Chapter 6
Temperature Control

Miguel Azenha, Ioannis P. Sfikas, Mateusz Wyrzykowski, Selmo Kuperman and Agnieszka Knoppik

Abstract Temperature rises are definitely one of the most important driving forces for thermal cracking in mass concrete, together with the restraint to deformation. Therefore, amongst the most widespread measures that can be taken to minimize the risks of thermal cracking, the temperature control of concrete since its production and throughout construction is of utmost significance. Following Chap. 5 where temperature control of concrete by limiting the heat generation potential of the binder in the mixture was already addressed, this chapter is dedicated to a review on measures that can be taken to control concrete temperature at several levels, mainly focused in limiting temperature rises due to cement hydration heat: (i) pre-cooling of mix constituents; (ii) cooling concrete during the mixing procedures; (iii) controlling temperature during transport and placement; (iv) selecting and designing suitable surface measures for temperature control; (v) post-cooling with water or air; (vi) scheduling of construction stages.

M. Azenha (✉)
ISISE, University of Minho, Guimarães, Portugal
e-mail: miguel.azenha@civil.uminho.pt

I. P. Sfikas
Mott MacDonald Ltd., Croydon, UK

M. Wyrzykowski
Empa, Swiss Federal Laboratories for Materials Science and Technology,
Dübendorf, Switzerland

S. Kuperman
Desek Ltda, São Paulo, Brazil

A. Knoppik
Silesian University of Technology, Gliwice, Poland

E. M. R. Fairbairn and M. Azenha (eds.), *Thermal Cracking of Massive Concrete Structures*, RILEM State-of-the-Art Reports 27,
https://doi.org/10.1007/978-3-319-76617-1_6

6.1 Introduction

6.1.1 General Considerations

Curing in mass concrete is mostly related to three issues:

i. ensuring adequate moisture conditions for concrete hydration, through formwork selection for formed surfaces or proper evaporation hindering (or even watering) of freely exposed (unformed) surfaces. Wet/moisture curing, in addition to promoting hydration and reducing early shrinkage cracking, also reduces the coefficient of thermal expansion considerably, therefore reducing the risk of thermal cracking;
ii. controlling temperature differentials below a maximum level as to avoid excessive temperature gradients, either cross sectional or along time, which can potentially result in thermal cracking (Bamforth 2007);
iii. limiting maximum temperature in concrete, which is also critical in order to mitigate long-term cracking due to the delayed ettringite formation (DEF) and avoid hydration at higher temperatures that leads to the production of a poorer quality of hydrate that can compromise long-term strength capacity.

While issue (i) can normally be handled by good practices of application/workmanship and quality control, including direct application of suitable formwork materials (ACI 2014), such as controlled permeability formwork (CPF), physical curing membranes or even anti-evaporating agents/curing compounds or liquid membranes (ACI 2011; Buenfeld and Yang 2001; Concrete Society 2014; Vicroads 2000), issues (ii) and (iii) are more complex to tackle. In fact, maintaining maximum levels of temperature and temperature differentials within concrete are considered to be challenging to control, in view of the multiplicity of climatological factors that contribute to the temperature development (e.g. cold or hot weather concreting, relative humidity, wind velocity, solar radiation), as well as the influence of the initial temperature of concrete (fresh concrete temperature), the heat generation potential of the hydrating binder in the concrete mix, the effectiveness of curing and post-cooling measures and also the size of the structural element itself (often dictated by the adopted construction phasing strategy), as well as the anticipated construction stages (new concrete on previously constructed elements).

The present chapter is targeted to issues related to approaches that may be adopted during the construction phase of a concrete project in order to control temperature, comprising the set of influencing factors mentioned above. As mass concrete temperature issues are normally related to cooling necessities or minimization of peak temperature and associated temperature gradients, the present chapter is mainly focused on such aspects.

6.1.2 *Outline of Strategies for Temperature Control*

The selection of appropriate constituent materials for the concrete mix production targeting the reduction of heat generation potential has been discussed in detail in Chapter 5 and will not be further discussed. Apart from this method, different strategies or combination of strategies for temperature control can be followed and they are summarized in the list below, linking to sections where they are discussed:

1. Pre-cooling methods, including cooling of ingredients and cooling during the mixing procedures, to reduce the concrete temperature at the time of delivery (Sects. 6.2 and 6.3);
2. Post-casting measures to control heat fluxes from concrete and thus limit the temperature rise and associated differentials (Sects. 6.4 and 6.5);
3. Construction management, including scheduling of construction stages and procedures to achieve lower temperatures and associated differentials (Sect. 6.6).

6.1.3 *Regulatory and Non-regulatory Frameworks of Temperature Control*

In Europe, the general purpose specification for normal concrete, EN 206:2013 (CEN 2013), solely establishes a minimum temperature of 5°C for concrete upon delivery. According to EN 206:2013, if a different minimum temperature is necessary or a maximum temperature needs to be established, such limits should be specified (together with permitted tolerances), and any requisites for the artificial heating or cooling of concrete constituents and/or concrete mix should be agreed amongst the producer and the user.

The ACI 301-16 specification (ACI 2016) for structural concrete sets minimum temperature immediately after placement that varies between 4.4 °C (40 °F) and 12.8 °C (55 °F), depending on ambient conditions to be encountered on site and size of structural element (least dimension), along with a permitted tolerance. A maximum temperature of the delivered concrete is also specified, as 35 °C (95 °F).

The recommendations of the Japanese Society for Civil Engineers for concrete (JSCE 2010a, b) point to a minimum placement temperature of 10 °C (that may be further reduced to 5 °C in mass concrete) and a maximum casting temperature of 35 °C.

In the scope of recommendations for concrete temperature upon placement in mass concrete, the following documents and guidelines can be highlighted as examples, which though cover a great range of areas on a worldwide scale:

- ACI 207.2R-07 (ACI 2007) provides recommendations for maximum temperature limits according to several factors, such as the properties of concrete and the type of restraint to deformation.
- ACI 301-16 (ACI 2016) sets maximum limits both for concrete temperature after placement and for temperature differentials between the centre and surface

of placement. Specifically, the maximum temperature should not exceed 158 °F (57 °C) and the temperature differential should not exceed 35 °F (19 °C).

- The Florida Department of Transportation Specifications (FDOT 2010) establish a maximum allowable temperature for concrete of 82 °C, while ensuring that the temperature differential between the concrete core and the exterior surface does not exceed 20 °C.
- The JSCE guidelines for Dam Concrete (JSCE 2010a) recommend minimum and maximum placing temperatures of 5 °C and 25 °C, respectively.
- The Japanese Concrete Institute Guidelines (JCI 2012) are based on stress computations to evaluate the risk of cracking, rather than providing specific recommendations on temperature placement/variation limits. It is nonetheless quite relevant to address the temperature-based criterion for formwork removal. In fact, it is recommended that formwork can only be removed when the temperature difference between the inside of concrete and the ambient air is less than approximately 15–20 °C.
- CIRIA C660 (Bamforth 2007) acknowledges the ‘rule of thumb’ of limiting temperature rises in concrete to 20 °C and explains the limitations of such approach. It provides an integrated methodology for cracking calculation based mainly on mix parameters, heat of hydration and exposure and restraint conditions.
- The Qatar Construction Specifications (QCS 2014) limit fresh concrete temperature at placing to a maximum of 21 °C to minimize thermal cracking, but allowing for a temperature up to 27 °C, subject to demonstrating a satisfactory performance of concrete, including mock-up and thermal calculations. Furthermore, a maximum differential temperature between the interior and the exterior of the mass concrete element is specified as 20 °C. Finally, the drop in concrete surface temperature during, and at the conclusion of the specified curing period, is not allowed to exceed 11 °C in any 24 h period.

As stated in the beginning of the current subsection, the decisions about requisites should be agreed amongst the contractor and the owner. It is indeed frequent to observe the existence of specific demands on behalf of owners of mass concrete structures (such as electricity companies that own massive structures such as dams or nuclear containments). These demands tend to vary in value and type of restriction amongst different countries and companies.

6.2 Pre-cooling of Mix Constituents and Cooling During Mixing

6.2.1 General Considerations

An important factor in temperature control of mass concrete is the initial temperature of the concrete mix. Due to the temperature increase during hydration, the difference between the temperature of the concrete element and the ambient temperature increases. That is why it is advised to cool the concrete mix before placement in order to reduce both the maximum temperature in the core and the thermal gradients (along space and time), and thus mitigate the risk of thermal cracking.

Pre-cooling can be achieved by one of two methods (or, as a combination of the two): pre-cooling the components of concrete before the actual mixing, or by cooling the freshly mixed concrete before placing. The choice of the method for pre-cooling depends on the local conditions, on the capacity, competence and experience of the concrete supplier and contractor, but also on other project-related parameters, such as acceptable levels for cracking, extent of repairs.

