Precooling Mass Concrete

Liquid nitrogen proved to be the best alternative on the San Francisco-Oakland Bay Bridge

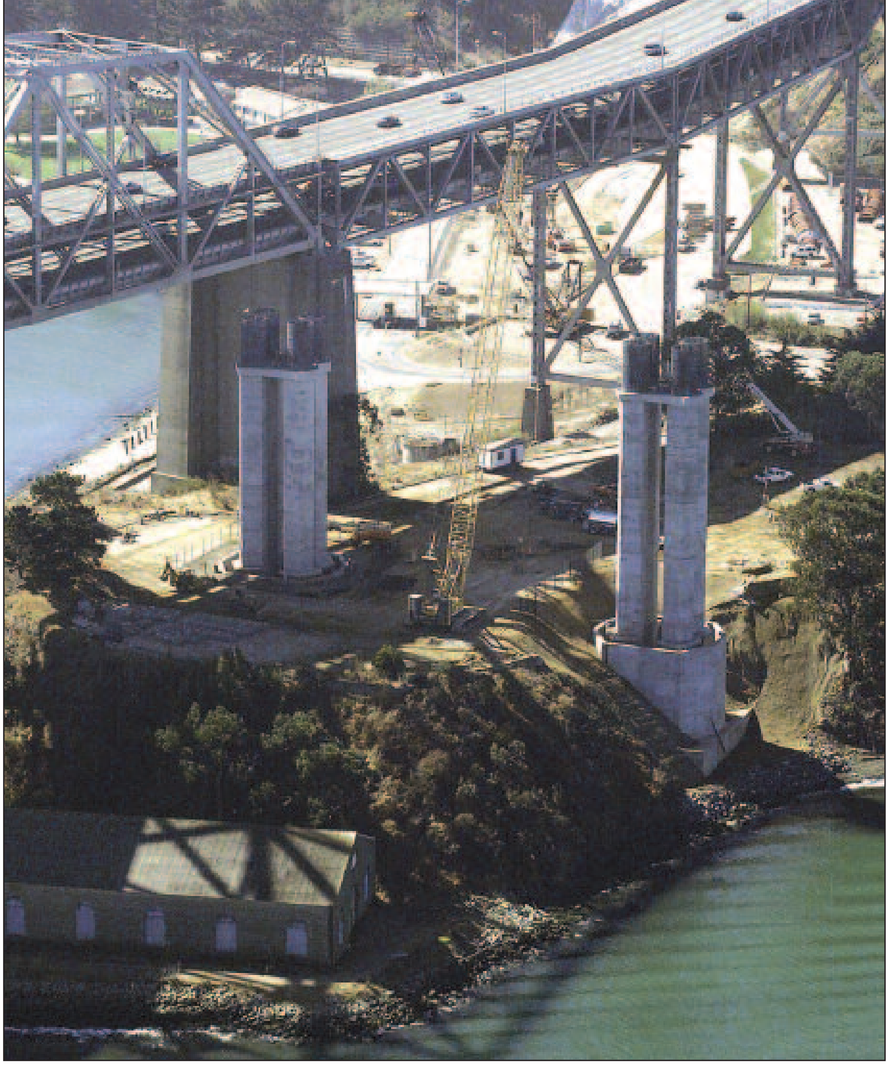
By John Gajda,
Alfred Kaufman, and
Francisco Sumodjo

Many new concrete structures are designed to include long spans and carry heavy loads. The sizes of the necessary components—drilled shafts, foundations, footings, and columns—often push the envelope of standard construction practices. A greater emphasis on durability also has led to higher cementitious material contents, lower water-to-cementitious-material ratios, and deeper cover over reinforcing steel. These requirements have resulted in more concrete placements that are subject to high internal temperatures.

The problem with high internal temperatures is the increase in the potential for thermal cracking that can decrease concrete's long-term durability and ultimate strength. Thermal cracking negates the benefits of less permeable concrete and deeper cover by providing a direct path for corrosion-causing agents to reach the reinforcing steel. To deal with these issues, designers and owners are treating more concrete placements as "mass concrete," traditionally defined as any placement greater than 3 feet thick. While there are numerous ways to control the internal temperature in mass concrete placements, using liquid nitrogen is one of the most effective.

