Concrete in the Verrazano-Narrows Bridge

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This paper describes the use of ice in the concrete mix to reduce the maximum internal temperatures in the mass concrete of bridge anchorages. It shows the effect of varying amounts of ice on the initial concrete placing temperature. It also gives some data on the maximum achieved internal temperatures (150 and 110 F), and the variation of temperature with time and ambient temperatures.

The effect of the use of ice in the bridge pavement concrete is discussed. A novel type of concrete pavement for bridges is described. The difficulties of control of the surface of the pavement on a flexible structure are explained as well as the method used to solve this problem.

•THE Verrazano-Narrows Bridge across New York Harbor has the longest span in the world—4,260 ft between main towers. With a total of 729,330 cu yd of concrete, a degree of care in the solution of design and construction problems was implicit. This paper will cover two phases of construction, the anchorage mass concrete and the deck slab on the suspended structure (Fig. 1).

Figure 1. General view of Narrows Bridge.

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ANCHORAGES

In a suspension bridge the function of the anchorage is to resist the pull of the main cables. It does this by friction developed on the supporting soil; hence mere weight is important. The design pull exerted by the four main cables of this bridge is 136,000 tons. Due to differences in topography at opposite ends of the bridge the two anchorages were not identical, their respective contents being: (a) Brooklyn anchorage, 205,980 cu yd; and (b) Staten Island anchorage, 172,400 cu yd.

With weight at a premium, the heaviest economically available coarse aggregate (trap rock) was selected. Its average specific gravity was 2.90. The restriction to crushed stone in the specifications led to a strong protest from other aggregate producers. However, they were able to understand and accept the necessity for this restriction once it was explained.

The mix proportions for one cubic yard for the Brooklyn anchorage were:

Class of Concrete	A	B
Required 28-day strength	3,000 psi	2,500 psi
Number of cubic yards	56,440	149,540
Portland cement	493 lb	410 lb
Natural cement	63 lb	53 lb
Sand	1,150 lb	1,100 lb
¾-in. crushed stone	1,363 lb	983 lb
1½-in. crushed stone	907 lb	-0-
1½- to 2½-in. crushed stone	-0-	1,353 lb
Water	29 gal	31 gal
Darex (for air entrainment)	About ¾ liq oz per sack	
Plastiment (retarder-densifier)	About 2 liq oz per sack	

The class A concrete was for buttresses, columns, beams and structural slabs, the class B for mass concrete.

The anchorage is made up of large interlocking concrete blocks whose size depended upon: (a) the daily concrete plant capacity, (b) shrinkage considerations, and (c) the geometry of the anchorage. With a plant and delivery capacity of about 120 cu yd per hr, the maximum practical volume of block was about 1,000 cu yd. For a perfect cube this would give an edge dimension of 30 ft. Blocks of this size and shape present real problems in the dissipation of heat during the summer months. Actually, the blocks were considerably flatter than a cube and occasionally as thin as 7.5 ft. This flatness is an advantage since this shape presents a larger surface area to permit cooling, by exposure to air and contact with other (cooler) blocks which were previously placed.

Given the daily plant capacity of 800 to 1,000 cu yd, the shape of each block was largely controlled by the geometric details of the several masses of each anchorage. However, an effort was made to limit the maximum horizontal dimension to 75 ft to minimize shrinkage in the individual blocks. Of course, a skip sequence of day's work was adopted to minimize overall shrinkage.

The anticipated maximum temperatures were judged low enough not to require internal cooling by circulation of cooling water in embedded pipes. The specifications required that, except for winter concreting, the temperature of the concrete at time of depositing should not exceed 60 F. With this specification, a relatively low starting temperature is achieved which has the additional advantage of a slow initial heat development, since the rate of hydration of the cement depends in part on the temperature of the mass.

The maximum achieved internal temperature should depend upon:

1. The amount of and rate of heat developed vs
2. The rate of heat dissipation.

Number 1 depends upon: (a) the initial concrete temperature, (b) the type of cement used, and (c) the number of bags of cement per cubic yard.

Number 2 depends upon: (a) the spread of temperature between highest internal and the ambient temperature, or temperature of an adjacent block in contact; (b) the rate of heat conductivity of concrete; and (c) the distance from the center of the block to the cooling surface. From information given later in this paper it will be apparent that the conductivity coefficient of concrete must be low.