Even though the effectiveness of pre-cooling of concrete depends on the mix design (e.g. cement quantity, binder type and content, total aggregate volume, etc.) and on several other parameters that are related to further heat exchange with the environment, such as the thickness of the concrete element, the climatological conditions and the activation energy, some rules of thumb of expectable benefits of reducing the initial temperature can be established. It is normally considered that a reduction of 1 °C in the placing temperature decreases the peak concrete temperature by approximately 1 °C (Gajda and Vangeem 2002).

6.2.2 Prediction of Mix Temperature

In order to make decisions in regard to the most desirable measures to take for pre-cooling (or preheating) concrete before/while mixing, it is desirable to have a predictive tool that assists on the evaluation of the expectable temperature of the mix based on the temperatures of the constituents. Based on such predictive tools, contractors can take sustained decisions on the constituent that should be cooled/heated and the best method to apply for such purpose, always taking into account both technical and economic feasibilities.

Several predictive models exist to allow the estimation of the temperature of the concrete mix and they are mostly based on weighted averages of the temperature of the individual constituents, with the critical factor being the specific heat of each constituent (ACI 2010; JCI 2012; Bofang 2013).

By using the model suggested by ACI 305R-10 (ACI 2010), the initial temperature of the concrete mix can be then estimated as follows:

$$T = \frac{0.22 \cdot (T_a W_a + T_c W_c) + T_w W_w + T_a W_{wa}}{0.22 \cdot (W_a + W_c) + W_w + W_{wa}} \tag{6.1}$$

where W is mass (kg/m^3) and T is temperature (°C) of the mix components, denoting by subscripts a—aggregate, c—cement, w—water added to the mixture (excluding ice and absorbed water in aggregates) and wa—free and absorbed water by the aggregates. This expression underlies that the relation between the specific heat of cement and aggregate with respect to water can be assumed as 0.22. If the actual situation deviates from such a typical relationship, the equation needs to be revised. It is additionally remarked that, in the absence of solar shielding or cooling measures, the temperature of aggregates to be considered in the equation is normally higher than the average daily temperature. For example, Bofang (2013) recommends adding 5 °C to the temperature of the aggregates used in middle China over the summer period.

The above-described method for predicting the temperature of the mix does not take into account that, typically, the initial temperature of a concrete mix is slightly higher than the ambient temperature (1–2 °C in accordance with JCI 2012) because of the mechanical work made during the process of the concrete mix preparation. It is therefore advised that such a correction is made at the end of the calculation process. It should also be noted that Bofang (2013) recommends an additional term to the predictive equation that takes into account the power of the motor of the concrete mixer, the time of mixing and the effective volume of concrete in the mixer.

Based on the predictive equation, and the usual proportion of the components of concrete mixes, it is possible to infer that the most influential factors in the final temperature of the mix are:

- the aggregates, because of their large mass contribution within the mix;
- the liquid components of the mix (i.e. mixing water and other liquid additions, such as superplasticizers) because of the fact that their heat capacity is practically five times higher than that of solid components.

When the cooling of the concrete mix is performed by addition of chipped ice, the prediction of temperature of the mix needs to take into account the energy absorbed during the process of phase change that further enhances the capacity of ice to decrease concrete temperature (ACI 2010) and Eq. (6.1) is amended as follows:

$$T = \frac{0.22 \cdot (T_a W_a + T_c W_c) + T_w W_w + T_a W_{wa} - 79.6 \cdot W_i}{0.22 \cdot (W_a + W_c) + W_w + W_i + W_{wa}} \tag{6.2}$$

where W_i corresponds to the mass of added ice (kg/m^3). The above expression makes the simplifying assumption that ice is at its melting temperature. If more accurate predictions are desirable, ACI 305R-10 (ACI 2010) provides alternative predictive equations. In concern to alternative ways of estimating concrete mix temperatures, it is also worth mentioning the nomogram suggested by CIRIA Report 135 (Bamforth and Price 1995).

The introduction of liquid nitrogen for cooling concrete mixtures, which is further discussed in Sect. 6.2.7, is usually done after the mixing process, when concrete is already in a truck. The quantity of liquid nitrogen varies according to the proportion and the extent of concrete temperature reduction that is intended. Normally, the use of 10 kg of liquid per m^3 of concrete allows reducing its temperature by approximately 1 °C.

If phase-change materials (Bentz and Turpin 2007; Choi et al. 2014) are being added to the mix, their melting temperature is usually higher than mixing temperatures, so their latent heat does not need to be taken into account in computations of Eqs. (6.1) or (6.2). However, due account should be taken in regard to the mass of phase-change materials added, as well as their initial temperature and specific heat (outside the range of phase change).

6.2.3 *Cooling Mixing Water*

Most of the times, water is the easiest constituent of concrete to cool (Juenger et al. 2010; ACI 2005a, b). Moreover, its impact on the final temperature of the mix is quite efficient in view of the high heat capacity of water. Lowering water temperature by 2 ~ 2.2 °C usually allows reducing the mix temperature by approximately 0.5 °C. Nonetheless, as water usually represents a relatively small mass fraction in concrete, it is hard to lower the overall concrete temperature by more than 4.5 °C through the use of water cooling alone. The technology behind the industrial water coolers falls beyond the scope of this chapter. However, it can be mentioned that this technology is mostly based on combination of several other technologies (depending on the manufacturer), such as heat exchangers, compressors and evaporators. It is nonetheless relevant to remark that nowadays commercial products can assist the production of a few tens of cubic metres of concrete per day up to more than 3000 m^3 of concrete with one single piece of equipment. The cooling capacity of these systems allows them to cool water from the environmental temperature to values as low as 4 °C or even 1 °C. It is nonetheless remarked that, even when the refrigerating unit is installed within the concrete plant, thermal gains occurring between the outlet of the cooling system and the entrance of the concrete mixer are normally responsible for an increase of approximately 1 °C in water temperature.

6.2.4 *Introduction of Ice in the Mix*

As an alternative to the use of liquid water alone, it is possible to partially replace it by ice in the form of shaved, chipped or flaked ice. These forms of ice are more attractive than crushed ice because of their high slenderness and specific surface that facilitate the melting process within the concrete mixer. The partial substitution of liquid water with the recommended forms of ice offers additional cooling capacity, not only due to its lower temperature as compared to liquid water, but mainly because of the energy (enthalpy ~333 J/g) involved in the phase-change process from the solid state to the liquid state (endothermic). In effect, ice can substitute up to about 75% of the mix water to reduce the concrete temperature by up to 20 °C (Neville 2011; ACI 2005a, b). For reference, it is usually considered that each 7.5 kg of added ice (per m^3) allows reducing the temperature of fresh concrete by 1 °C. Taking into account that the normal range of ice added to concrete for cooling is within 35–100 kg/m^3, temperature reductions from ~5 to ~14 °C may be expected (ICOLD 1990; Vallarino 1998). It should, however, be taken into account that the times for mixing can increase due to the necessity of liquefying the ice. From a practical point of view, this can represent losses in the efficiency of the concrete plant by up to approximately 20%. Care should, however, be taken in ensuring that the mixing process effectively melts all the ice, which would otherwise cause problems in casting or even generate voids if large pieces of ice remain intact until setting. That is why the ice to be introduced in the mix should always have a high surface area (such as thin chips, flakes) to allow its quick melting upon contact with other concrete constituents within the mixer.

The manufacturers of cooling systems for water are normally also suppliers of systems to produce ice in several forms suitable for adding in concrete mixers. Currently existing ice plants vary in size and capacity, but they are able to produce daily outputs of as much as 150 tons of ice per unit. Specific information about ice replacement in the mixture, with particular focus on construction site requirements (e.g. machinery, energy) can be found in Oliveira (2015). It is further remarked that be aforementioned reference also provides practical information for other pre- and post-cooling techniques relevant to the present chapter.

6.2.5 Cooling Aggregates

Aggregates have a pronounced effect on the final temperature of the concrete mix because of the fact that they usually represent a large proportion (up to 70–85%) of the overall concrete mass. As a rule of thumb, in order to lower the temperature of the mix by ~0.5 °C, it is usually necessary to cool the aggregates by between 0.8 and 1.1 °C. Aggregates can be cooled using different methods, such as processing and stockpiling of aggregates during colder seasons (when applicable), shading aggregate stockpiles from the direct solar radiation, processing in chilled water during final classification, controlled misting or water sprinkling of coarse aggregate stockpiles, immersion cooling of coarser aggregates, chilled water spraying when on the belt conveyor, vacuum cooling/cold air circulation or use of liquid nitrogen (Bamforth 2007; ACI 2005a, b, 2010).