Specifications typically limit concrete temperatures to a maximum of 160° F due to durability concerns related to delayed ettringite formation (DEF). DEF is an uncommon form of internal sulfate attack that can result from concrete being cured at high temperatures. Precooling the concrete can reduce the peak temperature.

Maximum temperature differences within the concrete are also usually specified to minimize the likelihood of thermal cracking. Historically, a maximum difference of 35° F (from the center of the concrete placement to the face nearest to the form) has been specified based on experience with unreinforced concrete dams. Insulation of the forms to keep the concrete from cooling too rapidly can limit the temperature difference. Other specifications, such as a maximum initial concrete temperature or cooling rate, can indirectly limit the maximum temper-



KIEWIT/FCI/MANSON, JV

ature or temperature difference.

The easiest and most cost-effective way to limit concrete temperatures is often with a properly engineered low-heat concrete. But when mix design changes are not practical, the concrete can be precooled. There are several ways to precool concrete.

■ *Evaporative cooling:* Often overlooked, evaporative cooling of coarse aggregate (sprinkling) is the most economical, cooling method. Sprinkling water can reduce the stockpile temperature by 10° F or more. Use only enough water to keep the stockpile wet, not saturated. Using chilled water is unnecessary, as the heat loss is simply a result of evaporation.

■ *Ice:* The most common, yet perhaps least understood, cooling method is replacing mix water with ice. This cools concrete in two ways: It first lowers the mix-water temperature and then lowers the mix temperature by extracting heat during the phase change from ice to water. This distinction is important, because ice is five times as effective for cooling as water chilled to 40° F. Ice can be added directly to the ready-mix truck or premixer. When a large project requires large quantities of ice, a dedicated ice production plant may be justified. Ice can be substituted for about 80% of the batch water, which limits the cooling that can be achieved with ice to about 20° F.

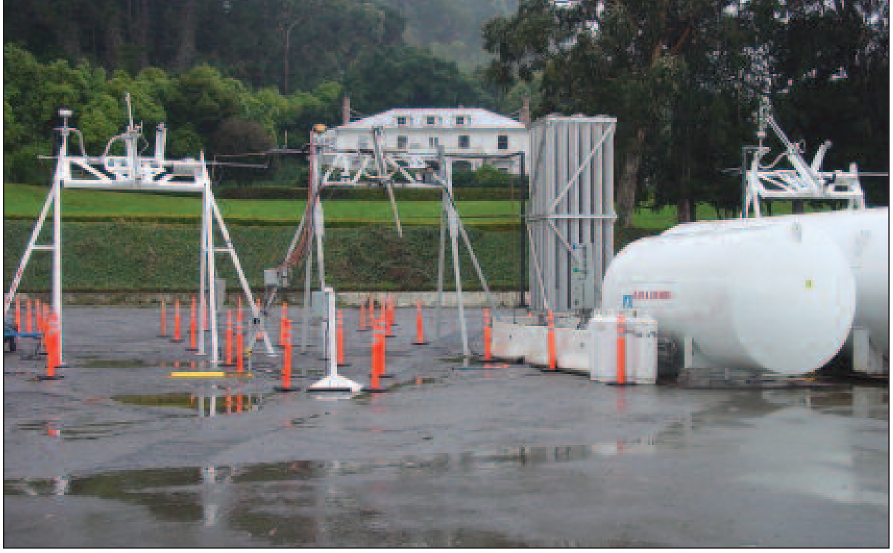
■ *Chilled water:* Chilled water can be used in the concrete mix to lower the temperature. Chilled batch water alone generally will not lower the concrete more than 8° F, depending on the water temperature and the water/aggregate ratio. If ice is used, then the reduction of mix water makes the use of chilled water ineffective. Where an ample supply of chilled or cool water and a way to drain the pile is available, inundation can be an economical way to cool coarse aggregates.

■ *Liquid nitrogen (LN_2):* When concrete needs to be precooled more than about 20° F, or where ice is not available, the most effective method usually is liquid nitrogen.

