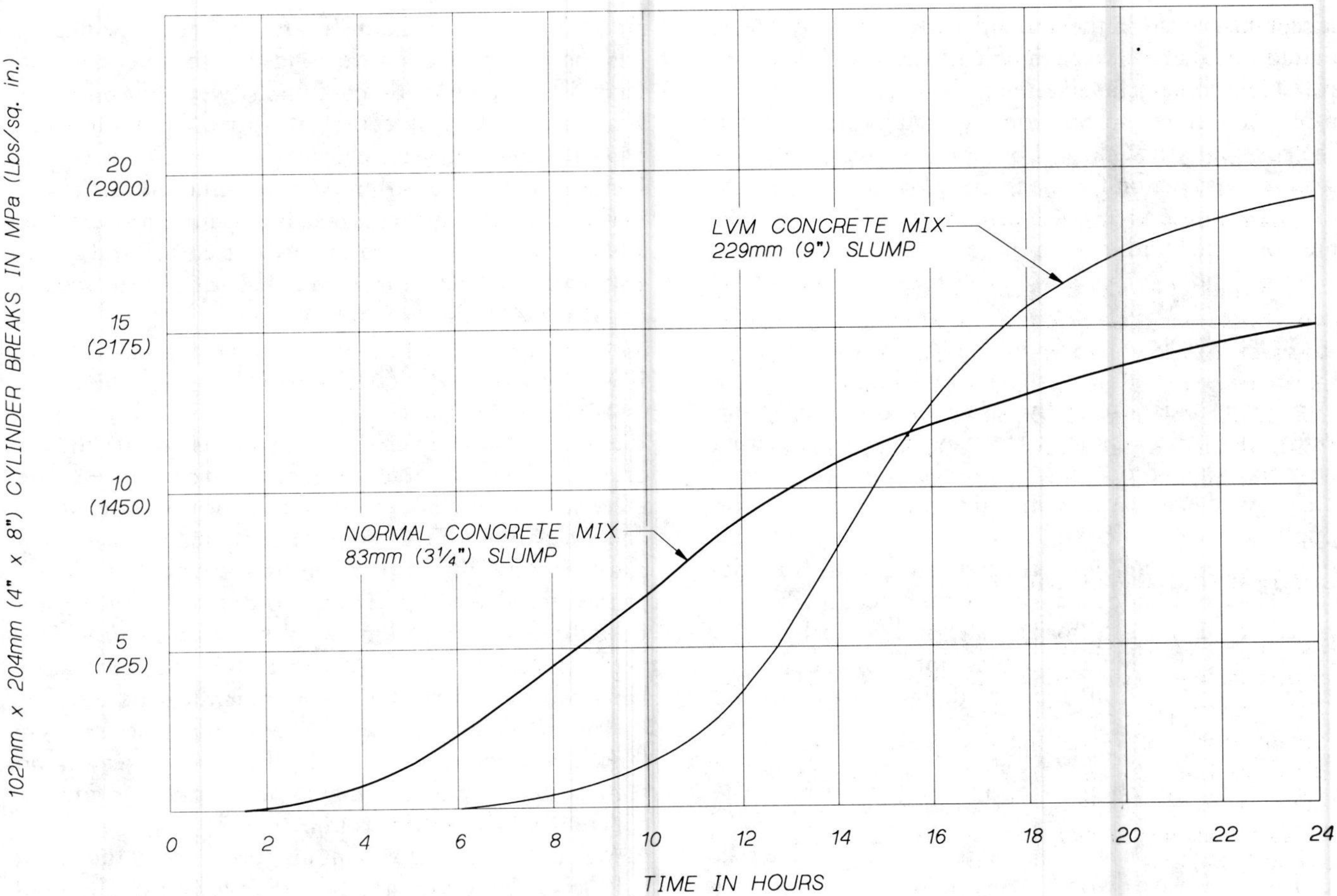

FIGURE 3 LVM concrete mix initial strength gain.

FIGURE 4 Completion of bottom slab and erection of wall forms.

