CINPAR 2023
XIX International Conference on Building Pathology and Constructions Repair
8th to 10th, june 2023 - Sobral, Brazil

Thermal evaluation of the use of liquid nitrogen as a pre-cooling methodology for mass concrete for use in an onshore wind tower

Wanner Kelly Damasceno da SILVA[1], Leonária Araújo SILVA[2], Antônio Eduardo Bezerra CABRAL[3], Marcelo Silva MEDEIROS JÚNIOR[4], Gustavo de Medeiros PINHEIRO[5], Antônio Medeiros de OLIVEIRA[6]

[1] Federal University of Ceara (UFC), Fortaleza/CE, Brasil, kellydamasceno@alu.ufc.br
[2] Federal University of Ceara (UFC), Fortaleza/CE, Brasil, leonaria@alu.ufc.br
[3] Federal University of Ceara (UFC), Fortaleza/CE, Brasil, eduardo.cabral@ufc.br
[4] Federal University of Ceara (UFC), Fortaleza/CE, Brasil, marcelomedeiros@ufc.br
[5] Company Dois A Engenharia e Tecnologia, Natal/RN, Brasil, gustavo.pinheiro@doisa.com
[6] Company Dois A Engenharia e Tecnologia, Natal/RN, Brasil, antonio@doisa.com

Abstract: Onshore wind turbines are commonly supported by massive foundations, composed of hundreds of cubic meters of concrete and tons of steel. This mass concrete releases high heat of hydration during the construction process, especially in the initial period. The high temperature gradient generates significant tensile stresses in the outer zones of the pouring volume, causing the appearance of cracks. As a pre-cooling method for mass concrete, liquid nitrogen (LN) is used to cool the constituent aggregates, with a marked reduction in the temperature gradient of the concrete. The present study aims to evaluate the efficiency of using liquid nitrogen in improving the thermal properties of fresh and hardened concrete in foundations of onshore wind towers. For this purpose, three different mixes of concrete were produced, varying the concentration of liquid nitrogen. The proportions of 80 liters of LN and 110 liters of LN were used for each cubic meter of concrete for cooling the coarse and fine aggregates. For standard or reference sample, no cooling method was used. The heat loss of the concrete over seven days or until the thermal equilibrium of the specimens was analyzed. In parallel, cylindrical specimens were molded, with dimensions of 10 centimeters in diameter and 20 centimeters in height, to evaluate the physical-mechanical properties of the developed concretes. Standardized tests were carried out according to Brazilian regulations, such as the water absorption, void index, specific mass, axial compression strength test and modulus of elasticity. The results show the efficiency of liquid nitrogen application for significant temperature reduction in concreting conditions in hot climate regions.

Keywords: Onshore wind energy; Mass concrete; Temperature gradient; Liquid nitrogen.

1. Introduction

Cement hydration is an exothermic process with energy of up to 500 J/g, which can be released into the cementitious composite and the maximum concrete temperature can reach 60–70 °C in the initial hydration period (BAKOUR; FTIMA, 2021). Due to concrete being a material of low thermal conductivity, cement hydration can result in a sharp temperature gradient between the surface and the interior of the concrete, which is why thermomechanical control measures are required (OUYANG *et al*., 2019; SMOLANA *et al*., 2021). During the curing of the mass concrete, the interior of the structure initially expands more than the external region, due to the heat exchange of the surface with the environment, consequently, there is the formation of tensions in the concrete element and the appearance of cracking (SMOLANA *et al.*, 2021).

Changing the temperature of the mass concrete, that is, an increase followed by a decrease in temperature, can lead to risks of damage in the short and long term, compromising the durability of the structure, since early cracks can initiate corrosion of the reinforcement, penetration of chlorine ions, leaching of concrete, among other pathological manifestations (OUYANG *et al*., 2019). Initially, cracks may occur due to self-restrained deformations, these being essentially thermal deformations; and also, due to delayed ettringite formation. For Chiniforush *et al*. (2021), early thermal cracking and delayed ettringite formation are the main durability risks associated with mass concrete.