The physical constants of the problem for summer conditions in New York reveal that in a cubic yard of class B concrete:

	Approx. Wt (lb)	Specific Heat	Temperature (F)
Coarse aggregate	2,336	0.2	75
Sand	1,100	0.2	75
Cement	463	0.2	75
Water (city mains)	258	1.0	60

For these assumed conditions, the resulting concrete temperature (discounting heat developed by grinding action in mixing), would be 71.3 F and even if the 258 lb of water were cooled to 32 deg, the concrete temperature would be 64.3 F. The mass of mixing water, even with its high specific heat, is too much smaller than the mass of the solid materials to have much cooling effect. Some means other than cooled water is necessary.

Figure 2. Ice crushing machine—Brooklyn.

TABLE 1

ICE REQUIREMENT

Air Temp (F)		Ice per Cu Yd (lb)	Concrete Temp (F)	Remarks
Low	High			
66	83	100	59	With no ice: 72 F
66	83	90	61-64	
70	79	90	60-62	
69	82	125	60	
73	88	115-145	60-65	With no ice: 80 F
76	84	145-165	58-62	
72	90	130-145	60	

On the Narrows Bridge additional cooling was achieved by using ice in place of some of the mixing water. Since the amount of heat necessary to change one pound of ice to one pound of water is 144 BTU (as contrasted with one BTU to heat water from 32 to 33 F), the large cooling effect of the heat of fusion of ice is apparent. The heat required to melt the ice must come from the concrete itself.

The mixing plant for the Brooklyn anchorage consisted of two Smith turbine mixers of 3 cu yd capacity each, plus an ice crusher capable of handling about 2 tons of ice per hour (Fig. 2). The crushed ice moved from the crusher to the mixer in a pipe. Because turbine mixers have not been in general use in this country many years, it may be useful to note that, even with a short mixing time of 1¼ min per 3-yd batch, and with lump ice in the mix, the resulting concrete was entirely satisfactory.

The temperature of the concrete at placing time depends on the ambient temperatures prevailing during the previous days due to their heating effect on the stockpiled aggregates and cement. To meet the 60 deg specified maximum placing temperature for the concrete, the amount of ice required was varied by trial. Some idea of how pertinent factors varied may be seen in Table 1 from records selected at random.

The net added mixing water per cubic yard of concrete was determined by subtracting the weight of ice added from the design value of 258 lb. Normally one would assume that flakes would be required to assure thorough melting and mixing; actually pieces from one to 3 in. were used to avoid the jamming in the feed pipe which occurred when flakes were used. The turbine mixer (with high speed blades) handled this size satisfactorily, although conceivably standard concrete mixers might not. The cost for the addition of ice was approximately $0.75 per cu yd of concrete. The ice itself cost 50 cents per 100 lb.

To determine the maximum internal concrete temperatures achieved, a series of remote-reading thermocouples were embedded in the concrete. These were read at approximately daily intervals for two to three months after placing (Figs. 3, 4). While it may not be reasonable to generalize from the small sample shown, certain facts seem significant:

1. The difference in cement content per cubic yard (556 to 463 lb) did not produce a very significant difference in maximum temperatures reached internally.
2. The influence of nearness to a cooling exterior surface exercises a profound influence.
3. Other readings too numerous for reproduction here gave evidence of the effect of ambient temperatures on the rate of cooling. In the summer months the highest internal temperature recorded was about 150 F, whereas during the cooler weather the highest temperature was 110 F.
4. There was some evidence that when the internal concrete temperature was approaching the ambient temperature (about 60 F) and another concrete block was placed