Advantages of liquid nitrogen

Liquid nitrogen is produced by compressing and cooling nitrogen gas below its evaporation point of about –320° F. The main advantage of LN_2 is its versatility. LN_2 can be used to chill the aggregates or mix water but most com-

Left: The huge foundations for the San Francisco-Oakland Bay Bridge could have resulted in heat buildup and large temperature differentials. Above: The massive concrete foundations and piers on the San Francisco-Oakland Bay Bridge required special mix designs and construction practices to control concrete temperatures.



CTLGROUP

Top: Liquid nitrogen was injected into the ready mix trucks at this lancing station, shown here one with lance extended and one retracted. Bottom: Precooling concrete with liquid nitrogen generates a white fog, as water vapor in the air is also cooled below the dew point. Gaseous nitrogen is colorless, tasteless, and odorless.

monly is injected directly into the ready-mix truck drum.

LN_2 can cool concrete as little as 1° F or as much as is needed. LN_2 equipment runs on power from small field generators, so neither an external power connection nor a large-capacity generator is required. When injected directly into the concrete, LN_2 has the advantage of changing the concrete temperature directly. All other concrete cooling methods rely on cooling materials before or during batching.

LN_2 is the only cooling method that allows field readjustment of the concrete. It requires fewer workers than are needed to add ice at the batch plant. LN_2 injection does not require any plant or truck modifications. Mix proportioning and batch procedures are not affected by LN_2 use in the field.

The potential drawbacks of LN_2 primarily relate to cost. Equipment and unit materials costs can be higher than for other cooling methods, depending on material availability and related local costs. Setting up and administering the field operation require extreme care and add to the LN_2 costs. Liquid nitrogen is extremely cold—at normal atmospheric pressure it reverts from liquid to gas, and its temperature is about –320° F. Therefore, operators and maintenance personnel must wear proper protective clothing and safety gear and must be trained in its safe use and handling.

On the other hand, unless the project is large enough to justify aggregate inundation, LN_2 is the only practical way to cool concrete by more than 20° F. On some projects, LN_2 has been used to precool the concrete mix to 35° F.

How it's done

The liquid nitrogen supply system consists of one 11,000- or 13,000-gallon cryogenic vessel, one optional additional small cryogenic vessel, and a vaporizer. The small cryogenic vessel supplies nitrogen gas for pneumatic controls and maintains constant pressure in the large cryogenic vessel throughout the cooling process. The need for it depends on the withdrawal rate of LN_2 from the supply vessel. The pressure of the liquid nitrogen supply vessel and the size of the nozzle determine the flow rate of the liquid nitrogen. A variable timer allows for close control of the final concrete temperature.

The liquid nitrogen injection station consists of a liquid nitrogen lance, which is moved in and out of the ready-mix truck drum using a pneumatic cylinder. From the control panel, the lance can be moved right or left and up and down, allowing the operator to position the lance correctly.

A pneumatically operated ball valve controls the flow of liquid nitrogen through each lance, and the entire process is sequenced from a pushbutton control panel. A bank of lights helps the driver and operator to position the truck properly and lets them know when cooling is complete.

A practical example

Under a California Department of Transportation (CalTrans) contract, construction of foundations that will eventually support the western portion of the San Francisco-Oakland Bay Bridge was recently completed. This project is a practical example of mass concrete construction, including the extensive use of liquid nitrogen for precooling.

The project included footings (62½ feet square and 32¾ feet high), and columns (144 feet high, with a diameter of about 11¾ feet). The footings were constructed at the bottom of 70-foot-deep excavations in rock.

The project specifications designated all concrete placements as mass concrete and required that a thermal control plan be developed to control temperature and temperature differences in the concrete. The specs limited the maximum temperature of the columns to 149° F and the maximum temperature of the footings to 122° F. The specification imposed large monetary penalties if concrete exceeded these temperature limits, and, in addition, prohibited all thermal cracking. Temperature control was critical.

