Fig. 1: Ready-mix truck being loaded with cooled aggregates via a NITROcrete liquid nitrogen cooling system

Hot Weather Shotcreting with Liquid Nitrogen

By Jamie Curtis

For shotcreters in the field, you know how difficult shotcrete placement can be; even on a good day. You're also aware of how this type of work is made exponentially more complicated when fighting a high-heat environment. Unless all precautions and preventative measures are utilized, the process can feel like a losing battle from the very beginning — even for the short period until initial set. Hot weather can adversely affect things like worker safety, productivity, pumpability, proper placement, material quality, meeting specifications, quality control, durability, and more.

The ACI SPEC 305.1-14(20) *Specification for Hot Weather Concreting* defines hot weather as: "One or a combination of the following conditions that tends to impair the quality of freshly mixed or hardened concrete by accelerating the rate of moisture loss and rate of cement hydration, or otherwise causing detrimental results: High ambient temperature, high concrete temperature, low relative humidity, and high wind speed." ACI SPEC 301 and ACI SPEC 305.1 also establish a default maximum concrete discharge temperature of 95 °F (35 °C), unless otherwise specified by the project or contract documents.

One of the key considerations for proper placement in hot weather is the concrete material temperature itself. For placement crews, cooler ready-mix concrete temperatures can reduce slump loss, improve workability, and delay set times. For the ready-mix concrete itself, properly cooled material will help meet specifications, reduce shrinkage and thermal cracking, and allow for an overall higher-quality finished product.

Material temperature is largely controlled by the batch plants themselves, and in particular, the temperature of the materials that are being mixed into it. Aggregate represents the largest component of most concrete mixtures and is often responsible for creating the majority of the heat load in the batch, especially since they are typically stored outdoors in the summer heat. Batch plants typically have standard measures in place to mitigate hot aggregate. Precautions taken before batching often include shading stored materials from the sun or using water sprinklers to keep stockpiles cooler. Cooling the aggregate during batching can provide significant reductions in final concrete temperatures as the material arrives onsite and is placed within a 90-minute window. But how do you efficiently cool aggregates during batching?

Fig. 2: Insulated cryogenic liquid nitrogen storage tank

Liquid-nitrogen aggregate cooling systems have quickly emerged as one of the most effective ways to accurately control material temperature. Systems, such as the one provided by NITROcrete, provide cooling by dosing liquid nitrogen directly into the aggregate stream as it travels along the conveyor or, in many cases, at the point of aggregate discharge. With contact, the liquid nitrogen rapidly converts to gaseous nitrogen (a process known as phase change) and absorbs heat from the aggregate, lowering its temperature dramatically before entering the truck or mixing drum.

In large commercial projects, mass concrete pours (such as slabs, bridges, dams, walls, and columns) can build up internal heat leading to possible thermal cracking and durability issues. In more specialty shotcrete applications, the reduction of early-age plastic shrinkage cracking, increased pumpability and longer workability are the main objectives. In both scenarios, the benefits of cooler ready-mix concrete deliveries are appealing.

Fig. 3: Dispensing heads apply the liquid nitrogen to the warm aggregates

THE AGGREGATE COOLING SYSTEM

Aggregate cooling systems (Fig. 1) are automated cooling systems which ready-mix plants must have preinstalled to offer the product to its customers. However, the process and the ability to access it are becoming much more readily available across the United States.

Liquid nitrogen used for cooling concrete aggregates is at its boiling point of approximately –320 °F (-196 °C). When liquid nitrogen is dispensed on hot aggregate at the dispenser or conveyor belt, it immediately changes from liquid to gas. That is when it absorbs a large amount of heat (its latent heat of vaporization), reducing the aggregate temperature. This phase change is what drives the majority of cooling. It also explains why these systems must be sophisticated enough to ensure the proper supply of liquid being dosed to the aggregate, as to prevent a multiphase (liquid nitrogen and vapor together) flow. Secondarily, the sensible heat (temperature change without changing the physical state; i.e. liquid stays liquid) accounts for very little of the heat transfer and cooling in comparison to the phase change. Aggregate entering at 120 °F (49 °C) may be cooled to 60 - 80 °F (16 - 27 °C), depending on a variety of factors.