Some of the aforementioned methods, such as retaining aggregates in shadowed zones, and regularly sprinkling them with water to promote evaporative cooling, are fairly simple and cost efficient. The evaporation of water from the aggregates removes heat from them because of the enthalpy of the phase-change process. This process is especially effective when the environmental relative humidity is low.

The use of air circulation cooling systems is another alternative. However, it requires dedicated equipment. Even though this is a relatively economic system, and it does not require the consumption of resources such as water, it has a limited cooling capacity associated to the low heat capacity of air (Andriolo and Skwarczynski 1988).

It is also possible to submerge aggregates in silos, in which cool water is circulated. This technique allows very fast cooling of the aggregates due to the high heat capacity of water. However, the cost is relatively high, it involves significant water consumption and is, therefore, a less sustainable solution. Furthermore, after the cooling process, some drying is usually necessary to reduce the humidity of aggregates. This drying process can reduce the effectiveness of cooling due to exposure to the environmental temperature, particularly in fine aggregates. The design of silo-based cooling systems can be performed with the method proposed by ACI 207.2R-07 (ACI 2007). Significant applied information, based on extensive application of aggregate cooling methodologies of several types, can be found in the report of Andriolo and Skwarczynski (1988).

6.2.6 Cooling Other Constituents

The volumetric content of cement in concrete is relatively low, and the heat capacity of cement is also low when compared with that of water. Therefore, cooling cement has a low impact on the overall temperature of the mix. In fact, a reduction of 5 °C in the temperature of cement usually only allows a reduction of approximately 0.5 °C in the mix. For similar reasons, there is usually no use in cooling other binders (e.g. fly ash, slag), or minor constituents such as admixtures.

6.2.7 Cooling by Injection of Liquid Nitrogen

One of the methods of pre-cooling concrete before placement consists of cooling either the fresh concrete or its constituents with liquid nitrogen (LN), also referred to as cryogenic cooling of concrete (Beaver 2004; Gajda and Vangeem 2002). Liquid nitrogen is a cryogenic fluid with boiling temperature of −196 °C obtained industrially from cryogenic fractional distillation of liquefied air or by liquefying the nitrogen obtained from separation of gaseous air. The low boiling temperature together with its non-reactivity makes LN a commonly used refrigerating agent in industrial and laboratory applications. Using LN for cooling concrete has been proposed as early as in the 1970s (Koudelka and Kelly 1971). Nevertheless, the widespread application of the method has been initially limited, mainly due to safety concerns regarding operating the cryogenic gas at the construction sites and the high costs. Since recently, specialized companies offer LN cooling technologies aimed at pre-cooling concrete directly at the construction site, allowing for reduction of costs and relieving safety-related issues, thus increasing the disseminated use of LN (Beaver 2004). A typical example of application of LN cooling in site can be seen in Fig. 6.1.

In fact, LN cooling may be in some regions cheaper than chilled water or ice cooling (Beaver 2004; Luff and Bhasin 1983). Cooling by LN is also recognized by ACI 305R-10 (ACI 2010). In practice, cooling by means of LN may be realized in one of the following ways (or as combination of them): cooling of mixing water

Fig. 6.1 Photograph of typical in-site application of LN cooling in concrete truck (courtesy of O. Kunc, TBG Metrostav)

before mixing, cooling of dry cement in a truck or a silo (Luff and Bhasin 1983), cooling aggregates (Kurita et al. 1990) or cooling the mixed concrete in a central mixer or in a truck drum (Beaver 2004). The latter method seems practically most feasible for adjusting appropriate placing temperature and is obtained by placing a lance into the mixer/drum and spraying the LN directly on concrete surface for a required time while mixing. Relatively short cooling times are required, e.g. as reported by Beaver (2004): 8 min LN spraying was needed to cool down 6 m^3 of concrete from initial 35 °C–24 °C and reach the placing temperature after transportation equal to 26 °C (15 min from batching). The quantity of LN varies according to the mixture proportions and the targeted temperature reduction. Normally, 10–12 kg of LN per m^3 of concrete allows reducing its temperature by 1 °C (Bamforth and Price 1995). Regarding the injection of LN into mixing water, it has been suggested (ACI 2005b) that, in most cases, a placing temperature of less than 18 °C can be normally achieved.

It has been reported by Juenger et al. (2010) that cooling can take place even up to 1 h from the end of mixing which allows applying it directly before placement (e.g. in the mixing drum of a concrete truck) and compensate for the prolonged transportation time.

It is important that the LN is not sprayed on the equipment (mixer walls) since thermal shock can cause cracks as cooled metal loses its ductility (Juenger et al. 2010).

Even though LN is an inert gas, and therefore its influence per se on concrete properties should not be an issue, the influence of cryogenic cooling should be considered. This may in particular regard performance of admixtures if local temperature of concrete during cooling is lower than specified by the manufacturer. Further, too intense cooling may lead to partial freezing of the mixture and cause its inhomogeneity or problems with pumping, compaction, etc. A comprehensive study on the effects of LN cooling in laboratory conditions and at the site on the properties of concrete, both at early age and hardened, can be found in Juenger et al. (2010). In the study, it has been shown that LN cooling shows no significant negative influence on the properties and performance of concrete. In particular, no negative influence on hydration and microstructure evolution, workability, setting time, yield (volume loss due to cooling), strength, chloride penetration. Some reduction of air content for LN-cooled concretes was, however, a case.

6.3 Transport and Placement

6.3.1 Temperature Issues During Transport

The transport of concrete from the mixer to the placement point can sometimes be a relatively lengthy process in terms of duration. This is particularly the case when the concrete plant is not directly located in the same place as the construction site itself. In such cases, the transport is usually made by trucks. In cases where the ambient temperatures are high, and particularly during the day in sunny conditions, concrete temperatures are bound to rise. Under such conditions, it is then recommended to minimize transport distances and to use light-coloured vehicles, or place reflective aluminium insulation in the concrete drums (low absorptivity that reduces the effects of solar radiation), or favour night time for transport and casting (when feasible). To avoid rejection of batches, suitable on-site measures may be taken, such as the provision for a liquid nitrogen injection system, as mentioned in Sect. 6.2.7.

According to ICOLD (1990), it is possible to obtain an estimate of the temperature increase per hour (ΔT), based on a formula that depends on the ambient (T_a), the initial temperature of concrete (T) and a coefficient K that varies between 0.1 and 0.2 (empirical nature):

$$\Delta T = K \cdot (T - T_a) \tag{6.3}$$

An alternative more complex prediction model for concrete temperature has been proposed by Bofang (2013), which specifically takes into account the solar radiation, the conductance of the transporting vessel, and a variable number of empiric coefficients related to episodes of loading/unloading and change of transporter and duration of the transport process.

6.3.2 Temperature Issues During Placement

There are two fundamental temperature issues that can be brought about when concrete placement is under discussion: (i) the thermal exchanges that occur when concrete is moved from the transporting container (e.g. truck drum, blondin bucket) or the concrete plant itself to the placement spot; (ii) the thermal exchanges that occur during the placement itself, which tends to span through several hours in mass concrete castings.

Regarding issue (i), one has to take into account the possible means of moving concrete from the transporting container or the concrete plant itself to the placement spot. Indeed, several techniques exist, such as pumped concrete, transfer belts/ conveyors, buckets and hoppers, buggies, (drop) chutes (ACI 2000). Regardless of the adopted moving technique, the basic intent is normally to keep concrete within the same temperature as it was inside the transporting container. Therefore, it is advisable to minimize distances, speed up the process (e.g. by preferring bucket transport to belt transport) and ensure thermal insulation and solar shielding throughout the process (e.g. insulation material around the transportation belt, which could also include active cooling measures ACI 2005a, b). In some cases, the pipes through which concrete is pumped may be surrounded by ice, as to minimize heating effects, or even ensure some degree of cooling during transport. Transport of concrete in refrigerated boxes has also been reported (Schrader and Swiger 1988; Schleiss 2011).

Of course, when concrete heating is to be avoided, it is advised to commence concreting at night, especially in summer, both due to the lowest diurnal temperature and solar action (Riding et al. 2009; Klemczak and Knoppik-Wróbel 2012; Witakowski 2001; JCI 2012).

Another important issue raised above (ii) pertains to the fact that casting mass concrete is usually a relatively lengthy process, mostly due to the relevant thickness of the concrete layers that may easily span from 1 to 3 m. Therefore, the casting of a given layer is normally done in sequential sub-layers of approximately 15–30 cm height that are cumulatively placed and vibrated. During this process, the top surface of each sub-layer is normally relatively large and subject to thermal exchanges with the surrounding environment before the placement of the subsequent layer commences. These heat exchanges can be minimized by: (a) prioritizing night castings, thus avoiding solar energy intakes and the higher temperatures during daytime; (b) using solar shielding panels when diurnal times of casting are involved; (c) accelerating construction by increasing casting rates and multiple casting points (by deploying additional workforce and equipment). In regard to the potential prediction of temperature rises of concrete during this placement process, Bofang (2013) proposes a predictive equation, with a set of empirical coefficients, that depend on the air temperature, the solar radiation, as well as the time to spread the layer.

