4 Concrete Defects and Curing Chemistry

Concrete is basically the product of a mixture of two components: aggregate and paste. The paste consists of cementitious materials, such as pozzolan in Portland cement, water, and entrapped or purposely entrained air. The properties of concrete may be changed by adding chemical admixtures during the batching process. In newly mixed plastic concrete, the coarse and fine aggregates are held in suspension by the paste until the mass hardens into a rigid, homogeneous mixture of components. The semi-fluid mixture hardens into concrete by the chemical action of hydration of cement, not by loss of moisture. Cement hydration will continue to occur, increasing concrete strength with age, provided the concrete is properly cured. Proper curing requires deliberate action, such as using a sealing compound or insulating blankets, to maintain the moisture and temperature conditions in the freshly placed mixture. Concrete strength will continue to increase with age provided that water is available to react with unhydrated cement, a relative humidity above 80% is maintained, the concrete temperature remains above freezing, and sufficient space is available for hydration products to form in the matrix. The chemical and physical changes that occur in the concrete during the curing process fundamentally determine the strength and durability capabilities of the final concrete product.

Cement is the binding material that locks the mineral aggregates in a solid structure. Cement is classified as a ceramic material, with typical properties listed in Table 4.1. Perfect ceramic crystals have extremely high tensile strengths, with some ceramic glass fibers having ultimate strengths over 700 MPa. However, ceramic crystals often contain many cracks and other defects, reducing their tensile strengths to near-zero levels. This explains why cement has a high compressive strength, but a relatively low tensile strength. The ceramic cement crystals contain many cracks at the micro-scale, and weaken further as cracking propagates to a larger scale.

Table 4.1 Properties of Typical Ceramics

High melting point
High hardness
High compressive strength
High tensile strength (perfect crystals)
Low ductility (brittleness)
High shear resistance (low slip)
Low electrical conductivity
Low thermal conductivity
High corrosion (acid) resistance
Low coefficient of thermal expansion

The term corrosion is somewhat imprecise, but generally refers to progressive oxidation of metals. Ceramics consist of oxidized materials, so they do not oxidize or corrode. Ceramic materials, although not vulnerable to oxidation, are still vulnerable to other chemical processes that react with and break down the material. These processes can be compared with the weathering of rock in nature.

There is a definite impact of the chemical composition of the cured concrete on final shaft performance. The strength of continuous uniform chemical matrices of cement and concrete can be theoretically calculated. In practice, concrete is never a continuous matrix such as plastic or metallic materials. Similar to ceramics, concrete is rigid. Rigid materials can take only a limited amount of stress before cracking. Such stresses are inherently produced by the processes that form the concrete, particularly for large structures. As a result, an extensive body of literature has evolved to study the cracking of concrete.

The stresses that occur in curing concrete are a natural result of the processes that create the rigid concrete structure from the initial fluid concrete mix. The matrix formed has a different structure, and thus a different density, than the original liquid. In addition, a large amount of heat is generated in the hydration process, resulting in an initial rise in temperature. The temperature then gradually declines as the chemical reaction comes to completion and generated heat is conducted outward. This process can vary from a few hours for small structures to many years for very large concrete structures, such as dams. A rise in concrete temperature creates a corresponding expansion, followed by contraction as the concrete cools. Once the concrete has substantially set up into a rigid matrix, expansion or contraction can easily cause cracking.

Structurally, the significance of cracking varies depending on the type of concrete. Concrete inherently is a material with good compressive strength, but has weak tensile strength strongly affected by cracking. Thus, for un-reinforced concrete, cracking can seriously affect performance. For reinforced concrete where the steel rebar absorbs tensile load, the effect is minor by contrast. For drilled shafts, where reinforced concrete is used and the major load is compressive, cracking is not a serious problem structurally, especially in the short run. Cracking causes more problems for shafts that experience substantial lateral loads. Cracking does however accelerate environmental attacks on both concrete and rebar over time.

Successfully modeling the curing process of concrete to predict cracking is an essential part of understanding the processes that lead to CSL velocity variations in drilled shafts.

4.1 Hydration Rates and Heat Generation during Concrete Curing

Modeling the curing process of concrete essentially entails modeling the cement hydration processes, together with the resultant physical effects of hydration. This includes modeling heat generation, temperature dissipation, microstructure formation, and the resulting stiffening or setting of the concrete. The curing process for a typical Portland cement concrete mixture involves four major hardening compounds, together with gypsum, as shown in Table 4.2.