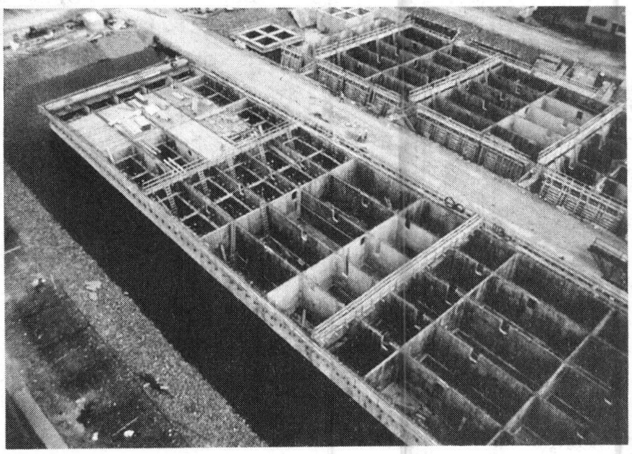

FIGURE 5 View of pontoon interior with watertight compartments.

being constructed in the graving dock. Each pontoon is divided into small watertight compartments for controlling flooding. The exterior walls were made of cast-in-place concrete construction required by the contract. The contractor had the option of using cast-in-place or precast construction for the interior walls. The contractor chose to use precast elements for the interior walls interconnected with cast-in-place concrete.

Consolidation of Concrete

Proper consolidation is key to achieving durable concrete. It was the subject of extensive discussion during the development of project specifications. For silica fume concrete, it was determined that external vibration supplemented by internal vibration was essential to ensure dense concrete and a concrete surface without defects. The contractor used rotary-type external vibrators spaced at 1.2 m (4 ft) horizontally and vertically.

Quantitative information was not available on the design of forms. Forms must be designed to withstand the lateral fluid pressure of concrete and the repeated reversing stresses induced by external vibration and to transmit the vibration in a uniform manner to the concrete.

Steel was the generally preferred forming material, but it is expensive. Wood forms perform adequately if properly designed. The final construction specifications allowed wood, steel, or a combination of the two materials. The contractor was required to design and fabricate the forms to ensure proper consolidation. The test sections provided some needed information on the design of the forms and placement of vibrators.

Wood forms with plywood lining were used for the project. The system performed satisfactorily. However, after three or four cycles of reuse, the wood forms and liners began to show signs of damage and were in need of repair or replacement. Steel forms would have lasted much longer and might be more cost-effective in the long run.

Curing of Concrete

Silica fume concrete mixes yielded little or no bleed water to the surface, creating a high potential for difficulty in finishing surfaces of flatwork and for plastic shrinkage cracking and short cracks just before final set of the concrete. Fog spraying immediately after the concrete was placed and screeded helped avoid such problems.

Moisture curing of the exposed concrete surface was essential to ensure crack-free and impermeable concrete. The unformed concrete surfaces were fog sprayed immediately and continuously after initial screeding or floating. The surfaces were ponded with water soon after finishing to provide continuous wet curing for not less than 14 days. A concrete relatively free of cracks and other trouble was achieved.

Wall forms were permitted to be removed 72 hr after final set, which was defined as penetration resistance of 3445 kPa (500 psi). Continuous wet curing had to begin within 4 hr after form removal and continue for not less than 14 days.

Performance of LVM Concrete

The contractor had very limited experience with the use of silica fume concrete when the project started, and there was some concern about the concrete's stickiness and workability. The contractor started learning by constructing a mockup section that was representative of the typical work. The mockup gave the contractor a valuable lesson in working with the relatively new high-performance concrete. Subsequently, the contractor built two more test sections to refine the procedure.

The contractor soon discovered that the concrete flowed readily with adequate vibration, there was no segregation despite the high slump, and the finished concrete was relatively trouble-free.

When the contractor went into production, the initial casting cycle of a pontoon took 19 weeks. The contractor had start-up problems and had to learn to work with the new mix. Through constant effort in improving construction techniques and skills, the casting cycles were reduced to 12, 9, and finally 8 weeks. The contractor was pleased with the results. The contractor also benefited from several cost-saving features of the high-performance concrete mix. The finished concrete required very little patching or repair. The high early strength of the concrete enabled posttensioning to be done sooner than with conventional concrete. Part way into the construction the contractor asked to use the high-performance concrete in other parts of the pontoons where normal concrete was specified. The substitution was made with no additional cost to the state. This demonstrated the contractor's satisfaction with the mix and the successful application of high-performance concrete.

Figure 6 shows a completed pair of pontoons arriving at the job site and being maneuvered into position. The concrete was uniformly dense and impermeable. There were very few signs of repair, rework, or patching.

Cost Information

Concrete suppliers indicated that adding 8 percent silica fume to normal concrete mix would add about $60/m^3

FIGURE 6 Pair of pontoons being maneuvered into position.