6.4 Surface Measures for Temperature Control

After placement, the boundaries between concrete surfaces and the surrounding environment tend to be regularly cooler than the interior regions of mass concrete elements, in which near-adiabatic conditions are normally endured in mass concrete. Therefore, when the temperature of near-surface regions is significantly lower than that of the inner core, the thermal gradients induce differential volumetric changes between surface and core that can generate thermal stresses. These surface-induced thermal stresses are naturally more significant in cold weather conditions that maximize the thermal gradients. The typical approach to this problem is to provide surface insulation to concrete, which limits thermal exchanges and thus keeps the surface temperatures higher (Bofang 2013; ACI 2005a, b; ICOLD 1990). As a consequence of the insulation, the peak temperature of concrete in its inner core is retained for a longer period, and the duration of the hydration heat dissipation is prolonged. As the insulation measures are preferably taken in cold weather conditions, the increase in peak temperature and the extended cooling period are not usually considered problematic.

The insulation issue is also relevant in formed surfaces, which need to ensure adequate thermal resistance as to hinder excessive thermal fluxes. Furthermore, surface concrete may be susceptible to thermal shocks upon formwork removal (e.g. at ordinary stripping ages, that often vary between 1 and 3 days of age). Such thermal shocks may also be responsible for potential cracking and thus the application of surface insulation immediately after formwork removal, or, alternatively, a delay in formwork removal is advisable (Huo and Wong 2006; Lawrence et al. 2014; Klemczak and Knoppik-Wróbel 2011). The formwork removal issue can also bring about added thermal shock hazard associated to the intense evaporation that occurs from the wet concrete surface to the surrounding environment. In hot and dry climates, this evaporation induces significant rapid cooling of concrete (several °C) and may provoke relevant stresses, thus contributing to cracking. This phenomenon has been documented as the shock of evaporative cooling (Kovler 1995) and should be carefully taken into account in hot and dry climates through adequate curing measures immediately after formwork removal.

For insulation, in most cases concrete insulating blankets are used; however, any insulating material is usually acceptable; cracking risk decreases with lowering the value of thermal conductivity of the covering material (Liu et al. 2014a, b). The important issue is that insulation should be kept in place until the hottest portion of concrete cools to the ambient temperature (Klemczak and Knoppik-Wróbel 2011). The effectiveness of the insulation on the reduction of the temperature difference and thermal stresses depends on the thickness of the insulation layer but also on the size of the insulated element: it was observed that the effectiveness of the increase of the insulation thickness is greater in thicker elements (Lawrence et al. 2014). The same research team (Tu et al. 2014) has further performed a numerical sensitivity analysis that led them to the proposal of recommendable insulation thicknesses (using expanded polysterene products) for temperature control in concrete footings, based on the ratio between volume and surface area of the concrete element.

An important point to take into account when selecting the system (material, thickness, etc.) for providing adequate thermal protection is its thermal resistance, R. The R-value is normally addressed in building physics to express the thermal resistance of a given element to heat fluxes. It is calculated by dividing the thickness of the material (measured perpendicularly to the heat flux) [m] by the thermal conductivity [W/(mK)]. According to (ACI 2005a, b), a minimum R-value of 0.70 m^2 K/W has been found to be adequate for surface thermal insulation in the context of mass concrete in moderate climate countries, whereas in severe climates, a minimum R-value of 1.76 m^2 K/W is recommended. These values are clearly not achievable by typical plywood formwork solutions: for example, a 21 mm thick plywood board (with thermal conductivity 0.15 W/mK) has a R-value of only 0.14 m^2 K/W. Therefore, even formed surfaces usually need to deploy specialized insulation materials such as (Bofang 2013): foamed polystyrene boards, namely expanded polystyrene (EPS) and extruded polystyrene (XPS) with typical conductivity ranging 0.03–0.04 W/mK; foamed polythene wadded quilt; polyurethane foamed coating ($k \sim 0.02$ W/mK). Formwork removal should be done carefully, preferably during the hottest time of the day to reduce the thermal shock. If inner temperatures of concrete are still elevated, the formerly formed surface should be immediately insulated with an adequate system (usually boards or blankets) (ACI 2005a, b).

Additional challenges are placed in the case of horizontal surfaces of fresh concrete that are not formed, and that are supposed to support the upcoming stages of construction. In these cases, applying insulation is more challenging and typical approaches involve the use of straw bags or blankets (mineral/glass wool blankets or batting in thicknesses up to 50 $\sim$ 100 mm, or roll-on rubber-type materials) (ACI 2005a, b; Bofang 2013). These alternatives demand more than one layer of bags/blankets to be applied in order to achieve the desirable insulation. This multiple layer approach is considered by ACI (2005a, b) as an interesting feature in the sense that it allows mismatching the joints between adjacent bags/blankets in consecutive layers and also allows a progressive removal of the bags/blankets, thus minimizing the thermal shock of a sudden/instant removal. The application of these insulations should be made immediately after walking over the fresh concrete is possible and should allow easy removal/re-collocation for the preparative works of the next lift. The lightweight character of typical insulation materials can often induce the necessity of measures to avoid uplift by wind, such as anchors (ICOLD 1990). As an alternative to bags/blankets, sand can be used for thermal insulation. However, this method demands more workmanship for removal, even if a geotextile membrane is used below the soil. It is therefore usually only recommended when a relatively long pause in the construction is foreseen (ACI 2005a, b). Other less conventional techniques of ensuring adequate temperature at the surface of mass concrete can involve hot fog spraying or even actively heated insulation materials (ICOLD 1990; Bofang 2013).

The protection of the insulation system from solar radiation can be a relevant issue. In fact, the point of the insulation is avoiding strong heat dissipation, and not necessarily feeding concrete with additional heat. Therefore, solar shielding through reflective or light-coloured materials might be desirable in critical cases (ACI 2005a, b).

6.5 Post-cooling of Mass Concrete

6.5.1 Strategic Background of Post-cooling

Post-cooling of concrete with embedded pipes has been applied since the 1930s (ACI 2005a, b). The point is to control the internal temperature of concrete within specified limits by actively circulating water (or another cooling fluid) through the embedded pipes, as to mitigate the risk of thermal cracking. It is usually oriented towards the reduction of the peak temperatures of concrete during the hydration period, thus minimizing the volumetric variations associated to the corresponding temperature variations. The design of post-cooling systems comprises the optimization of pipework properties (geometrical layout, heat transfer, fluid flow rate, inflow/outflow temperatures) to achieve the desired peak temperature reduction with the minimum possible energy consumption. Examples of structures and their corresponding typical piping layouts can be seen in Fig. 6.2. The output of this design can then be directly provided to suppliers for sizing of cooling pipe systems and procurement of suitable generators (Sfikas et al. 2016).

The technique is quite effective, but it has relevant costs of effective design, material procurement, installation and operation. For that reason, its area of application is generally limited to bigger structures, such as arch dams that require internal cooling before joint filling/sealing (ICOLD 1990); the cooling system can be activated during the early days/weeks after casting, thus allowing thermal control of concrete. Other applications of post-cooling include, but are not limited to, production of concrete segments for immersed tunnels, retaining walls and slabs (Baber et al. 1998; Kim et al. 2001; Lunniss and Baber 2013), which are nowadays commonly analysed and designed using dedicated finite-element analysis (FEA) software. An extended review of the current state-of-the-art for the use of

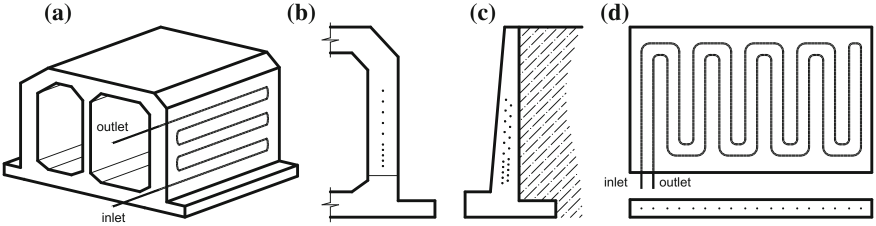


Fig. 6.2 Examples of embedded concrete pipe systems layouts for **a** tunnel segment, **b** gallery wall (linear set-up), **c** retaining wall (staggered set-up) and **d** slab. (Sfikas et al. 2016)

FEA for thermal dynamics and a briefing paper have been recently published by Sfikas et al. (2016, 2017).