The contractor engaged CTLGroup, Skokie, Ill., to develop thermal control plans for the mass concrete. CTLGroup worked with San Francisco-based ready-mix supplier RMC-Cemex to develop appropriate concrete mix designs. The specifications required a high cementitious materials content that would result in a "high heat" concrete. Through considerable pretesting, RMC-Cemex designed concretes that met the specified criteria but also had a low temperature gain, a high compressive strength, and a low coefficient of thermal expansion. These properties greatly helped limit temperatures and temperature differences.

The contractor elected to use several progressive measures to reduce construction time and costs. These included a calculated allowable temperature difference to prevent thermal cracking and reduce the time when insulation was required, a maturity-related procedure to account for faster compressive strength development at elevated temperatures, and internal cooling pipes to remove internal heat quickly.

Precooling procedures

To meet the 122° F maximum temperature limit, the contractor opted to precool the footing concrete before placement. The column concrete also was precooled for convenience and economy.

Liquid nitrogen in conjunction with ice was used for cooling because it was able to adequately cool the 570 truckloads of concrete for each footing, and it worked quickly enough to maintain the hourly supply. Air Liquide Industrial U.S. designed and operated the precooling system at the jobsite and supplied and dispensed the liquid nitrogen, to help ensure that concrete would be 50° F when placed. This setup also allowed for recooling any concrete that might become warm because of jobsite delays. Of the 17,000 cubic yards of concrete needed for the project, none was lost because of temperature. If a load was rejected for temperature at the placing site, it was recooled and used. Other cooling methods don't allow for recooling.

Five injection stations were required to cool up to 24 mixing trucks per hour. Of these, one was a spare that could be used when too many trucks came in at the same time or one of the other stations needed servicing. Each footing was placed in about 30 hours.

The maximum concrete temperature reached after placement in the first footing was about 104° F, well below the specified 122° F limit. The temperature difference also was well below the calculated allowable temperature difference. The contractor discontinued monitoring the temperature of the footings after 7½ days. At that point, the contractor was able to remove the insulation from the exterior faces, turn off the cooling pipes in the center of the placement, and begin work on the columns.

The results were similar for the second footing and the columns. The column concrete was sufficiently cooled after about 5½ days to allow the surface insulation to be removed and the cooling pipes turned off without thermal cracking. Without the preplanning, proper mix design, precooling, and other progressive measures, the columns would have taken significantly longer to cool.

The use of liquid nitrogen to precool concrete is still relatively uncommon. As mass concrete provisions that are now being applied to large projects, such as the San Francisco-Oakland Bay Bridge, trickle down into the design and construction of smaller projects, concrete contractors everywhere may soon be faced with an LN_2 project of their own. ■

— John Gajda is a principal engineer with CTLGroup, Skokie, Ill. Alfred L. Kaufman is technical services manager with RMC-Cemex, San Francisco. Francisco Sumodjo, who is based in Union City, Calif., is an applications specialist with Air Liquide Industrial U.S. LP.

All projects are different; LN_2 cooling may not be appropriate in all cases.

Lessons learned from LN_2 precooling on the San Francisco-Oakland Bay Bridge

1. Notify local officials in advance and explain the process. While the work is under way, what may appear to be a release of toxic fumes is really inert N_2 and water vapor.
2. Keep the drum rotating while injecting LN_2 to prevent nitrogen pools from accumulating in the drum.
3. Be prepared for "chunks" of concrete from buildup to be discharged with the first couple of loads in each truck. The cold drum contracts causing buildup to drop off.
4. Don't try to clean buildup by injecting LN_2 in an empty drum.
5. Don't inject partial loads unless the nozzles are properly positioned to spray LN_2 into concrete since this can result in nitrogen spray or pooling against the drum.
6. Don't buy cheap infrared thermometers. Expect to spend around $500 for a good unit. Check batteries often. Accurate infrared readings are obtained only on concrete "in motion." Do not use infrared thermometers to measure in-place concrete.
7. Set up traffic patterns to leave a way to get a truck quickly back to the injection station if additional cooling is necessary for placement.
8. Have a preplacement meeting and calibrate all temperature-measuring devices to read the same. It's bad enough to argue over concrete temperature without the added element of which thermometer is correct.
9. Read the MSDS to become familiar with safety issues for gaseous nitrogen and liquid nitrogen.