Table 4.2 Compounds Involved in the Concrete Curing Process (Kosmataka 2002)

Chemical Name	Chemical Formula	Shorthand Notation	Percent by Weight
Tricalcium Silicate	$3CaO.SiO_2$	C_3S	50%
Dicalcium Silicate	$2CaO.SiO_2$	C_2S	25%
Tricalcium Aluminate	$3CaO.Al_2O_3$	C_3A	12%
Tetracalcium Aluminoferrite	$4CaO.Al_2O_3.Fe_2O_3$	C_4AF	8%
Gypsum	$CaSO_4.H_2O$	CSH_2	3%

All of the hardening compounds, C_3S, C_2S, C_3A, C_4AF, and CSH_2, hydrate at different rates and generate differing amounts of heat per unit weight, although only the silicates contribute to strength. Exact measurement of heat generation is complicated, but generally the amount of heat generated is proportional to the hydration of the cement. An example hydration/heat generation curve for a typical cement mixture, generated empirically, is shown in Figure 4.1.

Although a rough approximation, the rate and quantity of heat generation is a function of the following cement parameters (Breugel 1998):

- Cement chemical composition
- Cement fineness and particle size distribution
- Water/cement ratio
- Reaction temperature

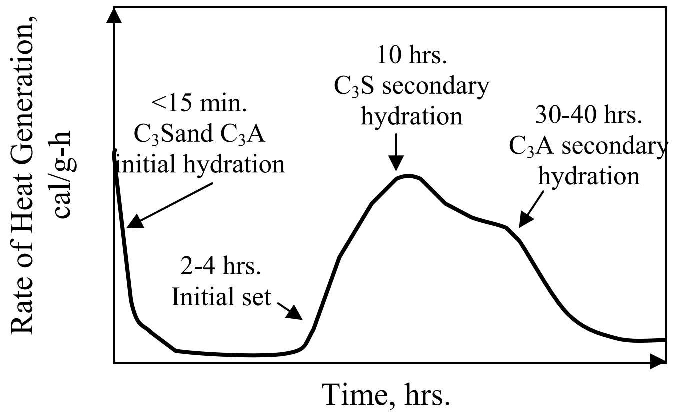

Figure 4.1 Typical Rate of Heat Evolution during Cement Hydration

The reaction temperature is variable, as the heat generated by the hydration reaction increases the temperature. The degree to which this occurs depends on the size of the concrete sample and insulation from the ambient environment. Essentially all the heat of hydration generated in small un-insulated concrete structures is conducted to the environment, resulting in a temperature isothermally equivalent to that of the environment. By contrast, larger structures such as drilled shafts have an almost adiabatic regime, meaning that generated heat is self-adsorbed, causing a corresponding increase in temperature. In these cases, the temperature may rise 40°C or more, and may require significant time for cooling. Some very large structures such as dams may require years before the heat entirely dissipates. The majority of structures have a temperature regime somewhat between these extreme cases.

The reaction temperature is affected by the heat of hydration, which in turn affects the hydration process. As with most chemical reactions, the rate of reaction increases with temperature. Concrete in warmer, more insulated environments hydrates faster. Also, higher curing temperatures cause changes in the concrete microstructure, reducing the molecular length and size of the hydration structures in the paste. This reduces the strength of the concrete, which in turn increases susceptibility to cracking.

As hydration and concrete setting is highly dependent on curing temperature, modeling the temperature profile in curing concrete is important for estimating resulting properties, performance, and durability of the structure. The ideal case for maximizing concrete performance would be a cool isothermal environment, both at initial pouring and during setting, in which all heat generated is conducted out of the concrete, maintaining a cool uniform temperature profile throughout the concrete structure at all times. Unfortunately, this is typically not the case, with regions of increased temperature and steep temperature gradients existing within the structure. Both a general increase in temperature and non-uniformity can negatively affect the properties of the concrete structure. Any measures which can be taken to reduce the impact of heat and heating on concrete structures and improve the structural properties of the concrete is a key part of concrete engineering, and certain aspects are presently active subjects of discussion in civil engineering.