6.5.2 Post-cooling with Water Circulation

The control capacity that the embedded pipes permit can provide interesting alternative insights into construction phasing that would be unthinkable with pre-cooling techniques alone. A good example of such situation is the application of embedded pipes in the walls of a reservoir in Germany, with 1.2 m thick walls and 12 m tall (Bamforth 2007). Through judicious placement and activation of the embedded pipes, it was possible to cast the entire wall simultaneously with its foundation slab (2 m × 27.4 m × 28.2 m), in a total of 1100 m^3 of concrete applied within 32 h.

Most applications reported in the literature for post-cooling with water use 1″ (2.54 cm) diameter steel pipes with wall thickness of 1.5 mm. According to ACI 207.4R-05 (ACI 2005a, b), the alternative of using aluminium pipes is only recommendable for cooling applications with durations of less than 3 months, as these may tend to degrade due to reaction with the alkalis from cement. It is further possible to apply PVC, polyethylene or other plastic-based pipes (Zhu 1999), but it is recommended to take special care in respect to the mechanical strength of the piping system to apply, in order to avoid unwanted damages. Apart from being cheaper than steel pipes, the plastic pipes have lower thermal conductivity, thus minimizing the heat absorption of the flowing fluid along the embedded path of the pipe. This advantage allows to apply longer piping systems (i.e. less inlets/outlets), but it also carries the drawback of limiting the cooling capacity in comparative terms to that of steel pipes. The plastic-based pipes usually have the advantage of being flexible thus allowing a much easier and fast placement than that of steel pipes (that require ‘knees’, ‘turns’, etc.) but may be more vulnerable to unintended movements during casting.

In mass concrete structures, where layered casting is made, cooling pipes are usually placed on the top level of each casting phase, corresponding to the bottom plane of the subsequent casting phase. This option is mostly related to the ease of application of the pipes, and the potential added difficulties that would be faced in holding the pipes at an intermediate level, as mass concrete structures do not usually have enough inner reinforcement for such kind of support (thus demanding for dedicated supports). Typical layouts of pipes can be seen in Fig. 6.3. The efficiency is related to the layout of the pipes and number of individual pipe networks. In effect, several independent piping systems, both in terms of their layout in plan and their distribution over the depth of the element, can be used within the body of mass concrete.

The horizontal spacing between adjacent pipes varies according to the thermal design. However, according to CIRIA C660 (Bamforth 2007), spacings of 1.0 m are usual in large castings of low-heat cement, as opposed to smaller spacings of

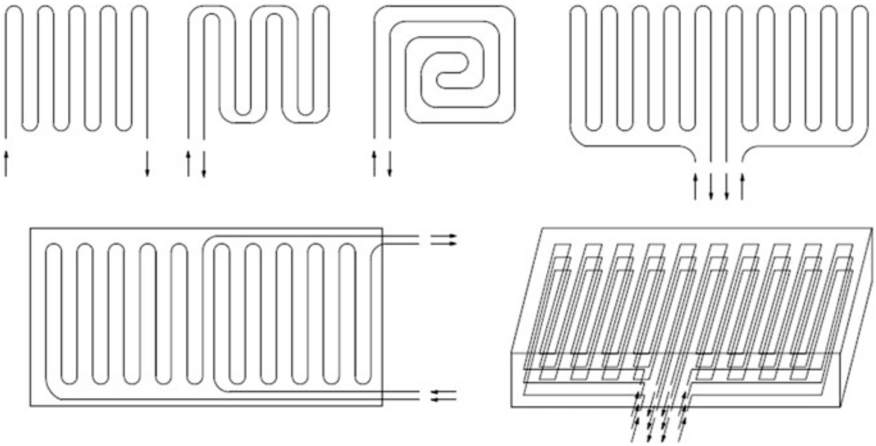


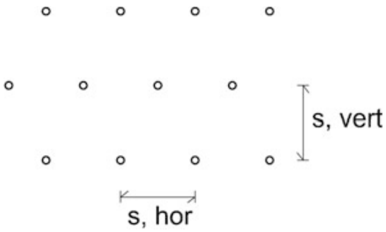
Fig. 6.3 Examples of cooling pipe layout

approximately 0.5 m when concrete with high quantities of rich cement is used. The reason for these relatively small spacings is related to the low thermal diffusivity of concrete, which makes the influence zone of each pipe to be small in the context of the early ages of concrete. In fact, if the placement of pipes were solely related to the cooling of a dam for joint sealing purposes, the spacing could easily be enlarged to 2–3 m as the cooling can be much slower in such cases (there is no competition with the pace of hydration heat development).

Under optimum conditions, the horizontal and vertical spacing of pipes should be identical, with quincunx arrangement as shown in Fig. 6.4. This is however not always possible due to restraints to the height of lifts.

The total embedded length of a water cooling pipe should avoid significant heating of the circulating water. In spite of that, pipes as long as 180–350 m can be applied without relevant heating problems (ACI 2005a, b). The flow rate of water is usually fixed amongst 15–17 L/min. The water that circulates in the pipes is normally originated in a natural source such as a river (quite easy in the particular case of dam construction), with adequate filtering measures as to avoid clogging of the pumping/piping system. When river water is used, the natural water temperature is normally adequate for the purposes of concrete cooling (Bamforth 2007). If water

Fig. 6.4 Quincunx arrangement of adjacent cooling pipes for optimized performance



cooling is necessary, it is required to ensure a water chilling system with enough capacity for the flow rates of the several pipes that might need to be active simultaneously. Even though it is known that the capacity of cooling may be increased by increasing pipe diameter, using higher water velocity and diminishing the temperature of water, it is necessary to take into account that excessive coolness can induce thermal shock to the concrete surrounding the cooling pipes and induce thermal cracking around the pipes. The recommendations of JCI (2012) point to a maximum admissible difference of 20 °C between the temperature of the circulating water and its surrounding concrete.

The operation of cooling pipe systems demands for a watertightness test to be made before casting, with the corresponding repairs being made before pouring operations. The pressure inside the pipes should be monitored as to ensure that the intended flow rates are met during operation. The measurement of water temperature at the inlets and outlets, as well as several points of the cooled concrete is desirable for assessment of the operational conformity. Particularly for the cases in which the cooling water suffers relevant heating along its embedded path, it is recommendable to invert the direction of the circulation flow according to intervals around 12–24 h, as to avoid inducing significant thermal imbalances in concrete (JCI 2012).

The activation of water circulation can be made simultaneously with the casting operations (Korol 1968). The adequate fixation of the pipes together with the relatively small internal flow rate can ensure that no damaging vibrations are transmitted to the fresh concrete. However, as the heat generation of concrete is quite low before the setting point, it is possible to await for such threshold in order to activate the circulation of water. The water circulation should be kept at least until the peak temperature of concrete is reached. After the core concrete reaches thermal equilibrium with either the outer environment or the water in the pipes (similar temperature), there is no point in continuing the water circulation. However, care should be taken of avoiding that the internal cooling causes excessive rates of temperature drop in concrete, which could be potential causes for thermal cracking. According to recommendations of ICOLD (1990), during the first 3–4 weeks after placement, the cooling rate of concrete should not exceed 0.5 °C/day as to prevent thermal cracking. In case the water circulation is stopped when the peak temperature is reached in concrete, it may be re-activated if the peak temperature is reached again (ACI 2005a, b; Korol 1968).

Even though there are simplified design methods for water pipe cooling systems, they are mostly targeted to the cooling period that precedes the sealing of joints in dams. The simplified solutions that have been proposed for the context of concrete at early ages (Yang et al. 2012) still have very limited applicability due to their subjacent simplifications. The most precise way to design and optimize post-cooling systems is definitely the explicit spatial simulation of temperature development, which is most frequently achieved through the finite-element method. The numerical simulation tools that are nowadays available to the practising community allow for the explicit simulation of thermal fluxes occurring between concrete and the embedded pipes, which inclusively allow to calculate the increases in water temperature along the cooling pipe.