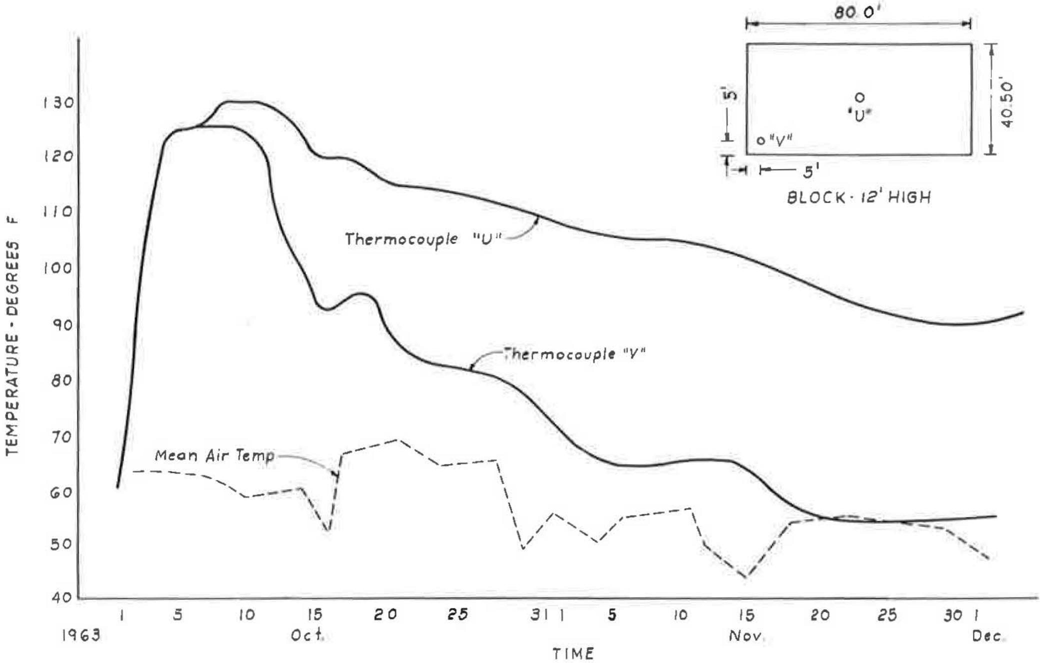


Figure 3. Curve showing internal concrete temperatures—class A concrete, Brooklyn anchorage.

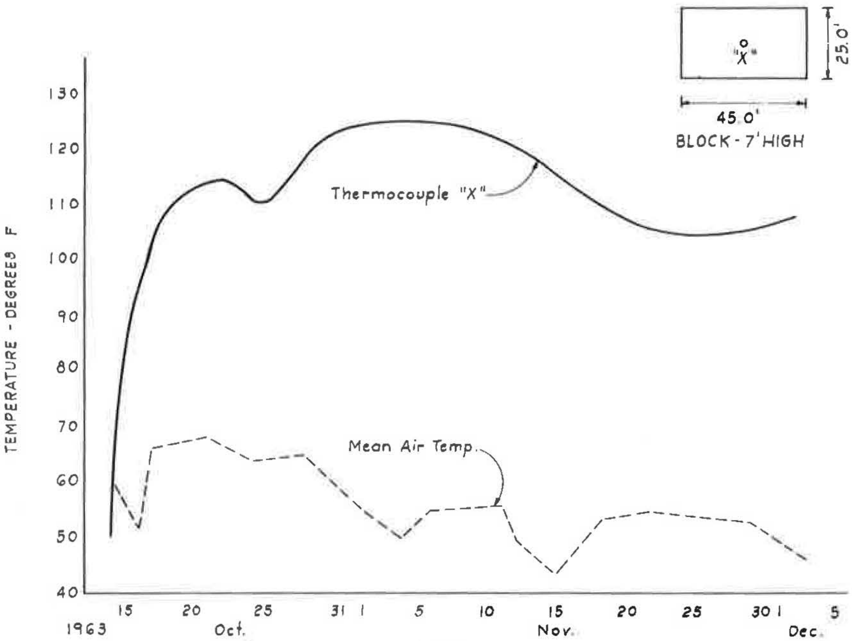


Figure 4. Curve showing internal concrete temperatures—class B concrete, Brooklyn anchorage.

over the first, thus insulating it from the cooling air, the internal temperature in the first block rose again as much as 20 F.

It may come as a surprise to the uninitiated how long higher temperatures persist internally in mass concrete. Low ambient temperatures often result in surface temperature cracks, which later disappear as the inner concrete contracts on cooling and a more uniform distribution of internal temperatures is reached with the passage of time.