($50/yd^3). For example, if 440 MPa concrete, including fly ash, cost $130/m^3 (6,000 psi concrete at $100/yd^3), silica fume concrete would cost $190/m^3 ($150/yd^3) delivered to the job site. The contractor would have to add other costs associated with the use of silica fume concrete to arrive at the in-place cost of concrete. On the basis of the average bid prices of the three low bidders, the in-place cost of concrete was $986/m^3 ($754/yd^3). The higher in-place cost reflected the additional care and requirements of working with the high-performance concrete. The test sections added cost to the concrete work but were worth every dollar in improving efficiency and avoiding construction problems. The formwork had to be designed for external vibration and higher form pressures because of the slow initial set of the concrete. The complexity of pontoon construction also added to the cost of concrete. The high average bid prices of the concrete reflected the concerns of the contractors and suppliers in dealing with a relatively new high-performance concrete with silica fume. About 38 000 m^3 (49,600 yd^3) of concrete were specified for the project.

This information is based on 1991 costs and is included here for general information only. The actual cost will depend on many factors, such as location, complexity of the structure, volume of work, and experience of the suppliers and contractors. The price is expected to drop as more silica fume concrete is used in highway construction.

Concluding Remarks

High-performance concrete containing silica fume and fly ash is very cohesive, will not segregate, and has good workability when properly proportioned. Enhanced with high-range water reducers, the concrete can be placed with a very high slump with no loss in strength or density.

Silica fume content of about 8 percent of total cementitious materials was used in the concrete mix for the project. However, the mix can be adjusted with different proportions of silica fume and fly ash to meet the strength, permeability, and durability requirements of a project. Some cost savings can be realized with mix modifications to meet objectives of the mix and performance demands of the fresh and hardened concrete. Research and development of concrete mixes should be carried out before or during project development to meet the project objectives. The data and findings should be incorporated into the project specifications and made available to the contractor.

The quality of plant mixing equipment, competence of plant personnel, experience with the specialized concrete mixes, commitment to quality, and team effort are necessary for successful development and application of high-performance concrete.

Valuable qualitative and quantitative information can be obtained by constructing test sections of typical

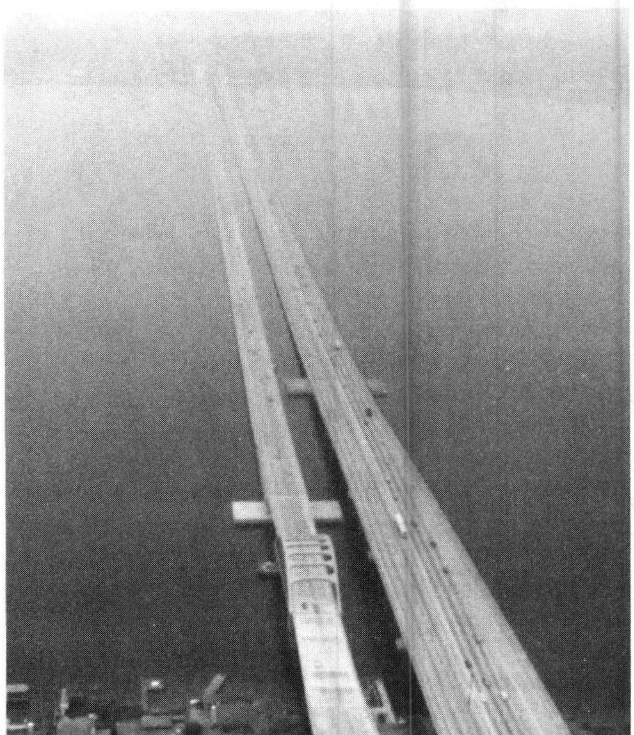

FIGURE 7 New LVM Bridge, on left.

portions of the work. The test sections should be constructed before production to gain experience in rate of pour, form pressures, effectiveness of vibration, and other construction techniques.

High-performance concrete has many applications in bridge construction. Some examples are

- Reinforced and prestressed concrete structures requiring high strength, corrosion resistance, and long-term durability;
- Bridge decks to reduce chloride intrusion;
- Precast, prestressed concrete girders to reduce weight, reduce depth, decrease number of lines of girders, or increase span lengths;
- Overpass structures subject to salt spray from traffic;
- Structures with thin or heavily reinforced walls; and
- Floating and other marine structures.

Figure 7 shows the new LVM Bridge alongside the Third Lake Washington Floating Bridge. The new bridge was completed and opened to traffic on September 12, 1993. The construction of the LVM Bridge has demonstrated that it is feasible and cost-effective to use high-performance concrete in highway structures for which high strength, impermeability, and durability are of prime importance.

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