Reducing the initial temperature of the concrete mix results in reducing the rate of heat release and the maximum temperature in the structure and, consequently, limiting the tensile stress that appears in the element (SMOLANA *et al*., 2021). Pre-cooling of materials can be carried out in the following ways: cooling the individual mix components (aggregates, cement or water), replacing part of the mixing water with ice or cooling the concrete mix using liquid nitrogen (LN). Considering the greater impact of aggregate on concrete temperature, treatment usually consists of adequate aggregate storage, cooling the aggregate with cold water, and vacuum evaporation of water (ACI, 2005). Aggregate cooling can reduce the temperature of the concrete mix by 8 °C to 12 °C below ambient temperature (ACI, 2005).

Cooling the mix by adding cold water can cause a decrease in the mix temperature by only about 1 °C to 2 °C (KIERNOŻYCKI, 2003, *apud*, SMOLANA *et al*., 2021), however, it may be the solution cheaper (KLEMCZAK; KNOPPIK-WRÓBEL, 2011). The total or partial replacement of mixing water by ice results in a reduction in the temperature of the concrete mixture by 12 °C to 18 °C in relation to the ambient temperature (NEVILLE, 2015) and does not change the consistency of the final concrete mixture (SMOLANA *et al*., 2021). Cooling the mixture with liquid nitrogen at -196 °C provides effects similar to the application of ice (ACI, 2005), however the use of liquid nitrogen cools the concrete more uniformly, promoting a more consistent slump (BEAVER, 2004), as having lower temperatures and occupying a smaller volume than ice, which makes it more convenient to transport and store (GAJDA; SUMODJO, 2012).

Kattoof, Hassan and Hasan (2022) point to ice and cold water as insufficient pre-cooling methods to reduce extreme temperatures in hot climate environments. When greater temperature reductions are required, cooling by injecting liquid nitrogen into concrete may be the most convenient means, not affecting the amount of mixing water and providing precise temperature control.

Despite the advantages of applying liquid nitrogen as a pre-cooling method for mass concrete, few studies address this use. Harith, Hassan and Hasan (2022) recommend that further investigations be carried out related to the effects of cooling with liquid nitrogen on the hardened properties and performance of concrete. Table 1 presents studies that evaluated the use of liquid nitrogen and their main conclusions.

Thus, this article aims to evaluate the thermal efficiency of using liquid nitrogen as a pre-cooling technology for mass concrete for use in foundations of onshore wind towers.

Table 1 – Studies that used liquid nitrogen as a pre-cooling method and its conclusions

Reference (Year)	Application of LN	Conclusion
Negami *et al*. (1990)	Fine aggregate freezing	Concrete temperature can be reduced by 25 °C when using liquid nitrogen frozen sand, which is a greater amount of reduction than achieved by conventional pre-cooling methods
Juenger; Solt; Hema (2010)	Cooling of mass concrete	The initial setting time of concrete is longer than expected when there is a significant delay in cooling the concrete with LN. Chilled concrete has low slump similar to uncooled concrete and in hot climates
Hansen; Forbes (2012)	Roller-compacted concrete dam cooling	The temperature of the concrete was reduced by 0.6 °C when using ice in the mixing water, and about 1.1 °C to 1.7 °C when using liquid nitrogen
Kattoof; Hassan; Hasan (2021)	Cooling of nanomodified concrete	The use of LN in cooling nanomodified concrete can achieve balanced and superior performance in terms of compressive strength and water absorption, making it a viable option in hot climate regions
Harith; Hassan; Hasan (2022)	Mixtures of binary and ternary binders	The results indicate that the peak temperature was significantly reduced by the use of liquid nitrogen. However, the arrival time to peak temperature was significantly extended
Kattoof; Hassan; Hasan (2022)	Concretes containing fly ash and nanosilica	Liquid nitrogen has a positive influence on portlandite consumption, especially in nanomodified concrete, which could eliminate the propagation of new cracks and result in finer and denser internal microstructures

