CHAPTER 5

Concrete

Concrete is without a doubt one of my favorite topics if for no other reason than the Romans did such an excellent job of producing and using concrete. We, on the other hand, seem to struggle with the proper production and installation of concrete. It is not unusual for us to hear of house foundations leaking like sieves or driveways cracking or even disintegrating well before they reach the end of their designed life expectancy.

To start, we will look at some definitions and then we will quickly move to looking at concrete from a historical perspective, seeing how the Romans fit into the story of the manufacturing and use of concrete. We will also take a close look at how both cement and concrete are manufactured today and some of the changes that are being made to cement in order to make it a more sustainable product. We will take a deep dive into the different classification systems used to describe cement and then look at some of the types of concrete. To complete our general review of concrete, we will take a close look at some of the factors that should be considered when installing concrete; including some of the dos and don'ts. Finally, we will look at one of my favorite concrete structures, the slab-on-grade. It never fails to amaze me how in the 21st century this relatively simple structure is so poorly constructed.

Definitions

First, a few definitions.

Cement
Water
} **Paste**

Cement, Water (Paste)
Fine Aggregate
Admixture (*Optional)*
} **Mortar or Plaster**

Mortar or Plaster
Coarse Aggregate
} **Concrete**

Diagram 5.1 – Definitions

At its most fundamental level, cement is a binder, it is the material that holds the concrete together.

Since aggregates affect everything from mixture proportions, final concrete strength, to the cost of the concrete, aggregate particle sizing (grading) is very important. Fine aggregate can be defined as having a particle size of up to 9.5 mm (3/8 in); remember that sand has a typical grain size of approximately 0.2 mm (0.008 in). Coarse aggregate ranges in size from larger-than 9.5 mm (3/8 in) to 150 mm (6 in), with a typical size of approximately 37 mm (1.5 in).

Admixtures, as shown above, are optional. Admixtures are substances that are added to the cementitious mixture in order to alter the concrete (or mortar/plaster) in some way. A good example of this would be the addition of a pozzolan (see origin below). By adding a pozzolan, concrete becomes hydraulic, that is, it can set under water (much more about pozzolans and hydraulic cement later). Other examples of admixtures include air-entrainment admixtures, water reducing admixtures, and admixtures for flowing concrete.

The difference between mortar and plaster relates to function. Mortar is used to bind masonry (e.g. stone, block or brick); plaster is used on floor or wall covering, mainly to waterproof or provide a smooth architectural finish.

Historical View

The Roman word for "concrete" was "opus caementicium" (Latin meaning – rubble work). The Romans were using concrete as early as the 3rd century BC. By the 2nd century BC they had started to add volcanic ash, a type of pozzolan or pozzolana (an Italian word which refers to modern day Pozzuoli - ancient Puteoli - the place where pozzolan was mined), to their concrete mix. This volcanic ash or "pulvis puteolanus", Puteoli dust or powder, as the Roman called it, made the concrete stronger and resistant to water (i.e. what we now know as hydraulic cement).

The Latin word "caementa" (a Latin noun) also meaning "rubble", is what we today know as aggregate. Their typical concrete work progressed using wooden formworks, the pouring of a layer of mortar and then hand-tamped placement of stone rubble. Usually construction was completed with the addition of a stone or brick facade.

So what were the Romans using for cement in the 3rd century BC? They were using a limestone based non-hydraulic cement. They started the process of making non-hydraulic cement by heating limestone in large kilns producing quicklime. At temperatures of approximately 1000 ºC (1832 ºF) a reaction called calcination occurs.

$$CaCO_3 + \text{heat} \rightarrow CaO + CO_2$$
$$[\text{Calcium Carbonate} + \text{heat} \rightarrow \text{Quicklime} + \text{Carbon Dioxide}]$$

They would then create a mortar type mixture of lime (quicklime), sand and water. Adding water to the lime produces the following reaction.

$$CaO + H_2O \rightarrow Ca(OH)_2 + \text{heat}$$
$$[\text{Quicklime} + \text{Water} \rightarrow \text{Slaked Lime} + \text{heat}]$$

This lime mortar hardens as the slaked lime reacts with the carbon dioxide in the surrounding air producing calcium carbonate and water.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$
$$[\text{Slaked Lime} + \text{Carbon Dioxide} \rightarrow \text{Calcium Carbonate} + \text{Water}]$$

The problem with the use of this type of cement is that it cures very slowly because it is reliant on the cement reacting with atmospheric carbon dioxide. This is the reason why the discovery and the use of pozzolana to produce a hydraulic mortar was such a significant technological breakthrough. With the use of volcanic ash, structures could be any thickness and even constructed under water.