4.2 Curing Chemistry Modeling

Modeling the temperature profile to predict thermally induced mechanical stress and cracking is important to predict concrete performance. These stresses are a byproduct of normal strength development in young concrete. Excessive stress results in cracking. At early stages, significant changes to material properties take place due to chemical hydration reactions in the cement. The remaining properties, such as the thermal and mechanical development of the young hardening concrete, all occur in response to hydration. Therefore it is important to understand and definitively model the hydration process.

The microscopic chemical processes in the developing microstructure are the driving forces behind the development of concrete properties. Mathematical modeling of the thermal and mechanical properties of the concrete can be approached in various ways. The traditional and established approach has been to empirically model the material properties of the concrete mixture from tables and charts. These properties can then be used to model the thermal and mechanical properties that describe the behavior of the hardening concrete mixture as a whole.

To go beyond empiricism requires developing models to link the microstructure of the developing concrete to macroscopic properties. This requires an understanding of how the micro-physics, chemistry, and associated micromechanics translate into microphysical phenomena such as creep, shrinkage, and fracture of the concrete structure. Up until very recently, this unified material science based approach has been viewed as very difficult, although new approaches are currently under development in these regards.

4.2.1 Empirical Modeling Methods

Empirically based models of concrete properties are focused on the macroscopic properties of the concrete. These models are related to uncertainties created by the variability of concrete curing. Variable parameters are used from tables and charts based on the study of concrete characteristics as a function of temperature, amount and type of cement and admixtures, water, and other variables. Dominant macroscopic characteristics such as the compressive strength or temperature are then used to estimate other macroscopic properties of the concrete.

Within this general category are a broad variety of techniques and formulas. Empirical approaches rely more on studying the material properties of the concrete mixtures from tables and charts. More mathematical approaches attempt to model the behavior of concrete based on formulas derived from modeling a particular aspect of concrete curing, or from analysis of a particular aspect of concrete curing chemistry. Lokhorst describes five of these chief concepts (Lokhorst 1993):

- The porosity concept
- The gel-space ratio concept
- The degree of hydration concept
- Maturity laws (equivalent time laws)
- Chemistry-oriented strength laws

These concepts are used to derive mathematical models for increasing compressive strength with time. These models use empirical coefficients based on different grades of concrete and cement types, and also consider other variables such as hydration and temperature, depending on the equation. The compressive strength in turn provides information on other concrete properties, such as durability, tensile strength and stiffness.

4.2.2 Micro-Modeling Methods (M3)

Going beyond empiricism requires developing models to link the microstructure of developing concrete to the macroscopic properties. Concrete hardening is the result of a chemical reaction, and therefore going below the macroscopic level requires analyzing and modeling the molecular changes and dynamics that will eventually produce the final mature concrete product. At the molecular level, physical phenomena like the production of heat, formation of new chemical hydration bonds, and use of water are linked to the physical properties of the micro-aggregates that are being formed by concrete hydration.

Micro-modeling of the concrete mixture can be approached in a variety of ways. Most current analyses focuses on the concrete mixture as a mixture of two types of particles: macroscopic-sized particles of aggregate and largely microscopic-solidifying particles of cement paste. Physically, the viscoelastic (i.e. fluid) mixture of the solid component (the aggregate) and the cement/water mixture gradually become more solid.

Modeling aggregate particles is fairly straightforward, since the aggregate is chemically inert and physically solid, with a fixed heat capacity and heat conductivity. Modeling cement is more complex, because all the physical, chemical, and structural properties of the particles are in transition. The cement is initially composed of course, dry particles, which start to dissolve and react upon contact with water. Modeling of this dynamic process using the solidification theory has been developed by leading concrete experts such as Bazant and Van Breugal (Bazant 1977).

Using solidification theory, the cement paste mixture is simplified using spherical cement particles divided arbitrarily into two layers: an outer layer of solidity, composed of hydrated cement, and an inner layer constructed of unhydrated fluid cement paste. Over the course of time, the liquid layer recedes while the solid layer propagates into the cement particle, and becomes more rigid.

Use of this solidification theory can allow combination of various physical equations governing and regulating the hydration reactions of concrete, such as temperature, moisture diffusion, and the physical properties of the concrete. However, its application is still under development.