2. Research method

In a wind complex located in northeastern Brazil, concrete blocks with dimensions of 58 cm x 58 cm x 145 cm were built, insulated by two layers of expanded polystyrene (EPS) and two layers of plasticized wood in order to minimize thermal exchanges with the external environment. Temperature sensors were inserted in these samples (type K thermocouples, for general use and more resistant to oxidation at high temperatures compared to types E, J and T), in which the sensors used have a sensitivity of approximately 41 µV/°C and are suitable for continuous measurement from -200 °C to 1260 °C. The temperatures developed in the mixtures were measured every hour over seven days, so 168 readings were taken for each concrete block made, with the aim of evaluating the thermal behavior of the concrete. Figure 1 shows the execution of the insulation and molds for the concrete produced on site. Figure 2 shows the final layout of the block insulated with EPS and its concreting.

Figure 1 – Preliminary steps for performing thermal insulation with expanded polystyrene sheets, layers of plasticized wood and sealing with acetic silicone adhesive

Figure 2 – Final disposition of the block isolated with EPS and execution of block concreting with mechanical vibration

Three mixtures were executed that differ in terms of the application of the pre-cooling method used in the concrete. For samples labeled as CR, no cooling method was used, which were named as references or standard samples; for CN80, 80 liters of liquid nitrogen were applied to each cubic meter of concrete, as a solution for cooling the constituent aggregates, since aggregates correspond to approximately 70% of the total composition of concrete (JUENGER, 2007), and, in the CN110 samples, a higher consumption of liquid nitrogen was used, which is equal to 110 liters for each cubic meter of concrete, also for cooling its aggregates.

Therefore, liquid nitrogen was used as a cooling material for mass concrete, specifically used in the freezing of fine and coarse aggregates. Nitrogen was supplied by the company White Martins in industrial cylinders and its physicochemical properties are shown in Table 2, according to the Safety Data Sheet for Chemical Products provided by that company. Figure 3 illustrates the application of LN in the cooling of aggregates, as the concrete plant when using liquid nitrogen.

Table 2 – Physical and chemical properties of liquid nitrogen

Properties	**Values obtained**
Aspect	Cryogenic liquid, colorless, odorless
Specific weight of the liquid at the boiling point and 1 atm (kg/m³)	808,5
Fusion point at 10 psig (°C)	-210,0
Boiling point at 10 psig (°C)	-195,8
Critical temperature (°C)	-149,9
Molecular weight	28,01
Relativy density at 21 °C (air = 1)	0,967

Figure 3 – Application of liquid nitrogen for the cooling of concrete aggregates

According Kattof, Hassan and Hasan (2022), an average amount of 13.8 liters of liquid nitrogen was required to cool one cubic meter of concrete by 1 °C. Gadja and Sumodjo (2012) found that 13 liters of liquid nitrogen are needed to achieve the same cooling effects. It is expected to reduce the concrete temperature by 6 °C to 8 °C based on the LN consumption applied in this article.

For the evaluation of the physical and mechanical properties of cementitious composites, concrete specimens with a diameter of 15 cm and a height of 30 cm were molded, in which water absorption, void index and specific mass tests were carried out (ABNT NBR 9778:2009), axial compression strength (ABNT NBR 5739:2018) and static modulus of elasticity (NBR 8522-1:2021), illustrated in Figure 4. The specimens were kept in wet cure for 28 days.

Figure 4 – Performance of physical-mechanical tests on the concrete produced

3. Results and discussions

The thermal profile curve, obtained for the maximum temperatures in the concrete blocks, can be seen in Figure 5, which shows the thermal behavior of the mixtures over time. It can be seen that the mixtures cooled with liquid nitrogen present a lower temperature rise and a longer delay for the occurrence of the thermal peak compared to the reference sample. Concrete placement temperatures equal to 32 °C, 27 °C and 20 °C were obtained for the CR, CN80 and CN110 samples, respectively, thus reductions of 5 °C and 12 °C were achieved for the mixtures cooled in comparison to the reference mixture. This result is similar to the references Gadja and Sumodjo (2012) and Kattof, Hassan and Hasan (2022), cited above.