As time progressed, the Romans continued to experiment with their concrete mixture and the use of concrete. Over time they discovered that crushed tiles and bricks could provide the same type of effect on their concrete mixture as the volcanic ash that they had been using. Today, we take advantage of this discovery by using clay in the production of our hydraulic cements (both volcanic ash and clay contain the silica necessary to produce hydraulic cement).

If you decide to learn more about the Romans and their construction techniques you will undoubtedly see references to both tuff and tufa. Both tuff and tufa were two typical types of rock used as construction materials by the Romans. Since many authors of Roman history have used these two words interchangeably, many times it is difficult to know which type of rock was actually used when discussing a specific construction project. To clear up the confusion: "Tuff" (derived from the Latin word "Tophus" or "Tufos") refers to a type of light porous volcanic rock; "Tufa" refers to a class of calcium carbonate containing rock (e.g. limestone).

Manufacture of Modern Cement

It can be argued that the Roman Empire ended sometime around the middle of the fifth century AD with the arrival of the Vandals, a barbarian tribe, outside the walls of Rome (455 AD). With the fall of Rome, all of the Roman knowledge and technology surrounding the use of concrete all but disappeared from civilization. It wasn't until 1824 that a British brick layer by the name of Joseph Aspdin produced for the first time a type of hydraulic cement by combining lime and clay at a high temperature. He named his product Portland cement. While Joseph Aspdin's Portland cement was close to modern day "portland cement", it was actually his son William who, in 1843, applied even hotter temperatures during the manufacturing process, thus producing what we call, portland cement.

Modern day cement is made-up of a variety of ingredients starting with limestone, shells, chalk or marl and to this starting material is added such ingredients as clay, iron ore, slate and fly ash (from the burning of coal). These materials are mixed, ground and fed into a refractory brick lined rotary kiln and heated to a temperature of approximately 1480 ºC (2700 ºF) (please see **Diagram 5.2 – Cement Plant Layout** below). The end result is the production of greyish green nodules called clinker, which are approximately the size and shape of marbles. Clinker, along with gypsum ($CaSO_3$; retards setting time of the concrete by reacting with tricalcium aluminate (C_3A)) and limestone, is ground to a very fine powder which we call cement. It is important to note that the addition of such materials as clay and iron ore are responsible for Portland cement being a hydraulic cement, that is, a cement that does not rely on carbon dioxide in the air to set. More specifically it is the presence of such compounds as silica (SiO_2), alumina (Al_2O_3) and ferric oxide (Fe_2O_3) that lead to the production of such compounds as tricalcium silicate, tricalcium aluminate and tetracalcium aluminate ferrite. All of these calcium compounds react with water in a process called hydration, resulting in the hardening of portland cement. (N.B. the heat generated during the hydration process can be a significant factor, depending on the size of the concrete pour.)