4.3 Thermal Issues for Concrete Construction in the Field

Large and medium-sized concrete structures, such as dams, tunnel linings, and drilled shafts, can generate large amounts of heat internally. High internal temperatures and temperature differentials can form between the interior and exterior of the concrete. This requires active measures to control heat related effects, such as using internal cooling or external insulation. Such measures are commonly used for massive structures, but rarely considered for medium-sized structures. Usually limitations are specified for the maximum allowable temperature difference. Most state DOTs limit the interior/exterior temperature differential to 20 ^{o}C (35 ^{o}F) (Concrete Construction Magazine 2001).

Limiting the temperature differential is not an issue for relatively small drilled shafts. This becomes a significant challenge for drilled shafts exceeding 2 m in diameter. Internal temperatures may reach levels as high as 90 ^{o}C. Limiting the temperature difference to 20 ^{o}C may be difficult, if not impossible, without special measures, such as internal cooling. This is a topic of recent discussion concerning proper temperature controls for drilled shafts.

4.3.1 General Aspects of Thermal Cracking Analyses

Thermal cracking is the most prominent of adverse temperature effects on concrete structures. Thermal cracking arises from the uneven expansion and contraction of concrete structures during heating and/or subsequent cooling. Thermal cracking refers both to cracking that occurs in concrete at a young age when it is still curing and generating heat, as well as non temperature-induced stress of early age shrinkage. In either case, predicting the likelihood of thermal cracking involves modeling the stresses that arise in the curing concrete. Four main factors must be considered in such modeling – the chemical reactions during the hydration and curing processes, the temperature development in the concrete element being cast, the mechanical behavior of the young concrete, and any forces acting on the shaft from the surrounding environment as the concrete cures. An independent analysis of both the temperature development and resulting stresses are necessary for a thorough analysis of cracking tendency.

Engineering practice often uses rough estimates to reduce cracking risk, such as the specification of the 20 ^{o}C temperature differential (ΔT) limit. The maximum temperature difference in the structure is generally estimated from simple rules of thumb, charts, or temperature simulations. Estimates from such methods often provide an approximation of the actual cracking risk to be encountered in the structure. Such criteria assume a general relationship between ΔT and tensile stress levels in concrete, an assumption not borne out in practice. Tensile stresses are directly correlated with cracking tendency, as cracking in a concrete element generally initiates when the tensile stress exceeds the tensile strength.

A review of Table 4.3 shows the weakness of estimating the cracking risk purely from the temperature differential. Cracking risk can be defined to be the point at which tensile stresses exceed the tensile strength of the concrete. This table concerns a 1.5-m thick concrete structure. Calculations are made of the maximum stress level using a temperature differential from 3 Cases: Case I-winter temperatures with warm initial concrete, Case II-summer temperatures with warm concrete and, Case III-summer temperatures with cool concrete. Case I approximates winter conditions, while Cases II and III correspond to summer temperatures. The cracking risk is lowest for Case I (winter scenario), even though it has the greatest internal/external temperature differential.

The cracking risk factors are from computations by Emborg (1994), of the maximum stress level (n_{max}) the concrete can absorb without cracking, compared to the actual thermal stress encountered. The cracking risk is much less in winter, in spite of a greater ΔT_{max}. A cooler initial concrete temperature reduces the maximum temperature differential, but increases the cracking risk, as shown in Case III. These calculations illustrate the problems with using a maximum temperature differential as the control factor for cracking risk.

Table 4.3 Surface Cracking Risks for a Structure with Concrete Thickness of 1.5 m

	Parameter	Case I	Case II	Case III
Initial Concrete Temperature	T_i	20 °C	20 °C	10 °C
Ambient Air Temperature	T_{air}	5 °C	20 °C	20 °C
Temperature Difference Cross-section	ΔT_{max}	24.5 °C	18 °C	14.5 °C
Cracking Risk – (Max. Stress)l	n_{max}	0.45	0.53	0.54
Cracking Risk – (Temp. Difference)	$\frac{\Delta T_{max}}{\Delta T_{cr}}$	1.225	0.90	0.752
Correlation Factor	$\frac{\frac{\Delta T_{max}}{\Delta T_{cr}}}{n_{max}}$	2.72	1.69	1.39

4.3.2 Problems with the 20 °C Limit

As construction of drilled shafts demands larger and larger concrete structures, meeting overly simplistic measures such as the 20° C limit become difficult, expensive, time consuming, and impractical. Using a measure designed for smaller concrete structures on large shafts can adversely affect structural integrity, rather than safeguard it. In some cases, specifying 20 °C temperature difference limit may be too restrictive, unnecessarily increasing time and cost and may not prevent damage from thermal cracking as intended. As foundation engineering complexity increases, the use of simple "rule of thumb" standards may not adequately meet design requirements. Criterion for better QA/QC during construction may be required. Development of these controls is based on more detailed and thorough planning, modeling, and engineering analysis of the thermal profiles and resulting thermal stresses on the structure. Some of the techniques for such modeling are described below.