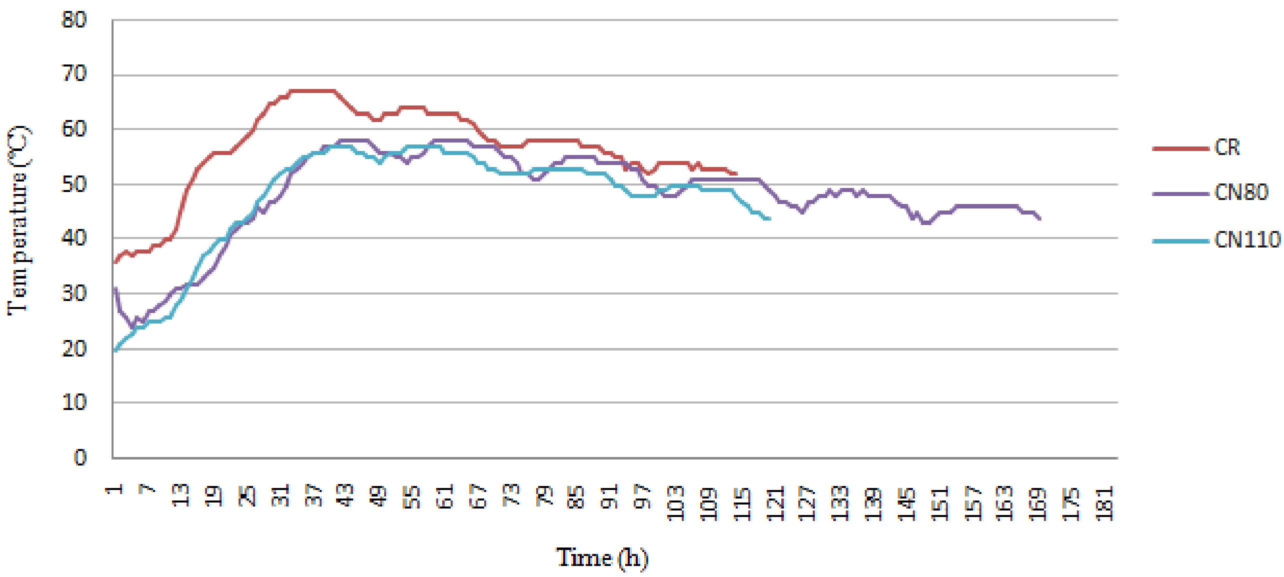

Figure 5 – Thermal profile for concrete blocks from maximum temperatures

Table 3 presents the maximum temperatures obtained in this study for the different proposed trait variations. A higher temperature peak (67 °C, 33h after concreting) is observed for the reference mix variation (CR), with this concrete being produced without a cooling system, which validates the need to reduce the temperature of the mass concrete. The CN110 variation has a lower temperature peak (57 °C, 40h after concreting), using 110 liters of LN per cubic meter of concrete as a pre-cooling system; and the CN80 variation (with consumption of 80 liters of liquid nitrogen for each cubic meter of concrete) showed a similar maximum temperature result (58 °C, 42h after concreting) to the solution with the highest consumption of LN. Therefore, there was a reduction in the temperature peak in the order of 10 °C and 9 °C due to the application of liquid nitrogen in the mass concrete with consumption of 110 L/m³ of concrete and 80 L/m³ of concrete, respectively. Also, it is observed the lengthening of the time for the occurrence of the maximum temperature when liquid nitrogen is applied.

Table 3 – Results obtained for the thermal analysis

Mix ID	Concrete pouring temperature (°C)	Amount of N_2 (L/m³ of concrete)	Maximum temperature (°C)	Maximum temperature time (h)
CR	32	0	67	33
CN80	27	80	58	42
CN110	20	110	57	40

Due to the use of liquid nitrogen, the initial temperature of the concrete mix is 5 °C to 12 °C lower than that of uncooled concrete, which helps to build the concrete structure correctly by preventing the appearance of thermal cracks. The research work verified that the thermal peak in concrete is reduced by a few degrees and, in addition, it is displaced in time by several hours, making concreting possible in the sun.