The system consists of an insulated cryogenic liquid nitrogen storage tank, typically located next to the aggregate conveyors and a dispenser. Liquid nitrogen is stored in vertical or horizontal tanks at –320 °F (Fig. 2). Pre-insulated copper piping runs to a valve control box which regulates flow to the dispensing heads situated over the conveyor (Fig. 3). Dispensing heads, or 'dispensing nozzles', apply the liquid nitrogen to the warm aggregates (approximately 100 – 130 °F [38 – 49 °C]). The liquid nitrogen boils upon contact with the aggregate, and heat is immediately absorbed from the material. First, surface heat is removed. Next, heat from the center as the particles conducts outward. Depending on the application, liquid nitrogen cooling can reduce aggregate temperatures by 20 - 50 °F (11 - 28 °C) or more. Finally, the liquid nitrogen instantly becomes a harmless nitrogen gas — those who have seen this process will remember a large fog cloud that develops and rolls through the plant as each load is cooled (Fig. 4).

Batch plants control dosing from the automated system, per load, to achieve the desired material temperature required on the job (Fig. 5). Special care is taken to adjust both the rate and the amount of aggregate that is being dispensed onto the conveyor. In addition, the speed at which aggregates pass under the heads and the amount of nitrogen applied to the material are both key to proper cooling. This ensures proper distribution of liquid nitrogen over the aggregate on the conveyor. The automated system control, typically in the batch house, provides precise, real-time control of cooling rates, enabling plant operators to quickly adjust liquid nitrogen flow to accommodate changing conditions in the field and consistently maintain target concrete temperatures throughout the various stages of production.

ADVANTAGES OF LIQUID NITROGEN AGGREGATE COOLING

Aggregate cooling can provide several key advantages over other more traditional cooling methods such as chilled water, ice, or even direct injection of liquid nitrogen. As a general rule, for every 10 °F (12 °C) increase in temperature of the ready-mix concrete, estimated set time is cut by 50%. This makes cool concrete critical to predicting set times for specific job types. Even at what is considered a light dose of 6 gal/yd^3 (30 L/m^3), one will discover multiple advantages in cooling aggregates, plus additional benefits over other more common methods. Consistent, predictable,

Fig. 4: As liquid nitrogen hits the warm aggregate, it instantly becomes a harmless nitrogen gas

Fig. 5: Automated aggregate cooling systems integrated into batch plant operations

and easily adjustable temperature control (via automated batching systems) makes this strategy very adaptable to ever-changing conditions.

Liquid nitrogen is a more sustainable cooling method. It reduces production-related impacts such as emissions, energy usage, and harmful particulate matter when compared to more traditional cooling methods like ice and chilled water. Benefits include:

HELPS MEET TEMPERATURE REQUIREMENTS

- Allows for hot weather concreting in higher ambient temperatures
- Helps meet specifications for specific concrete material temperature requirements

IMPROVED CONCRETE QUALITY

- Reduces plastic shrinkage cracking with decreased evaporation
- No impact on water-cement ratio
- Reduced thermal cracking caused by high internal temperatures during mass concrete pours

EXTENDS WORKING TIME

- Reduced risk of accelerated set times
- Slows rate of hydration by lowering temperature
- Ideal for high-strength mixtures with high cement content
- Beneficial for mass concrete pours
- Helpful for long transport times

IMPROVES WORKABILITY

- Improved workability and pumpability
- Retains slump longer and reduces potential for rapid slump loss
- Improved finishability
- Reduced rebound

IMPROVED WORKABILITY AND DECREASED EVAPORATION RATE

In hot weather, fresh concrete has a higher rate of slump loss, which can lead to workability and placement issues. When looking at the factors contributing to slump loss, consider water as it relates to an evaporation rate: Higher temperature ready-mix concrete has increased evaporation, resulting in water loss and decreased slump. More importantly, concrete's rheological properties, such as slump, are affected by the material's initial temperature immediately following batching and mixing. Evaporation during batching is directly related to slump loss. Liquid nitrogen immediately controls the temperature, thus properly managing the evaporation rate right from the beginning of batching each load. This provides the benefit of reduced shrinkage cracking in the finished concrete.

SELECTING THE RIGHT COOLING STRATEGY

While aggregate cooling is effective, it is also important to recognize that not all concrete mixtures contain coarse aggregate. The ideal cooling method depends on the specific shotcreted concrete mix being produced. Many shotcreted mixes use only fine aggregate (sand) and cementitious materials. so there is no coarse aggregate to cool. As a result, plant-based aggregate cooling is generally not a practical solution for these sand-only mixture designs. When shotcrete mixes contain only fine aggregate, the preferred solution is direct injection of liquid nitrogen in the batched concrete.