4.3.3 The Importance of Thermal Modeling in Concrete Structural Design and NDE

Thermal/chemical modeling of concrete elements is important to evaluate the soundness and integrity of drilled shafts. Controlling thermal development, through careful modeling, is a key aspect to understand concrete curing and to minimize the risk of thermal cracking. Construction of large diameter drilled shafts requires a thorough understanding of temperature development during concrete curing. Numerical models are useful, not only to provide answers to specific problems, but also to develop a fundamental understanding of interaction between the physical, mechanical, and chemical properties during the curing process.

Thermal modeling is also important for understanding and evaluating CSL data since temperature profiles have direct influence on velocities, and can result in CSL velocity variations. Temperature is generated in the model according to empirical measurements of heat generated from the concrete hydration process. Understanding the temperature history of a structure plays a key role in determining the ultimate integrity of the drilled shaft. The likelihood that velocity variations may be caused by thermal cracking and other temperature related defects in the structure is an important factor to consider when evaluating the CSL profile. Techniques to analyze CSL data for cracking could result in a significant improvement in determining shaft integrity. As thermal modeling is a critical factor for CSL data, its role will be discussed in more detail in the following section.

4.4 Engineering Practice for Controlling Thermal Issues in Concrete Construction

The physical and chemical properties of the concrete setting process make concrete vulnerable to curing defects. Stresses arising from heat generation during concrete curing lead to thermal stresses and hence concrete cracking. As a result, a substantial research has been conducted in the past to develop construction procedures to reduce concrete cracking.

There are two major categories of controls commonly used to control thermal development in concrete. The first sets of controls are designed to reduce the risk of thermal cracking in general. This includes measures that reduce heat build-up by using low-heat concrete, and measures that reduce the harmful effects of heat buildup using aggregate with a low-coefficient of heat expansion. These measures help ameliorate the effects of heat build-up, and generally improve the performance and durability of the finished product.

Excessively large heat buildup requires strict regulations to control, and may be expensive, time consuming, and impractical. Special controls may include external insulation and internal cooling. However, the effect of such measures may be problematic, regarding the actual performance of the concrete structure.

4.4.1 Temperature Profiling

The temperature of the water in CSL access tubes within a drilled shaft can be measured over time, as shown in Figure 4.2. Since the access tubes are generally at the same radial distance from the center of the shaft, no direct measurement of the higher central temperature is available. The temperature appears to peak at approximately two days, corresponding to the secondary hydration reaction.