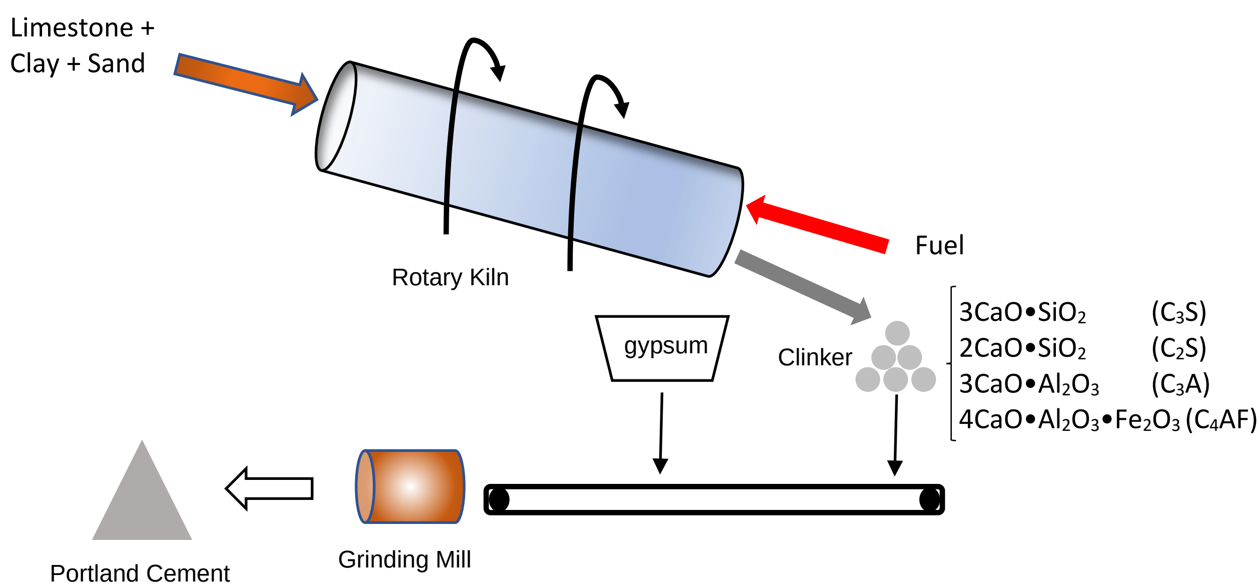

Diagram 5.2 – Cement Plant Layout

Types of Cement

Portland Cements

Depending on the standard or specification being applied, concrete can be defined in a variety of ways.

The American Society for Testing and Materials (ASTM) C150 defines the following portland cement types.

- Type I: General purpose
- Type II: Moderate sulphate resistance
- Type II (MH): Moderate heat of hydration and moderate sulphate resistance
- Type III: High early strength
- Type IV: Low heat of hydration
- Type V: High sulphate resistance

Sulphate resistance is important when the concrete will be exposed to high sulphate soils (e.g. foundations, retaining walls, etc.) or water containing sulphates (e.g. sea water). (This resistance is accomplished by reducing C_3A and C_4AF in the cement – see **Diagram 5.2 – Cement Plant Layout** for composition definitions.)

High early strength is required when the construction schedule or cost of formworks is driving the project. (This cement has higher C_3S content.)

Low heat of hydration is critical for mass concrete pours (e.g. dam construction). Without this type of cement the concrete could be subject to thermal cracking. Additionally, some pours are so large that the installation of cooling pipes is necessary. (This type of cement is produced by lowering the percentage of tricalcium aluminate and increasing the C_2S.)

One final note, given the emphasis on sustainability, C150 allows for an addition of limestone, up to 5 percent. This blending or intergrinding (i.e. ground together), helps to reduce the carbon footprint of the cement.

Blended Cements

ASTM C595 defines blended cements and ASTM C1157 defines performance cements. ASTM C595 focuses on carefully meeting component proportions; ASTM C1157 centers around meeting a specified performance tests without necessarily focusing on material composition. The use of both blended and performance cements have the potential to reduce the carbon footprint of concrete by up to 50 per cent.

Under ASTM C595, when cement manufacturers blend supplementary cementitious materials (SCMs) such as limestone (L), pozzolans (P) or slag (S) with portland cement the resulting blended hydraulic cement is represented as follows.

- Type IL(X): Portland-Limestone Cement
- Type IP(X): Portland-Pozzonlan Cement
- Type IS(X): Portland-Slag Cement
- Type IT(AX)(BX): Ternary Blended Cement

The (X) denotes the percentage of additive by mass. For example IL(10) would indicate a portland cement containing 10 percent limestone.

The use of IT indicates a ternary blended cement where three components are blended together, portland cement and two other additives. For example IT(S15)(P10) would indicate a portland cement containing 15 percent slag and 10 percent pozzolan.

Performance Cements

The six (6) hydraulic cement types under ASTM C1157 are as follows.

- Type GU: **G**eneral **U**se
- Type HE: **H**igh **E**arly-strength
- Type MS: **M**oderate **S**ulfate resistance
- Type HS: **H**igh **S**ulfate resistance
- Type MH: **M**oderate **H**eat of hydration

- Type LH: **L**ow **H**eat of hydration

In the United States the two major categories of cement promoted are portland-limestone cements (PLCs) and activated fly ash cements.

PLC is produced by replacing a portion of portland cement with an equal portion of limestone. In Canada the percentage of cement replacement ranges from greater-than 5 percent to a maximum of 15 percent (this is <u>not</u> permitted for use in sulphate exposure environments). Where appropriate, the cement naming convention is altered to include a designation for limestone (e.g. GU-L, LH-L). The addition of limestone is estimated to reduce CO_2 emissions by as much as 10 percent. In Europe the standard for PCL allows up to 35 percent limestone.

PLCs cements are without a doubt the most common performance cement, but there are a number of other alternative hydraulic cements defined under C1157, one of these cements is activated fly ash. This coal fly ash (>90 percent) based hydraulic cement reportedly can reach compression strengths in the range of 69 MPa (10,000 lbf/in^2) at 28 days.