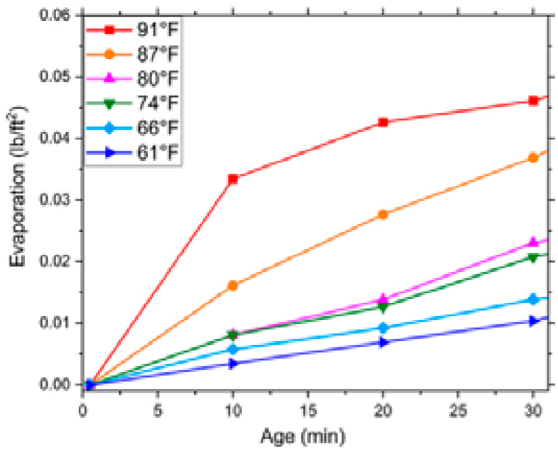
Rather than cooling the coarse aggregate during batching, injecting liquid nitrogen directly into the ready-mix truck during mixing is an available option. This approach cools the entire concrete mass, including sand, cementitious material, water, admixtures, etc. Because the entire batch is being cooled, injection can be used on virtually any shotcreted concrete mix design, including sand-only mixtures that cannot be cooled using plant-based coarse aggregate systems. The result is precise temperature control regardless of aggregate gradation, mix design, or batching location (Table 1).

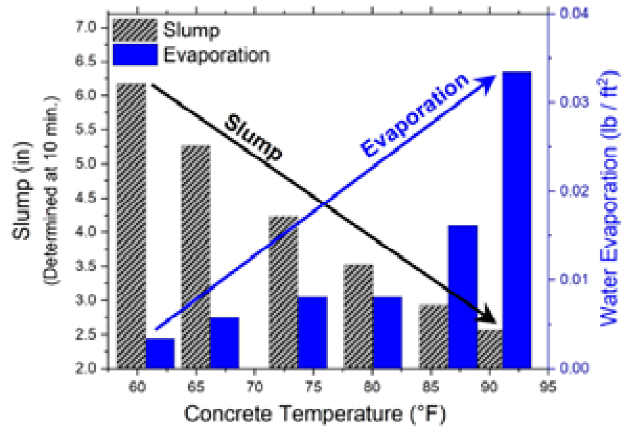
Mix Type	Aggregate Cooling	Direct Injection
Coarse Aggregate Shotcrete	Efficient Option	Less Efficient Option
Sand-Only Shotcrete	Not Applicable	Recommended
Plant-Based Cooling	Yes	No
Truck-Based Cooling	No	Yes
Cools Entire Concrete Mix	Yes	Yes
Water-Cement Ratio Impact	No	No