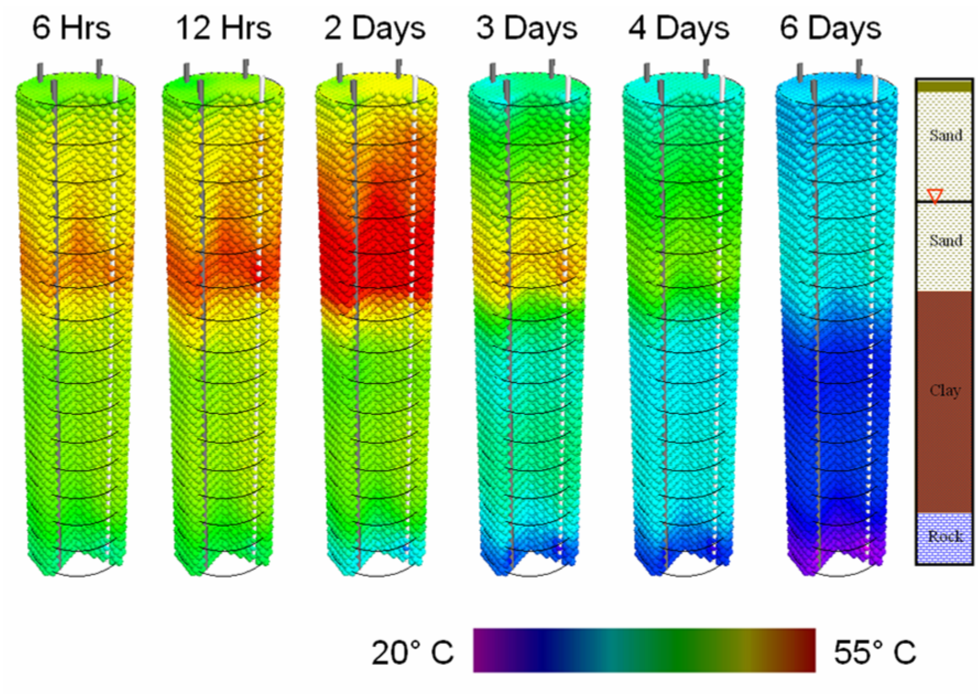

Figure 4.2 Temperature Plot from Data Progressively Collected from Access Tubes

4.4.2 Simple and Practical Techniques for Reducing Thermal Concrete Cracking With Standard Construction Techniques

A number of measures can be used to prevent cracking. The degree of susceptibility of a concrete mixture to crack can be quantified by the cracking temperature. A low cracking temperature is an indicator of low cracking tendency, and vice versa for a high cracking temperature.

4.4.2.1 Concrete Placement Temperature

The placement temperature with respect to the temperature of the surrounding strata is perhaps the most critical factor for cracking in drilled shafts. A high initial temperature causes an increase in temperature within the concrete as it hardens due to the increase in the rate of hydration. This produces a higher peak temperature during curing, which reduces concrete tensile strength, increasing cracking susceptibility. The high temperature also creates greater thermal contraction as the concrete cools to ambient temperatures. Therefore, reducing the pouring temperature can be one of the most effective means of reducing cracking susceptibility. A reduction in the pouring temperature by 10 K can reduce the cracking temperature by 13 – 15 K, a substantial decrease for improving concrete properties. However, unlike concrete pavement, the placement temperature for concrete structures is often not specified.

4.4.2.2 Aggregate Properties

Certain aggregate properties can reduce cracking susceptibility. A low coefficient of thermal expansion reduces thermal contraction. A large aggregate size reduces the amount of cement necessary for workability, reducing cracking susceptibility. Too large an aggregate size can reduce tensile strength, increasing cracking susceptibility. The use of crushed aggregate, with resulting rough surfaces, increases tensile strength and decreases cracking susceptibility.

4.4.2.3 Cement Properties

Reducing the heat produced by cement during hydration is a good way to reduce cracking susceptibility. Although formulating a good low heat cement mix can be tricky, there are some practical ways to reduce this heat. Reducing cement paste to a minimum reduces cracking susceptibility, as heat generation is reduced. Cement paste can be reduced by substituting a portion of the cement with more inert materials of similar consistency, such as fly ash.

In air entrained concretes, the tensile strain is typically increased by up to 20%, decreasing the stiffness of the concrete. Air entrainment significantly reduces cracking sensitivity for this reason.

Adjustments to the concrete mix may substantially reduce the overall cracking tendency and thermal stresses. There are intrinsic limits on how far the mix can be adjusted. Measures that reduce the heat output can result in a paradoxical effect. Concrete is a rigid ceramic material, with high compressive strength and a susceptibility to cracking. The rigidity which creates the compressive strength more specifically is a function of the cement, which holds the whole structure in place.

The quantity of cement paste is the most significant factor effecting heat generation in the concrete mixture. This is true whether the actual cement paste is minimized, the water content of the cement is increased, or with the addition of fly ash. Use of air-entraining agents to increase the air quantity also belongs in this category. All these measures reduce cracking, reduce rigidity, and reduce the compressive, shear, and tensile strength of the concrete. Fundamentally, these measures reduce cracking tendency by reducing the factors that give concrete its rigidity and strength. The overall effects of crack sensitivity reduction measures are quantified in Table 4.4.