Types of Concrete

In general terms, concrete is a mixture of cement (e.g. Portland cement), fine aggregates (e.g. sand), coarse aggregates (e.g. crushed stone), water and optionally, admixtures.

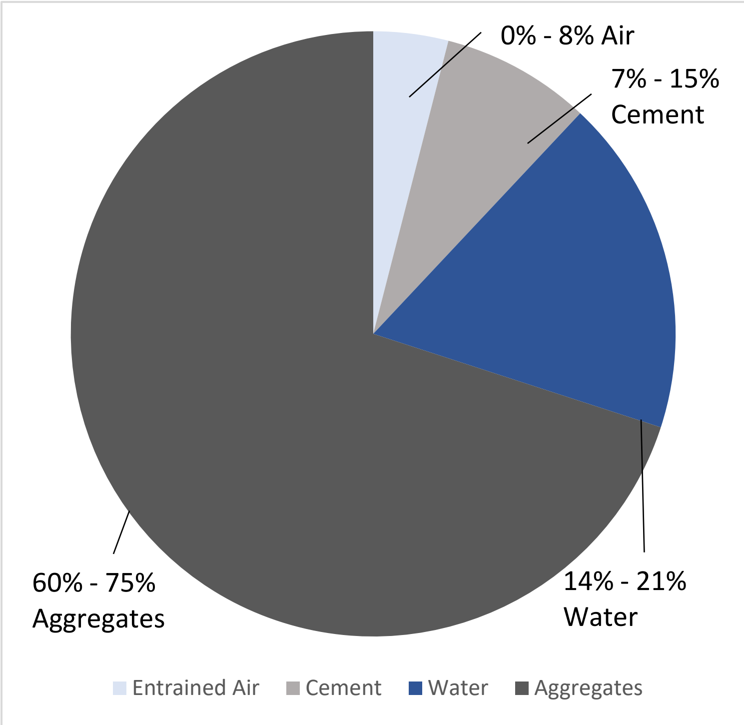

Diagram 5.3 – Typical Concrete Mixture

There are seemly an infinite number of concrete recipes. One way of helping to determine the type of concrete needed is to specify the performance properties that the concrete must meet. The Canadian Standards Association (CSA) has developed a concrete classification system based on exposure conditions, both environmental exposure as well as service use.

For example, non-structurally reinforced concrete, exposed to chloride salts (e.g. sodium chloride (i.e. table salt) – a common deicing agent) and freeze thaw cycles, would be classified as a C-2 exposure. A C-2 classification would set out certain properties, such as: water-to-cement ratio (0.45); minimum compressive strength (32 MPa at 28 days); and air entrainment (5-8% air). (Further information and additional examples can be found in CSA A23.1).

The American Concrete Institute (ACI) has an equivalent exposure classification system ACI 318.

Concrete Installation

There are many factors to consider when seeking to achieve a quality concrete installation. Some of the practices necessary to achieve a quality concrete installation are discussed below. The following is not meant to be an exhaustive list, but merely a strong starting point.

Concrete Application

The concrete application will assist in determining such things as the type of concrete to be used (e.g. Type I – General Purpose), concrete support (e.g. ground conditions; formworks), concrete strength (e.g. compressive strength of 30 MPa; reinforcement requirements), concrete exposure conditions (e.g. “F” Class – concrete exposed to freezing and thawing but not chlorides).

Pour Timing

In general, the concrete truck <u>must</u> be unloaded within two (2) hours. That is, from the time the concrete is mixed at the ready mix plant, to the time it is poured at site, the elapsed time should <u>not</u> be more than two (2) hours (some jurisdictions specify not more than one-and-a-half (1.5) hours). And, it is a big no-no to extend the pour time by adding water (or anything else) to the concrete mix on the truck. Do not forget to allow time to test the concrete mixture prior to the beginning of the pour.

Placement

The placement of the concrete should be conducted in such a way as to prevent segregation (where the cement paste and the aggregate start to separate). In other words, the concrete should not be allowed to free fall more than approximately 1.5 m; if greater than this, the concrete mixture may have to be adjusted appropriately. The concrete should be placed in horizontal layers with each lift properly vibrated into the previous lift in order to insure good bonding. (One sure sign of inadequate vibration is “honey combing”, this is where the set concrete has void spaces that resemble a honey comb.) The pour should be continuous for a given section of construction. In addition, the fresh concrete must be protected from adverse environmental conditions such as wind, precipitation, humidity and direct sun light.