The produced concretes had their performances compared in terms of their physical and mechanical characteristics. For this purpose, Table 4 presents the average values of water absorption, voids index and specific mass of the mixtures, with their respective standard deviations. Mixtures CN80 and CN110 showed results of 7% and 26%; 9% and 27%; 3% and 5% lower than the control sample for the water absorption, voids index and specific mass tests respectively. Lower values are observed in the physical tests for the mixture with 110 liters of liquid nitrogen per cubic meter of concrete, CN110. Figure 6 indicates the behavior of the mixtures produced for the analyzed physical characteristics.

Table 4 – Results obtained for the water absorption, void index and specific mass tests

Mix ID	Water absorption (%) (standard deviation)	Void index (%) (standard deviation)	Specific mass (g/cm³) (standard deviation)
CR	5,36 (± 0,57)	12,04 (± 1,25)	2,56 (± 0,03)
CN80	4,97 (± 0,32)	10,95 (± 0,66)	2,48 (± 0,01)
CN110	3,95 (± 0,68)	8,78 (± 1,47)	2,44 (± 0,03)

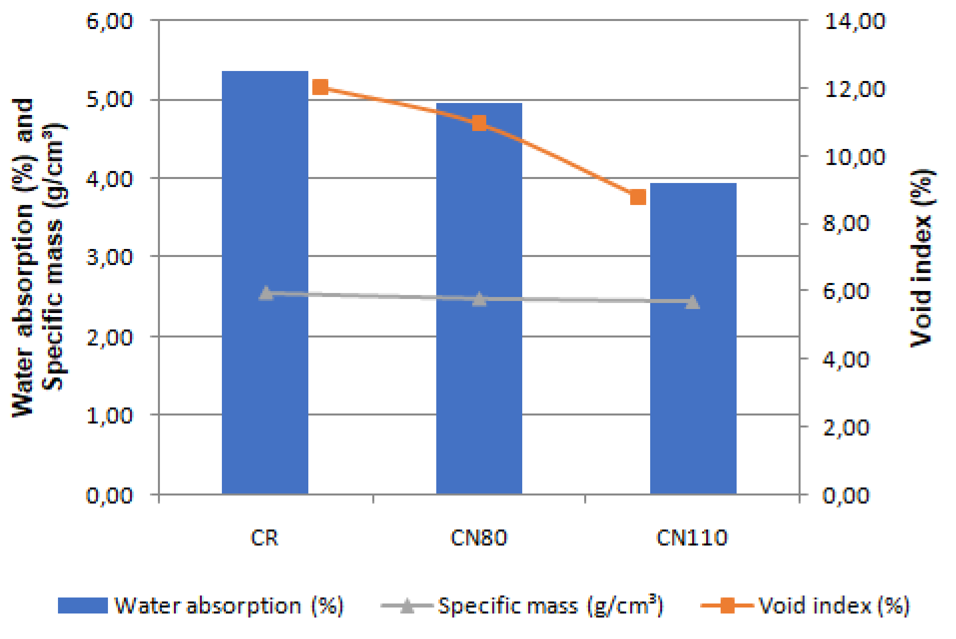

Figure 6 – Behavior of concrete produced for physical tests

It is observed, immediately after the injection of liquid nitrogen into the interior of the mixer, that the nitrogen changed from the liquid to the gaseous state and there are concerns with the water leaving the mixer, for example, the possibility of evaporation of water from the concrete (AZIM ; AFSHIN; CHARKHTAB BASIM, 2022). According Hema (2007), concrete cooled with liquid nitrogen presents a loss in air content compared to the control mixture. When nitrogen is discharged into the mixer there is often a loss of slump and this requires additional agitation to mix the concrete which can lead to additional loss of air.

In Figure 7, the average values of resistance to axial compression of the concrete produced at the failure ages of 3, 7, 14 and 28 days are presented, as Table 5 indicates such values with their respective standard deviations. An increase in axial compression strength is observed for the different mixtures as the curing age of the concrete increases (SANTOS; GODINHO, 2018).