Table 4.4 Effects on Crack Sensitivity (Springenschmid 1998)

Action	Decrease in Thermal Cracking Coefficient
Reduce fresh concrete temperature from 25°C to 12°C.	15-18K
Use optimum cement type	Up to 20K
Increase maximum aggregate size to 32 mm from 8 mm with corresponding allowable reduction in cement	5-10K
Use aggregates with a low thermal expansion coefficient	Up to 10K
Add air-entraining agents (Air content 3-6%):	3-5K
Use crushed aggregate instead of gravel	3-5K
Replace 20% cement with fly ash	3-5K

4.4.3 Field Measures to Reduce ΔT, Techniques and Implications

Drilled shafts with diameters greater than 2 m generate more heat internally than can be dissipated. Internal temperatures and thermal gradients can rise beyond prescribed limits. Measures to counter the amount of heat generated can include increasing the magnitude of measures presented in the previous section, or special construction measures such as insulation or internal cooling. These measures all have implications on performance and cost.

4.4.3.1 Special Construction Measures

The most direct means of dealing with heat generation involves the use of additional construction measures. Two common measures involve installing insulation on the external surface of the concrete structure, or a method of internal cooling, such as pipes circulating cooling water. Both measures can increase construction time and cost significantly. While both measures reduce the maximum temperature differential, the overall effect on concrete quality is not known, and may have detrimental effects on concrete quality and performance.

Use of Insulation

External insulation reduces the rate of heat conduction from the outer surface of the concrete structure, increasing the temperature of the outer surface and decreasing the temperature gradient. This causes the concrete to cool down slower and reach higher temperatures. Temperatures above a certain limit will have a negative effect on hydration structure, increasing crack susceptibility and decreasing concrete strength. The uniform temperature reduces thermal stresses, offsetting overall crack susceptibility somewhat. Many states have a maximum temperature requirement of 70 ^{o}C (160 ^{o}F) in some cases, which must be considered.

Insulation adds difficulty and expense to construction. The slower cooling rate requires more time for curing. Insulation cannot be removed for several weeks, in some cases. If insulation is removed prematurely, thermal shock can result. Care must be taken to remove insulation sequentially , layer by layer. Longer curing times expose the structure to weather or other external influences which could damage the insulation, resulting in thermal shock. Insulation may help meet temperature differential standards, but this benefit may be offset by potential complications, cost, and delay of construction.

Use of Internal Cooling

Installation of internal cooling is the most direct way of controlling the thermal development of concrete structures, and is also the most complex, expensive, and labor intensive. Special features must be incorporated in the overall engineering design of the structure from inception, requiring continuous and active oversight until the structure is completely set and cooled. There is no other option for controlling heat in massive concrete structures such as dams, where internal cooling has traditionally been applied.

As drilled shafts increase in size, internal cooling may become a consideration. Although internal cooling alleviates extreme temperature gradients, thermal stress will still exist, and differences in thermal expansion between the concrete and cooling pipes will result in cracking. These factors would need to be analyzed and accounted for in the engineering design.

4.5 Comparative Evaluation of Thermal Control Measures

A side to side comparison is useful to evaluate the effectiveness of various measures used to control concrete quality in drilled shafts. The respective measures should be evaluated to determine if the net effect in reducing cracking sensitivity is positive or negative on the integrity of drilled shafts. Modest reductions in the concrete placement temperature have the most significant effect, but even this measure has potential for negative effects if not used carefully.

Simple measures can have some positive effects in moderately sized structures. In larger structures, use of simplistic "rules of thumb" can lead to deterioration in the quality of the overall concrete structure. An understanding of the complex interactions of various parameters used in controlling concrete temperature may lead to improved structural integrity of large drilled shafts.

Table 4.5 Comparison of Measures on ΔT ,Concrete Strength, and Overall Concrete Quality

Actions calculated by effect on Cracking Temperature (Springenschmid 1998)	Decrease in Thermal Cracking Coefficient	Decrease in ΔT	Effect on Strength	Overall Effect on Quality
Reduce concrete pouring temperature from 25°C to 12°C.	15-18K	Strong Decrease	Increase	Strongly Positive
Reduce temperature of placed concrete from 12°C to 1°C.	Problematic	Strong Decrease	Increase	Problematic
Use optimum cement type	Up to 20K	Strong Decrease	Variable Decrease	Positive, if used carefully
Increase maximum aggregate size to 32 mm from 8 mm with corresponding allowable reduction in cement	5-10K	Decrease	Decrease (due to cement decrease)	Positive, if used carefully
Use aggregates with a low thermal expansion coefficient	Up to 10 K	No effect	No effect	Moderately positive
Add air-entraining	3-5K	No effect	Slight	Moderately