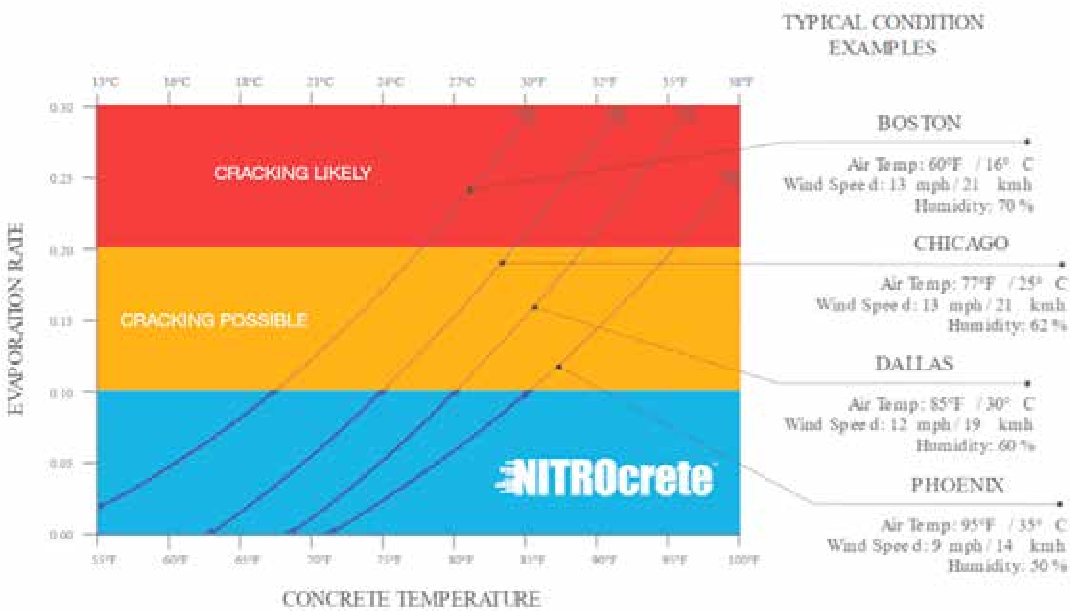
Table 1

COMBINING LIQUID NITROGEN WITH CONVENTIONAL HOT WEATHER TECHNIQUES

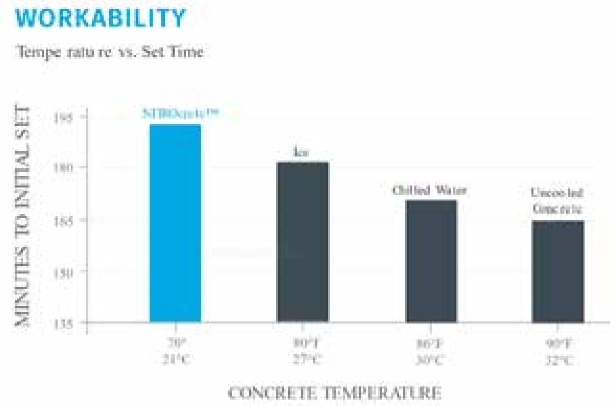
Combining other hot weather shotcrete precautions along with liquid nitrogen cooling can provide an enhanced and much more predictable placement environment to work in. The following techniques can address further concerns and

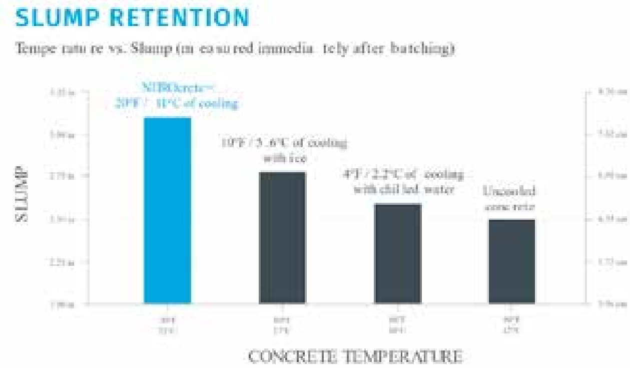






Graph Source: *NITROcrete™ Research and Development, 2019, based on NOAA weather data and ACI Materials Journal data 1998*





provide substantial benefits while working alongside the cooler material.

- Keeping substrate protected from the sun, cool and pre-saturated aggregates
- Casting or shooting early in the morning or later at night for cooler ambient temperatures
- Shading areas to be shotcreted (Fig. 6)
- Using misters or fog cannons to increase humidity in the air if required (Fig. 7)
- Protecting freshly placed concrete from high winds and direct sun
- Including a hydration stabilizer admixture to properly time the initial set time
- Applying evaporation retarders during placement if applicable
- Implementing an aggressive curing strategy with early wetting and an extended water curing period or using spray-on curing membranes with careful attention to full coverage and thickness

In Summary:

When planning any shotcrete project around hot weather, consider the return-on-investment of using liquid nitrogen. Aggregate cooling costs can vary geographically: Many plants will charge per cubic yard (m^3) by the desired delivered concrete temperature, such as 75/85/95 °F (24/29/35 °C), or by the gallons per cubic yard. Regardless, consider the value and the combined benefits your project will gain by having cooler material delivered to your jobsite.

In most cases, the benefits will outweigh the costs. Our shotcreting team prefers ready-mix concrete suppliers who have cooling capabilities installed (in particular nitrogen) when making a concrete ready-mix supplier selection. As ambient temperatures rise in summer, nitrogen cooling can become an invaluable option, especially as conditions can vary significantly daily. For safety, quality and feasibility, 'cool rocks' via liquid nitrogen can truly save the day.

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Fig. 6: Providing shade to the area being shotcreted provides immense benefits while shooting in the heat

Fig. 7: Utilizing a fog cannon to provide moisture in the air during hot weather shotcrete