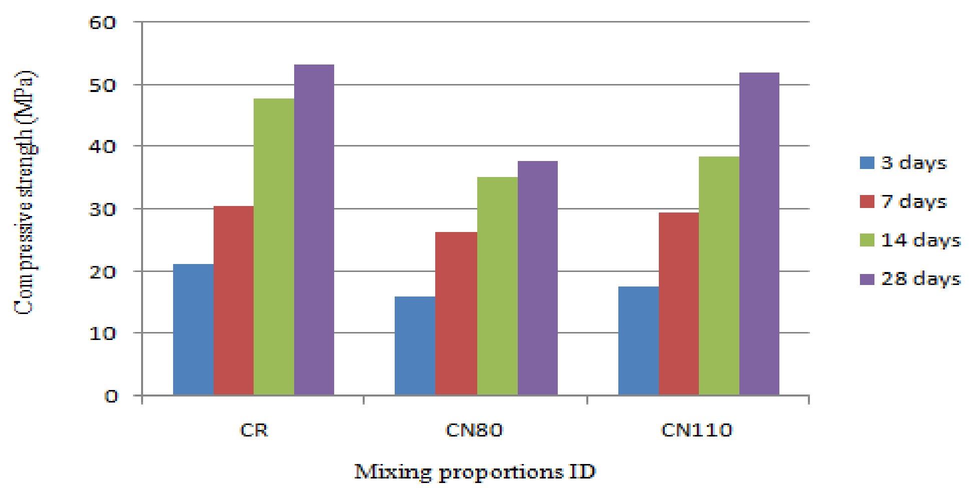

Figure 7 – Compressive strength for mixtures at 3, 7, 14 and 28 days

Table 5 – Average axial compressive strength at different curing ages

Mix ID	Average axial compressive strength (MPa) (standard deviation)			
	3 days	**7 days**	**14 days**	**28 days**
CR	21,3 (± 0,5)	30,4 (± 5,6)	47,9 (± 1,0)	53,4 (± 2,0)
CN80	16,1 (± 1,0)	26,3 (± 1,0)	35,1 (± 1,3)	37,7 (± 1,8)
CN110	17,7 (± 0,1)	29,6 (± 2,1)	38,6 (± 2,4)	52,0 (± 1,5)

For all ages, lower resistance to axial compression was observed in concrete cooled with liquid nitrogen when compared to the reference mix. However, the study by Hema (2007) did not show a significant effect on the use of liquid nitrogen for the axial compressive strength of concrete samples. Juenger (2007) also showed that the use of liquid nitrogen to cool cement paste at 0 °C does not affect the development of the microstructure and resistance of the mixtures.

Values of 39 GPa, 31 GPa and 36 GPa were obtained for the modulus of elasticity tested for the CR, CN80 and CN110 mixtures, respectively, where a performance similar to that observed for the resistance to axial compression was observed. Hema (2007) verifies such behavior in cooled mixtures with liquid nitrogen, where he indicates that the modulus of elasticity is directly proportional to the mechanical strength, that is, as the resistance increases, the modulus of elasticity should also increase.

Two factors stand out among the processes that influence the durability and strength of concrete, these being the pore microstructure, in its various shapes and dimensions; and the mechanism of transport of penetrating agents. The transport of fluids is related to the humidity of the compound, which is fixed on the concrete walls due to the process of physical adsorption and capillary condensation; and pore dimensions. Therefore, it is necessary to carry out a complementary analysis of the microstructure of the pores, through scanning electron microscopy (SEM) images, to verify the results obtained in the test of resistance to axial resistance and modulus of elasticity, in order to analyze the causes of the reduced values for the variation of the CN80 trait. The complexity of the transport phenomena involved justifies the performance of additional, more in-depth studies, as the development of a greater number of tests to confirm the results obtained.

4. Conclusions

In the physical-mechanical tests of this study, it was observed that the application of liquid nitrogen for pre-cooling of the concrete presented lower resistance to axial compression (for the ages of 3, 7, 14 and 28 days of curing) and lower modulus of elasticity (at 28 days) compared to the control sample. However, Hema (2007) points out that the use of nitrogen does not produce a significant effect on the resistance to axial compression and on the modulus of elasticity of concrete samples, requiring the investigation of its microstructure, in order to verify if there is interference in the formation of concrete hydration products.