Curing Conditions

Prior to curing the concrete is said to have an initial set time between 2 to 6 hours after mixing (batching) and a final set time within 4 to 12 hours after batching. This initial set time is where the concrete mortar reaches a penetration resistance of approximately 3.4 MPa (500 psi); the final set time is where the concrete mortar reaches a penetration resistance of approximately 27.6 MPa (4000 psi).

In order for freshly poured concrete to develop its strength, durability and other specified properties, the concrete's temperature and moisture content must be controlled. Failure to properly control these two parameters (i.e. temperature and moisture) will negatively affect compressive strength, permeability, volume stability, resistance to abrasion, resistance to freeze thaw cycles and resistance to deicers.

The curing of concrete is all about the promotion of hydration. Environmental factors play a pivotal role in proper hydration (please see below both **Cold Weather Conditions** and **Hot Weather Conditions** under the **Slab-on-Grade** section). There are many techniques and approaches available to manage the hydration of concrete; too many to mention in this work.

Curing times are dependent on a number of factors, including ambient temperatures, moisture loss, type and quality of cement used, mixture proportions, compressive strength specification and future exposure conditions. For example, a typical slab-on-grade (e.g. sidewalk) that is curing at ambient temperatures greater-than 10 ºC (50 ºF) may require a minimum curing time of 7 days or more, depending on the cement and admixtures used.

Quality Control and Quality Assessment

The American Society for Quality (ASQ) defines quality control (QC) as: "*the operational techniques and activities used to fulfill requirements for quality*". On the other hand, quality assurance (QA) is defined as: "*all the planned and systematic activities implemented within the quality system that can be demonstrated to provide confidence that a product or service will fulfill requirements for quality".*

One way to implement QA is to develop and use an inspection and test plan (ITP). Inspection and testing of materials, at the ready-mix plant, onsite and in the laboratory, is critical to the success of any project involving concrete. Testing methods are specified by a number of different agencies depending on the country or jurisdiction of interest (e.g. American Society of Testing and Materials (ASTM); Canadian Standards Association (CSA)). Typical tests include, but are not limited to:

- Slump – test of concrete fluidity/concrete consistency;
- Air content – especially important for freeze thaw exposure;
- Temperature – determine hot or cold weather conditions;
- Compressive strength – test field-cured specimens at 7 days; and,
- Aggregate particle size distribution – affects mixture proportions and workability.

Also, remember that when gathering samples it is important to obtain a representative sample, otherwise the test(s) may lead to false conclusions.

Slab-on-Grade

One of the structures that is the most common and yet appears to present a significant challenge for most modern-day contractor is the slab-on-grade.

A concrete slab, or a slab-on-grade, is defined as a slab which is wholly supported by the ground underneath the slab itself. Most residential home owners have at least two slabs-on-grade (e.g. sidewalk and basement floor) and many have four or more slabs-on-grade (e.g. sidewalk, basement floor, garage floor and patio). There are a lot of commercial and industrial slabs-on-grade as well, including, parking lots, airport runways and pavements. Since the slab-on-grade is so useful and ubiquitous, let's spend some time looking at a few of the factors that go into constructing a quality slab-on-grade.

Types of Slabs-on-grade

There are four basic slab-on-grade designs.

1. Unreinforced concrete slab. (Typically use: Type I or II portland cement).
2. Slabs that are reinforced to limit cracking. Construction methods would include:
    a. Using rebar, welded wire fabric (WWF), or fiber reinforcement; all with closely spaced contraction joints; or
    b. Continuously reinforced.
3. Slabs that are reinforced to prevent cracking due to shrinkage and applied loads. Construction methods include:
    a. Post tensioned; or
    b. Shrinkage compensated concrete (e.g. ASTM C 845 Type K cement)
4. Structural slabs as set out in ACI 318.

Design and construction of a slab-on-grade take into account a number of variables, including slab type, concrete mix, slab thickness, slab reinforcement, joints used (including spacing of joints) and construction process. Types of slabs, concrete mix and construction process have already been discussed; the remaining considerations will be discussed below.

Slab Thickness

Determining the thickness of a plain slab-on-grade (i.e. without reinforcement) can be accomplished using the following methods.

- Portland Cement Association (PCA) Method
- Wire Reinforcement Institute (WRI) Method
- Corp of Engineers (COE) Method

While using the above methods are beyond the scope of this chapter, the PCA and WRRI methods are for interior loadings where the loading is not experienced at the edges of the slab. The COE method includes loading at the slab edges and joints. Wheel loading is taken into consideration in all three methods.