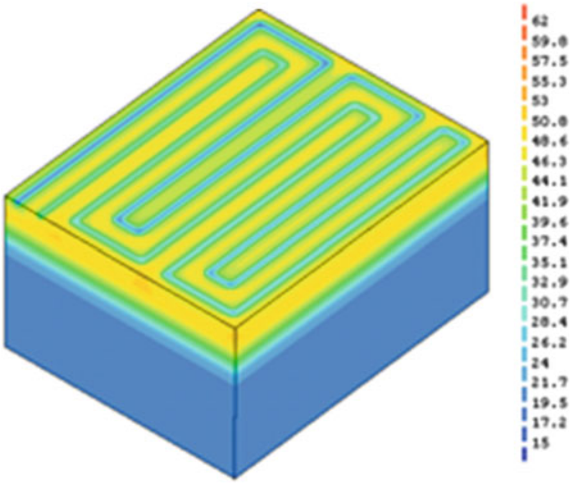


Fig. 6.5 Temperature map of a mass concrete element at the age of 30 h after casting: cutaway view through the place of the cooling pipes [Units: °C]—study made at the University of Minho (unpublished)

An example of such computation capacity is shown in Fig. 6.5, where a cutaway view of the temperature map of a mass concrete element through the plane of the cooling pipes is shown. The effect of the cooling pipes on concrete temperature is easily identifiable in the figure, as well as the inlet and the outlet of the cooling pipes through observation of the increasing temperature along the pipe.

A typical design for an immersed tunnel gallery wall design is shown in Fig. 6.6. It is evident that the incorporation of a cooling pipe system in the wall, with carefully designed geometrical and operation parameters using dedicated FEA software, can mitigate the risk of cracking by reducing the developed out-of-plane stresses over the curing period below the design tensile strength (ultimate tensile strength, usually factored by 50–70%). Another recent application of cooling pipes was reported by Du (2016).

The use of cooling pipes is frequently adopted as to allow thicker casting lifts and therefore accelerate construction cycles. An example of the advantages that can be obtained can be supported in a recent study conducted for a contractor on behalf of the University of Minho in Portugal. The study evaluated the possibility of increasing the thickness of casting lifts of a massive concrete element (spillway wall) from the originally planned value of 1.5 m, to a larger value of 2.4 m without increasing the associated cracking risk. The study allowed concluding that it was possible to increase the thickness of the lift by applying a single layer of high-density polyethylene (HDPE) pipes located at mid-height of the lift (1″ diameter and flow rate of 0.5 m/s), fed directly with river water and horizontally spaced by approximately 0.8 m. The computed temperature maps for the instant of peak temperature are shown in Fig. 6.7 for both the reference case (1.5 m thick lift without cooling measures) and the alternative scenario of 2.4 m lift thickness with active cooling. It can be confirmed that both the peak temperatures and the spatial thermal gradients in concrete are quite similar, thus confirming feasibility of the proposed alternative with cooling.

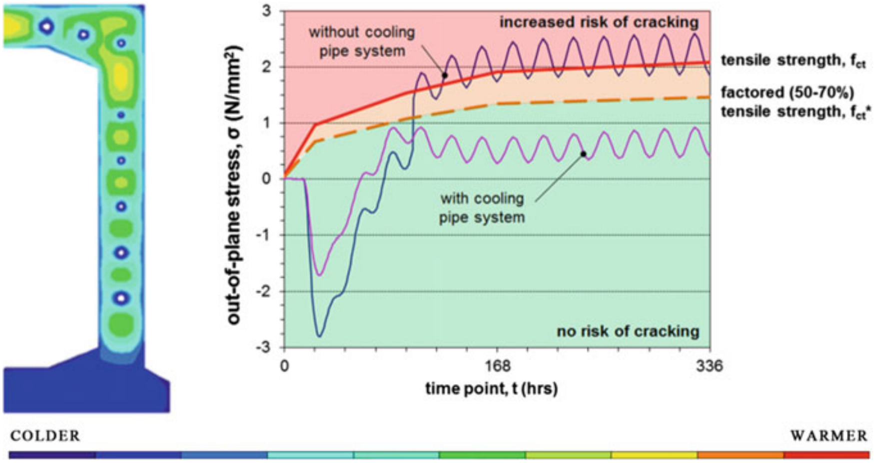
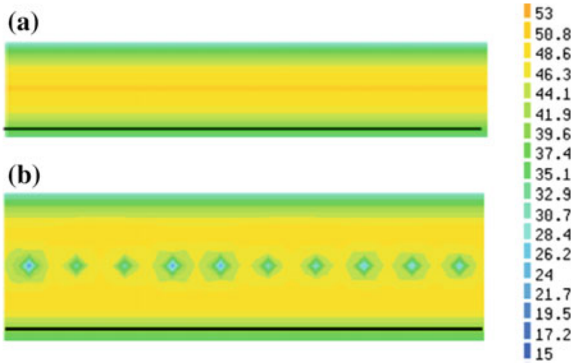


Fig. 6.6 Typical linear arrangement of cooling pipes in immersed tunnel gallery wall and assessment of the risk of cracking due to developed out-of-plane stresses (Sfikas et al. 2016)

Fig. 6.7 Calculated temperatures for the instant of peak temperature (t = 24 h): **a** 1.5 m lift thickness without cooling pipes; 2.4 m lift thickness with cooling pipes [Units: °C]—study made at the University of Minho (unpublished)



Amongst water circulation techniques, it is relevant to pinpoint the possibility of increasing the cooling effectiveness by using a water suspension of ‘phase-change materials’ (PCM) circulating in the cooling pipes. The principle is relatively simple, as the PCMs absorb and release heat upon passing through their phase-change temperature, which is selected to be somewhat above the casting/environmental temperature. If cooled PCMs (solid) are circulated within cooling pipes, the heat of the surrounding concrete tends to melt them and induces a significant heat absorption by the PCM because of the phase change, thus enhancing the heat exchange. The PCM should then be cooled down outside concrete and the cycle can be repeated. Such technique has been applied by Qian et al. (2015), who used a PCM with phase-change range 16–24 °C, and compared the performance of this method with the classic water circulation technique in two prototypes. The cooling with PCMs has shown a slightly better capacity of reducing the peak temperature in concrete. Even though the benefits were not outstandingly good, the technique has a good potential because the PCMs can be re-used in several cycles of circulation.

Qian et al. (2015) have also attempted the use of closed cylindrical cavities within concrete (without any kind of circulation), containing the PCM for temperature control in mass concrete. However, this approach has two major downsides: (i) the PCM only operates a single time upon its phase change; (ii) the quantity of PCM necessary to induce relevant effects on temperature ended up being very large and this impracticable.

6.5.3 Post-cooling with Air Circulation

The use of air as cooling fluid for hardening concrete has been initially proposed by Hedlund and Groth (1998). In such initial proposal, the authors proved the viability of the system with both laboratory and in situ applications. The use of air instead of water can be quite interesting in several applications because of the ease of application and lower cost. The piping itself can be quite cheap due to the possibility of using prestressing ducts, which have the interesting characteristic of having a well-proven long-term behaviour when embedded into concrete (both in terms of mechanical strength and tightness, as well as in terms of compatibility and durability). However, as air is a fluid with a much lower specific heat capacity as compared to water, it is necessary to use much higher circulation speeds (around 8 m/s for example) and larger diameter piping (8 cm diameter or more) to ensure similar cooling capacity. Based on the mentioned limitations, this type of cooling fluid becomes quite attractive for extremely massive constructions, such as dams. However, in the particular case of thick laminar concrete elements such as foundation slabs, tunnel or spillway walls, this type of cooling fluid can reveal an interesting attractiveness. An example of a successful application in a foundation slab in Qatar was reported by Ishikawa et al. (2007).

More recently, a more comprehensive application has been applied in Portugal, in the scope of the dam spillway (Azenha et al. 2014). The central wall of the spillway had a maximum thickness of approximately 2.7 m and longitudinal length of $\sim$27.5 m. One of the lifts of this wall required internal heating to ensure the safety to thermal cracking of its 2.5 m height. The option for a air-based post-cooling system was based on the low cost of the system and the easy availability of the necessary material: (i) prestressing ducts used as cooling pipes; (ii) industrial fans that had been used in the construction of a nearby tunnel. The cooling system consisted of six ducts with 90 mm diameter spaced by 80 cm from each other (at the thickest section of the wall)—see layout in Fig. 6.8.

The air intake was made through the downstream extremity of the wall, and the air outlet was placed in the upper surface of concrete, in the vicinity of the upstream extremity. The industrial fan had a diameter of 60 cm, and a ventilation capacity of 1200 m^3/h. In order to avoid unwanted vibrations in the fresh concrete, the ventilation system was only activated 14 h after the beginning of casting operations.