The application of liquid nitrogen showed relevant efficiency when analyzing the curve of the thermal profile of the concretes developed, over time, verifying lower launch temperatures for mixtures with liquid nitrogen (CN80 and CN110), in comparison with the reference sample. It was found that the higher consumption of liquid nitrogen per cubic meter of concrete leads to a greater reduction in the temperature of this composite, with the use of liquid nitrogen being a promising alternative as a method of pre-cooling mass concrete in regions with hot climates, as evidenced by Kattoof, Hassan and Hasan (2022).

Using LN in concrete is an effective cooling method and provides precise temperature control over time. With the use of liquid nitrogen as a pre-cooling method, the temperature of fresh concrete is not restricted by the water-cement ratio of the mixture, unlike solutions using cold water and ice flakes. Consequently, concrete temperatures at early ages can be reduced considerably with the application of liquid nitrogen compared to conventional methods, depending on the consumption of LN. It was observed in this study that the greater the consumption of liquid nitrogen, the lower the temperature peak developed.

Acknowledgments

The authors would like to thank the Ceará Foundation for Supporting Scientific and Technological Development (FUNCAP) for the financial incentive to the project entitled “Ultra high durability concrete for use in segments and foundations of wind towers: tests and computational modeling”, in which this article is inserted.

References

ACI COMMITTEE (2005). ACI 207.1 R-05. Guide to Mass Concrete. American Concrete Institute: Farmington Hills, MI, USA, p. 30.

Azim, A. G., Afshin, H., Charkhtab Basim, M. (2022). Investigating the Effects of Liquid Nitrogen on Concrete Properties in Hot Weather Concreting. Journal of Structural and Construction Engineering, v. 8, n. 11, p. 278-291.

Bakour, A. , Ftima, M. B. (2021). Experimental investigations on the asymptotic fracture energy for large mass concrete specimens using wedge splitting test. Construction and Building Materials, v. 279, p. 122405.

Beaver, W. (2004). Liquid nitrogen for concrete cooling. Concrete international, v. 26, n. 9, p. 93- 95.

Chiniforush, A. A., Gharehchaei, M., Nezhad, A. A., Castel, A., Moghaddam, F., Keyte, L., Hocking, D., Foster, S. (2021). Minimising risk of early-age thermal cracking and delayed ettringite formation in concrete–A hybrid numerical simulation and genetic algorithm mix optimisation approach. Construction and Building Materials, v. 299, p. 124280.

Gajda, J., Sumodjo, F. (2012). Precooling Mass Concrete with Liquid Nitrogen. Concrete international, v. 34, n. 7.

Hema, J. (2007). The effects of liquid nitrogen on concrete hydration, microstructure, and properties. The University of Texas at Austin.

Juenger, M. C. G. (2007). The effects of liquid nitrogen on concrete properties. Center for Transportation Research, University of Texas at Austin.

Kattoof, I., Hassan, M. S., Hasan, S. S. (2022). Effects of Liquid Nitrogen Cooling on the Microstructure Properties of Nano-Modified Concrete Under Hot Conditions. Arabian Journal for Science and Engineering, p. 1-15.

Klemczak, B., Knoppik-Wróbel, A. (2011). Early age thermal and shrinkage cracks in concrete structures – influence of curing conditions. Architecture–Civil Engineering– Environment, v. 4, n. 4, p. 47-58.

Ouyang, J., Chen, X., Huangfu, Z., Lu, C., Huang, D., Li, Y. (2019). Application of distributed temperature sensing for cracking control of mass concrete. Construction and Building Materials, v. 197, p. 778-791.

Santos, D. D., Godinho, D. S. S. (2018). Analysis of the evolution of the mechanical properties of concrete over time.

Smolana, A., Klemczak, B., Azenha, M., Schlicke, D. (2021). Early age cracking risk in a massive concrete foundation slab: Comparison of analytical and numerical prediction models with on-site measurements. Construction and Building Materials, v. 301, p. 124135.