Table 4.5 Comparison of Measures on ΔT ,Concrete Strength, and Overall Concrete Quality

Actions calculated by effect on Cracking Temperature (Springenschmid 1998)	Decrease in Thermal Cracking Coefficient	Decrease in ΔT	Effect on Strength	Overall Effect on Quality
agents (Air content 3%-6%):			Decrease	positive
Use crushed aggregate instead of gravel	3-5K	No effect	Slight Increase	Moderately positive
Replace 20% of cement with fly ash	3-5K	Strong decrease	decrease	Moderately positive

The following summarizes the results of the table above:

- Initial effect positive, as both ΔT and T_{max} are reduced.
- Further reduction limited. Table 4.3 shows how cooling cement well below ambient temperatures may actually increase thermal stresses.
- Reduction in cement and increase of water lead to workability problems and voids, so such changes intrinsically decrease the margin for error in concrete mix quantity.
- Fly ash acts as an inert cement substitute, and does not cement up. A large increases in fly ash merely reduces the strength and overall rigidity of the concrete.

4.6 Environmental Effects on Curing Chemistry and Concrete Quality

The initial characteristics of the concrete at placement, such as pouring temperature and constituents of the mix, determine a large portion of the concrete's quality and cracking tendency. However, the surrounding environment during curing can have a significant effect on the quality and durability of the concrete structure, due to its affect on the curing process.

Since non-uniformity in curing concrete is a major cause of cracking and other quality issues, any substantial local variations and non-uniformity in the curing environment, such as heating by the sun on the surface during the day, can adversely affect concrete quality. However, even assuming a fairly uniform environment, concrete quality is still strongly affected by both moisture and temperature. Excessive effects of moisture, such as a high water table, are usually handled by installing a water-proof barrier around the drilled shaft.

Temperature also strongly affects concrete quality. Low ambient temperatures, especially in combination with high pouring temperatures, increase the cracking susceptibility considerably, due to rapid cooling. The difference between the placement temperature and the ambient temperature of the surrounding environment is especially important in regards to surface cracking. Concrete surfaces exposed to the sun are often adversely affected by cracking.

Non-uniform temperature distribution has an especially strong negative effect on concrete quality because of the close relationship between heat of hydration and concrete maturity. Non-uniform temperature and maturity in concrete create internal stress gradients, potentially increasing the tendency for cracking.

Temperature gradients occur in large concrete structures even in a uniform external environment, due to heat gradients resulting from temperature buildup in the interior portions of the structure. The temperature gradient is reduced by utilizing internal cooling or insulation methods, commonly employed in large structures such as concrete dams.

However, drilled shafts usually do not have a uniform external environment, as the surrounding ground conditions can result in a highly variable and complex environment. As a consequence, a drilled shaft may experience radial, axial, and circumferential, non-linear temperature gradients.

4.6.1 Changes in Ground Water Heat Conductivity

The effect of ground water on the temperature gradient within a drilled shaft can be very pronounced, especially in regions near the water table. Ground water have a large heat capacity and readily absorb heat generated during the curing phases of the drilled shaft. As a result, ground water is capable of creating a substantial temperature differential in the drilled shaft at the contact surface interface.

The groundwater table usually does not vary significantly in depth over a the initial curing process of 3-4 days, except under very unusual circumstances, such as torrential rains or floods. However, horizontal movement of ground water can vary widely depending on conditions. For example, typical groundwater flow velocities lie in the range of 0 to 250 m/day. Lowest flow velocities are in heavy clays, with flow rates increasing with soil permeability, especially with significant head pressure.

Ground water flow should be considered when modeling heat flow into the surrounding soil, due to substantial differences in heat absorption of the environment. Variations in ground conditions surrounding the shaft may also have a substantial effect on the local temperature of the drilled shaft. Different types and consistencies of soils (clay, sand, gravel) or bedrock (shale, sandstone, or granite etc.) have substantial variations in heat capacity and thermal conductivity, both vertically and laterally.

Table 4.6 Ground Water Flow in Soil

Soil Type	Hydraulic Conductivity, K (cm/s)
Clay-like	10^{-9} - 10^{-6}
Silt-like	10^{-7} - 10^{-3}
Sand-like	10^{-5} - 10^{-1}
Gravel-like	10^{-1} - 10^{2}