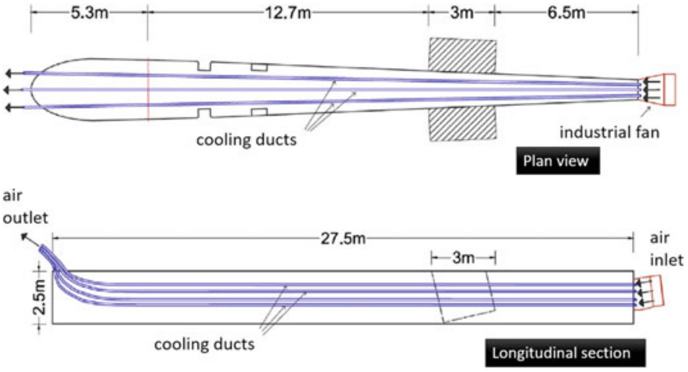


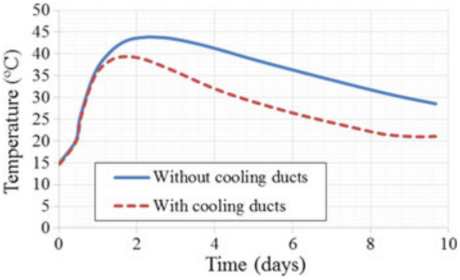
Fig. 6.8 Layout of the cooling ducts in the spillway wall. Adapted from Azenha et al. (2014)

The ventilation was turned off at the age of 8.6 days, in correspondence to the thermal equilibrium between core concrete and the surrounding environment. Before the placement of concrete in the subsequent casting phase, the prestressing ducts were filled with mortar with the same type of procedures that are normally applied to post-tensioning cables.

Through numerical simulation based on the finite-element method (duly validated by comparison with in situ temperature measurements), it was possible to confirm that the peak temperature of concrete at its hottest point was roughly 5 °C lower than that which would have occurred if pipe cooling had not been applied. Such difference can be appreciated along time in the comparison of both scenarios shown in Fig. 6.9. Additionally, Fig. 6.10 shows the same comparison in the shape of a temperature map plotted for the instant of peak temperature for both studied scenarios.

The field application that has just been reported allowed to confirm the viability of the air cooling technique, but it also allowed identifying another drawback in addition to the ones presented before: there is a significant heat gain in air along the cooling duct. Therefore, for optimized cooling efficiency, it is recommendable that the embedded path of each independent pipe should not be larger than approximately 10 m. In spite of the reported limitations, the low cost and ease of

Fig. 6.9 Temperature evolution in the hottest point of the wall for the case in which the cooling pipes were used, and for the hypothetical case of absence of such pipes (simulation) Adapted from Azenha et al. (2014)



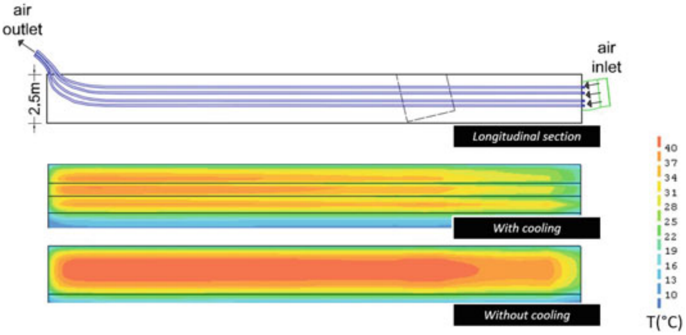


Fig. 6.10 Temperature maps for the longitudinal symmetry plane of the 2.5 tall casting phase for the two scenarios under study: with cooling pipes; without cooling pipes. [Units: °C]

application inherent to this cooling technique based on ventilated prestressing ducts make this an attractive solution in several situations for which the costs associated to water-based systems are not bearable.

6.6 Construction Phasing

Regardless of the temperature control measures taken in the production, transport, and placement, or even through the use of post-cooling, the thermal cracking risk is broadly affected by the strategies adopted for construction, especially in regard to the height of lifts and the waiting interval (dormant period) between consecutive/ adjacent casting blocks. Indeed, these two factors have a major impact on temperature development of mass concrete structures. However, unlike previous factors that have been analysed in an almost-individual manner throughout the document, in the sense that their impact could be assessed in a relatively easy manner, the only way of truly understanding the consequences of construction phasing on cracking risk (lift height and casting frequency) before the actual construction itself, is to conduct numerical simulations of temperature and stress fields. These simulation should aim at evaluating the merits and comparing the risks of each possible alternative scenario. In the end, it is always a matter of establishing a trade-off between the desirable tall lift heights combined with small waiting periods for casting, and the undesirable elevated cracking risk, when such bold construction measures are taken. Naturally, the simulation of construction scenarios demands that all variables are taken into account, including the relevant effects of initial concrete temperature, and the potential use of post-cooling measures. The number of potentially involved variables in a process of optimization of mass concrete construction could prove to be next-to-infinite, and therefore practitioners normally tend to rely on their intuition to set up a small group of potential scenarios of construction (as small as 2, 3 or 4). The subject of optimization of construction phasing in mass concrete has been tackled very few times in the literature. The most extensive work done on the subject was made by Fairbairn et al. (2004) through the application of genetic algorithms for the optimization of mass concrete construction. They have set up a group of variables for optimization aiming of minimization of costs, while keeping adequate cracking risk for construction: cost of the raw material and the construction costs associated to placing, cooling, formwork, lift height and time intervals between consecutive lifts. They have used a genetic algorithm to optimize global costs and applied their proposed framework to the 2D simulation of the cross-sectional thermo-mechanical behaviour of a small concrete gravity dam, reaching a set of recommended construction parameters, including the lift height and waiting periods. The example cannot be directly extrapolated for other situations worldwide because of its inherent specificities (e.g. types of concrete, climatic conditions). In spite of the encouraging results, this practice was not found in any work of the literature (practical or research) meanwhile.

In spite of the absence of works specifically targeted to the optimization of construction phasing of mass concrete structures, it is relevant to highlight the recent works of Klemczak and Knoppik-Wróbel (2015), Knoppik-Wróbel (2015) and Hónorio et al. (2016), who present insights into the relative relevance of construction parameters in the scope of mass concrete analyses through sensitivity analyses through numerical simulations.

Acknowledgements The kind contribution of the construction company SOMAGUE in sharing their experience in concert with temperature control in concrete is gratefully acknowledged. The sharing of information on behalf of the colleagues José Conceição and Shingo Asamoto is also acknowledged. This work was partially supported by: project POCI-01-0145-FEDER-007633 (ISISE), funded by FEDER funds through COMPETE2020—Programa Operacional Competitividade e Internacionalização (POCI), and by Portuguese funds through FCT—Fundação para a Ciência e a Tecnologia. FCT and FEDER (COMPETE2020) are also acknowledged for the funding of the research project IntegraCrete PTDC/ECM-EST/1056/2014 (POCI-01-0145-FEDER-016841).

References

American Concrete Institute ACI. (2005a). 207.4R-05 Cooling and insulating systems for mass concrete. ACI Committee 207. ISBN: 9780870311918.

American Concrete Institute ACI. (2005b). 207.1R-05 Guide to mass concrete. ACI Committee 207. ISBN: 9780870312014.

American Concrete Institute ACI. (2007). 207.2R-07 Report on thermal and volume change effects on cracking of mass concrete. ACI Committee 207. ISBN: 9780870312588.

American Concrete Institute ACI. (2000). 304R-00: Guide for Measuring, Mixing, Transporting, and Placing Concrete (Reapproved 2009), ACI Committee 304. ISBN: 9780870313080.

American Concrete Institute ACI. (2016). 301–16 Specifications for Structural Concrete. ACI Committee 301. ISBN: 9781942727866.

American Concrete Institute ACI. (2010). 305R-10 Guide to hot weather concreting. ACI Committee 305. ISBN: 9780870313967.

American Concrete Institute ACI. (2011). 308.1–11 Specification for Curing Concrete. ACI Committee 308. ISBN: 9780870314391.

American Concrete Institute ACI. (2014). 347R-14 Guide to Formwork for Concrete. ACI Committee 347. ISBN: 9780870319105.

Andriolo, F. M., & Skwarczynski, T. M. (1988). *Concreto pré-refrigerado no Brasil: Uma evolução com mais de 20 anos. (Pre-cooled concrete in Brazil: An evolution of more than 20 years) Grapho*, São Paulo, Brazil.

Azenha, M., Lameiras, R. M., Sousa, C., & Barros, J. (2014). Application of air cooled pipes for reduction of early age cracking risk in a massive RC wall. *Engineering Structures*, *62–63*, 148–163.

Baber, J., Salet, T. A. M., & Lundberg, J. K. (1998). Øresund tunnel control of early age cracking. In *Proceedings of the IABSE Stockholm Colloquium: Tunnel Structures*, Stockholm, Sweden (IABSE Report 78) (pp. 175–180). Zürich, Switzerland: IABSE.

Bamforth, P., & Price, W. (1995). *Report 135. Concreting deep lifts and large volume pours*. London: CIRIA (Construction Industry Research and Information Association). ISBN-13: 978-0727720252.

Bamforth, P. (2007). CIRIA *C660: Early-age thermal crack control in concrete*. London: CIRIA (Construction Industry Research and Information Association). ISBN: 978-0-86017-660-2.