CONCRETE PAVEMENT ON SUSPENDED SPANS

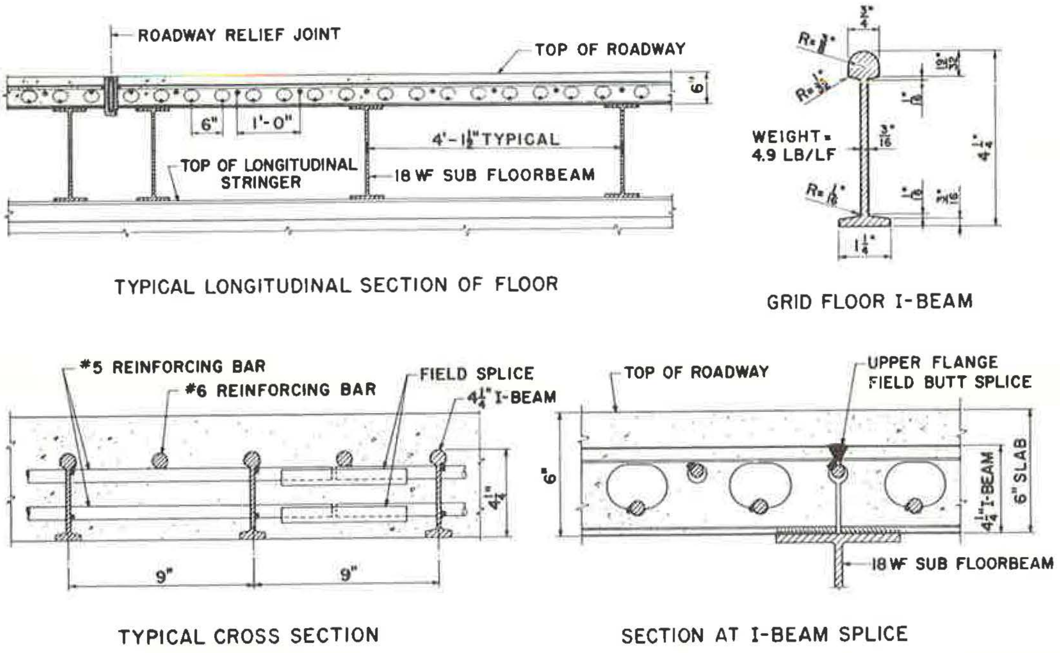
The concrete pavement slabs on the suspended spans are of interest because of: (a) their complete freedom from surface cracks; (b) the unusual slab design to meet unusual requirements; and (c) the uncommon method of screeding.

In recent years there has been an unusual amount of surface cracking in concrete bridge slabs. This is probably due not to any inherent characteristics of concrete, but to bad field practices which have evolved during the greatly enlarged highway construction program.

It was important to avoid surface cracking in this structure because (a) the very high frequency of traffic on this toll structure requires that maintenance operations be kept to a minimum, and (b) leakage of the upper deck slab would be troublesome for vehicles on the lower deck. These factors and necessary weight reduction led to an unusual deck slab design.

In long-span bridges there is a great emphasis on reduction in weight of slab and all other suspended elements since these directly affect the size of the main cables, the towers, the tower foundations and the anchorages. In fact, for every pound of weight carried there is required nearly a pound of more expensive materials to carry it.

Opposed to this requirement of weight reduction for the slab is the absolute need for a slab sufficiently strong to meet an extremely heavy load both as to intensity and frequency. The design which was developed had been used in slightly modified form on two of our previous suspension bridges. It is a 6-in. concrete-filled grid (Fig. 5). The principal slab reinforcement is longitudinal, consisting of specially rolled $4\frac{1}{4}$-in.



TYPICAL LONGITUDINAL SECTION OF FLOOR

GRID FLOOR I-BEAM

TYPICAL CROSS SECTION

SECTION AT I-BEAM SPLICE

Figure 5. Details of pavement slab.

I-beams spaced 9 in. on centers with a top $\frac{3}{4}$-in. bar between each beam. The transverse top and bottom reinforcement, which is threaded through the beam webs, consists of $\frac{5}{8}$-in. bars. The top transverse rods proved useful during construction in a way not contemplated during design. Since the bottom beam flanges are flush with the bottom of slab, there are $1\frac{3}{4}$ in. of concrete over the top of the embedded beams, thus providing sufficient cover to minimize the tendency to crack over the beams.

There are several significant peculiarities inherent in the paving of a flexible structure such as a long-span suspension bridge. Among them:

1. It is necessary to distribute the pavement load during placement by skipping several panels between successive pours in order to spread the load and so minimize angular distortions of the suspended structure and cables.
2. Transit mix trucks are too heavy to run on the grid so the concrete must be conveyed long distances in light buggies (up to 3, 700 ft).
3. Because of the inevitable large deflections of the suspended structure during loading with the pavement, it is not possible to screed the concrete to a surveyed profile.

For a detailed treatment of conventional deck paving operations refer to "Smooth-Riding Bridge Decks," HRB Bull. 243. It will be seen that allowance in setting screed rails for the support deflection, due to the addition of the concrete, is only 4 to 5 in. for even a 200-ft span. For the Narrows Bridge, the pavement slab was over 45 percent of the weight on the main cables and would cause deflections during placement of several feet, as well as appreciably change the shape of the roadway profile curve. For this reason it was not practical to run in a profile curve by survey, but rather to rely on some other means of controlling the screeding of the pavement surface.

The construction contractor proposed using, as a control, the top transverse reinforcing bars which were 12 in. on centers. These rods were welded to the upper surface of the holes punched in the webs of the embedded small beams. Their conformity to a smooth curve was tested in place and found to be surprisingly good. Accordingly, the contractor constructed a metal sled of $\frac{3}{8}$-in. steel plate about 5 in. high and 42 in. long. These sleds were framed into and supported the screed. In use, these metal sleds rode on the top surface of the upper transverse reinforcing rods and were continuously embedded about $2\frac{3}{4}$ in. deep in the wet concrete. Because of the small volume displacement by this $\frac{3}{8}$-in. plate, there was no need to add concrete to fill the space previously occupied by the metal sled. Of course, the screeding is only a strike-off, but this operation has always had a marked effect on the smoothness of a completed pavement slab.

It is apparent that the effectiveness of using the upper surface of the transverse reinforcing steel as a control depends on the exactness of the positioning of these rods. In this instance the shop punching of the holes in the webs of the small I-beams (through which the rods were threaded) produced a degree of regularity sufficient for the purpose. With respect to the possibility of long waves in the pavement surface, this was apparently eliminated by the nicety of the stiffening truss and floor system fabrication as well as by the uniform distribution of weight suspended from the cables. In any case, the riding quality of the surface is completely satisfactory.

PAVING OPERATION

No heavy vehicles were permitted to ride on the grid so the transit mix trucks had to discharge at a point on the bridge approach before reaching a suspended side span. They rotated for 5 min before adding the retarder in order to permit better dispersion of the cement. After mixing another 10 min the truck then discharged into a holding hopper which was used to load $\frac{1}{3}$-cu yd motorized buggies, which conveyed the mixed concrete along the suspended structure to where the paving was in progress. Since this distance was as great as 3, 700 ft, as many as 21 buggies had to be used for maximum runs. The concrete slump was held very uniformly at $2\frac{1}{2}$ in. to prevent segregation in the buggies. After deposit, electrically driven vibrators were pulled along in each 9-in. space between the small longitudinal beams. The double screed was then pulled manually to strike off the fresh concrete. Each screed consisted of a double beam 19 ft long carrying two gasoline driven vibrators (Fig. 6).

Figure 6. Paving operation.

The customary successive operations of luting, testing with a straight-edge, burlap drag, and curing by spraying a white pigmented compound are too well known to require description here. All operations following the screeding were carried on from cross-bridges to assure positively no walking in the wet concrete after strike-off. This is a simple and most essential requirement which is often not enforced.

Tests of pavement smoothness by a rolling "bump meter" confirmed compliance with the specified tolerance which was $^1/_8$ in. in 10 ft. This is also borne out by the experience of many critical automobile riders.

Since the entire pavement operation of 107,000 sq yd was carried out between June 22 and September 30, 1964, hot weather was a factor which could have had a seriously damaging effect on the pavement concrete. In addition to the heat, this bridge is in a location continuously exposed to wind which has a bad evaporation effect. The specifications made no mention of a maximum concrete placing temperature. However, to achieve a maximum temperature of 72 F, flake ice was added to the mix in amounts varying from 60 to 70 lb per cu yd. In this instance it was flake ice and not chunks, such as were used in the turbine mixers for the anchorages.

It is believed that the lower placing temperature contributed to the lack of surface cracks. Other favorable factors were: (a) the low slump, (b) the use of some natural cement, (c) the use of a retarder, and (d) the proper application of the sprayed curing compound. The fact that no stripping of slab forms was permitted before seven days had a favorable curing effect on the underside of slab. This may be the first time ice has been used in a concrete pavement mix.

The mix design for one cubic yard of pavement concrete was:

Portland cement	535 lb
Natural cement	69 lb
Sand (surface dry)	1,220 lb
$^3/_4$-in. crushed trap rock	1,990 lb
Water	31 gals (less ice)
Plastiment	2 liq oz per sack
Darex (for 6% air)	2.5 oz per cu yd
Ice	60 to 70 lb
Concrete placing temp	72 F (max)

The strength of the pavement concrete as measured by 57 test cylinders at 28 days averaged 4,524 psi.

Considering the many problems which arose in placing this concrete pavement on a flexible structure during the hot months under a very rapid schedule, the resulting slab has proved to be eminently satisfactory.