Beaver, W. (2004). Liquid nitrogen for concrete cooling. *Concrete International, 26,* 93–95.

Bentz, D. P., & Turpin, R. (2007). Potential applications of phase change materials in concrete technology. *Cement & Concrete Composites, 29*(7), 527–532.

Bofang, Z. (2013). *Thermal stresses and temperature control in mass concrete*. Tsinghua University Press, published by Butterworth-Heinemann. ISBN-13: 978-0124077232.

Buenfeld, N. R., & Yang, R. (2001). *C530 On-site curing of concrete—microstructure and durability*. London: CIRIA (Construction Industry Research and Information Association). ISBN: 9780870314391.

CEN. (2013). EN 206: Concrete: Specification, performance, production and conformity.

Choi, W., Khil, B., Chae, Y., Liang, Q., & Yun, H. (2014). Feasibility of using phase change materials to control the heat of hydration in massive concrete structures. *The Scientific World Journal*, *2014*, Article ID 781393, 6 p. http://dx.doi.org/10.1155/2014/781393.

Concrete Society. (2014). CAS20 Curing concrete. Concrete advice n.20. Concrete Society.

Du, C. (2016). Temperature control for the Gomal Zam RCC Arch-Gravity Dam. *Concrete International, 38*(11), 31–36.

Fairbairn, E., Silvoso, M., Toledo Filho, R., Alves, J. L. D., & Ebecken, N. F. F. (2004). Optimization of mass concrete construction using genetic algorithms. *Computers & Structures, 82,* 281–289.

FDOT. (2010). *Standard specifications for road and bridge construction*. Tallahssee, FL: Florida Department of Transportation.

Gajda, J., & Vangeem, M. (2002). Controlling temperatures in mass concrete. *Concrete International, 24*(2002), 58–62.

Hedlund, H., & Groth, P. (1998). Air cooling of concrete by means of embedded cooling pipes-Part I: Laboratory tests of heat transfer coefficients. *Materials and Structures*, *31*, 329–334.

Honório, T., Bary, B., & Benboudjema, F. (2016). Factors affecting the thermo-chemo-mechanical behaviour of massive concrete structures at early-age. *Materials and Structures, 49,* 3055–3073.

Huo, X. S., & Wong, L. U. (2006). Experimental study of early-age behavior of high performance concrete deck slabs under different curing methods. *Construction and Building Materials*, *20*, 1049–1056.

ICOLD. (1990). *Bulletin n°76, conventional methods in dam construction*. International Commission on Large Dams.

Ishikawa, S., Matsukawa, K., Nakanishi, S., & Kawai, H. (2007). Air pipe cooling system. *Concrete International, 29*(12), 46–49.

Japanese Concrete Institute JCI. (2012). Guidelines for control of cracking of mass concrete, 2012 (English version translated from the Japanese Version of 2008).

JSCE. (2010a). Guidelines for concrete N. 16. *Standard specifications for concrete structures 2007—Materials and construction*. Tokyo: Japan Society of Civil Engineers.

JSCE. (2010b). Guidelines for concrete No. 18. *Standard specifications for concrete structures-2007, Dam Concrete*. Tokyo: Japan Society of Civil Engineers: Tokyo.

Juenger, M., Solt, S., & Hema, J. (2010). Effects of liquid nitrogen cooling on fresh concrete properties. *ACI Materials Journal*, *107*.

Kim, J. K., Kim, K. H., & Yang, J. K. (2001). Thermal analysis of hydration heat in concrete structures with pipe cooling system. *Computers and Structures*, *79*(2), 163–171. http://dx.doi.org/10.1016/S00457949(00)00128-0.

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

Klemczak, B., & Knoppik-Wróbel, A. (2012). Wpływ wybranych czynników materiałowo–technologicznych na temperatury twardnienia betonu w masywnej płycie fundamentowej. In *Proceedings of "Dni Betonu" Wisła, Poland*, (pp. 291–301).

Klemczak, B., & Knoppik-Wróbel, A. (2015). Reinforced concrete tank walls and bridge abutments: Early-age behaviour, analytic approaches and numerical models. *Engineering Structures, 84,* 233–251.

Knoppik-Wróbel, A. (2015). Analysis of early-age thermal–shrinkage stresses in reinforced concrete walls. Ph.D. thesis, Silesian University of Technology, Gliwice, Poland.

Korol, S. I. (1968). Technology of pipe refrigeration for the Krasnoyarsk hydroelectric station dam. *Hydrotechnical Construction*, *2*, 961–966.

Koudelka, R. E., & Kelly, L. L. (1971). *Cryogenic cooling of concrete*, US Patent 3,583,172.

Kurita, M., Goto, S., Minegishi, K., Negami, Y., & Kuwahara, T. (1990). In *Precooling concrete using frozen sand, concrete international*, (Vol. 12).

Kovler, K. (1995). Shock of evaporative cooling of concrete in hot dry climates. *Concrete International, 17*(10), 65–69.

Lawrence, A. M., Tia, M., & Bergin, M. (2014). Considerations for handling of mass concrete: control of internal restraint. *ACI Materials Journal*, *111*(1), 3–12.

Liu, X., Jiang, W., de Schutter, G., Yuan, Y., & Su, Q. (2014a). Early-age behaviour of precast concrete immersed tunnel based on degree of hydration concept. *Structural Concrete*, *15*(1), 66–80.

Liu, X., Yuan, Y., & Su, Q. (2014b). Sensitivity analysis of the early-age cracking risk in an immersed tunnel. *Structural Concrete*, *15*(2), 179–190.

Luff, B. A., & Bhasin, D. P. (1983). Cooling concrete with liquid nitrogen. *Concrete Construction*, *28*, 391.

Lunniss, R., & Baber, J. (2013). *Immersed tunnels*. London, UK: CRC Press, Taylor & Francis Group.

Neville, A. (2011). *Properties of concrete*. Pearson Education Limited. ISBN: 978-0-273-75580-7.

Oliveira, J. P. (2015). Betão em massa. Pré-refrigeração e pós refrigeração. Master Thesis in Civil Engineering. Universidade Nova de Lisboa. 104 pp. http://hdl.handle.net/10362/15558.

QCS. (2014). *Qatar construction specifications*. Qatar: Ministry of Environment.

Qian, C., Gao, G., He, Z., & Li, R. (2015). Feasibility research of using phase change materials to reduce the inner temperature rise of mass concrete. *Journal of Wuhan University of Technology-Materials Science Edition*, *30*(5), 989–994.

Riding, K. A., Poole, J. L., Schindler, A. K., Juenger, M. C. G., & Folliard, K. J. (2009). Effects of construction time and coarse aggregate on bridge deck cracking. *ACI Materials Journal*, *106* (5), 448–454.

Schrader, E., & Swiger, W. (1988). Concrete dam construction and foundation treatment. In R. Jansen (Ed.), *Advanced dam engineering for design, construction, and rehabilitation* (pp. 540–577). New York: Van Nostrand Reinhold.

Schleiss, A. (2011). *Les barrages: du projet à la mise en service*. Lausanne: Presses Polytechniques et Universitaires Romandes.

Sfikas, I. P., Ingham, J., & Baber, J. (2016). Simulating thermal behaviour of concrete by FEA: state-of-the-art review. In *Proceedings of the ICE: Construction Materials*. http://dx.doi.org/10.1680/jcoma.15.00052.

Sfikas, I., Ingham, J., & Baber, J. (2017). Using finite-element analysis to assess the thermal behaviour of concrete structures. *The Concrete Society: Concrete Magazine, February,* 50–52.

Tu, D., Lawrence, A., Tia, M., & Bergin, M. (2014). Determination of required insulation for preventing early-age cracking in mass concrete footings. *Transportation Research Record: Journal of the Transportation Research Board*, (2441), 91–97.

Vallarino, E. (1998). Tratado básico de presas, tomo II., Madrid: Colegio de Ingenie-ros de Caminos, Canales y Puertos.

Vicroads. (2000). Technical Bulletin TB 42. Curing of Concrete. State Government of Victoria. ISBN: 0731129253.

Witakowski, P. (2001). Technologia budowy konstrukcji masywnych z betonu. In *Proceedings of the 13th Scientific Conference on Computer Methods in Design and Analysis of Hydrotechnic Structures*, Korbielów, Poland.

Yang, J., Hu, Y., Zuo, Z., Jin, F., & Li, Q. (2012). Thermal analysis of mass concrete embedded with double-layer staggered heterogeneous cooling water pipes. *Applied Thermal Engineering*, *35*, 145–156, 3.

Zhu, B. (1999). Effect of cooling by water flowing in nonmetal pipes embedded in mass concrete. *Journal of Construction Engineering and Management*, *125*, 61–68.