Slab Support

The native earth or soil below the slab is known as the subgrade. It is unusual to place a concrete slab directly onto native soils without at least preparing the subgrade in some way. Usually one or more layers of materials are placed on top of the subgrade, forming the base and subbase (see **Diagram 5.4 – Structural Support of Slab-on-Grade**). It is important to remember that the slab and soil interact to support any applied loads. The strength of the soil, its ability to handle loading, must be able to distribute the loads in order to insure the longevity of the concrete slab.

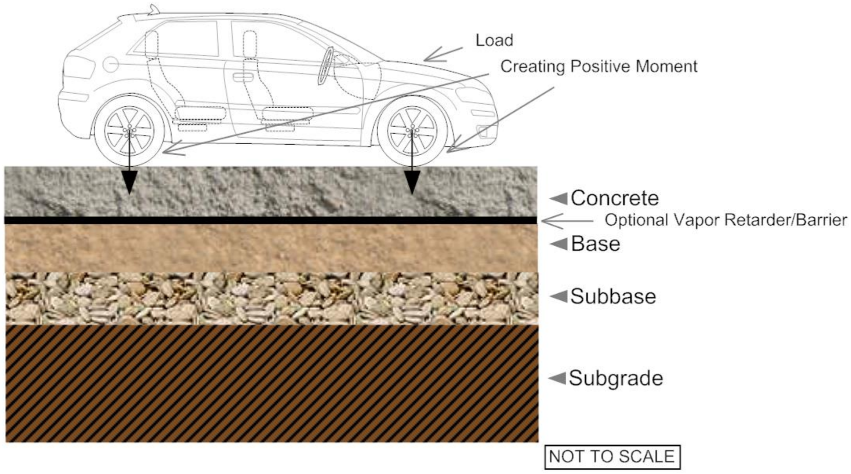

Diagram 5.4 – Structural Support of Slab-on-Grade

Soils are characterized by what is known as the modulus of subgrade reaction or k. In short, k is a measure of how much the soil deforms when put under pressure. The units of k are pounds per square inch (psi) per inch of deformation or pounds per cubic inch (pci). (In the Metric system, k is measured in kN/m^3.) Good values of k start at approximately 200 pci and most soils already have certain accepted values. For example, course grained soil, such as sand and gravel have k values at or above 200 pci. Fine grained soils can have k values as low as 50 pci or lower.

What is important to remember is that k values are important and help to determine if base courses are required. Base courses (layers) are used for a variety of reasons, including:

- Increasing the subgrade modulus (k);
- Controlling soil shrinkage and swelling;
- Improving water drainage; and
- Protecting against frost action.

The subgrade modulus, k, is usually based on the ASTM D1196 Plate Load Test. It is important to remember the subgrade modulus or subgrade reaction is not a fundamental soil property and as such will vary depending on the following.

- *The soil's elastic properties, considering both the initial soil response, as well as longer term soil response due to the soil consolidating under a sustained load.*
- *The size and shape of the load. The larger and wider the load, the more deep soil layers are involved.*

One final factor that should always be considered when determining subgrade modulus, the intensity of the load on the slab; both the duration of loading and the size of the load. There is a huge difference between an airplane's tires traveling down the runway versus the airplane parked at the terminal for hours. In short, there is no single k value for a subgrade because the relationship between load and deformation of the soil is nonlinear.

It can be easy to forget that concrete is permeable. Moisture from the supporting layers below the concrete can transmit water vapor upward through the slab, potentially causing a number of issues, including the failure of moisture-sensitive flooring materials. In addition, in locations where radon gas is a concern, radon can leak through the concrete floor, exposing inhabitants to radioactive radon gas. The placement of a vapor retarder/barrier can be very important, depending on the intended function of the slab-on-grade.

There has been significant discussion over the years as to where the vapor retarder/barrier is best placed. Like most construction practices, there are pros and cons to whatever decision is made, but it is now generally accepted that placing the barrier directly under the slab provides the best protection for floorings and building environments.

When laying down a base material, the type of base material (typically, Granular A), its depth (typically, up to 150 mm (6 inches)) and its compaction (typically, 95% of maximum dry density) are all specified. It is important to note that when requiring more than 150 mm of base material, then lifts of no more than 150 mm are compacted.

Slab Joints

Joints are used in slab-on-grade construction in order to prevent or reduce cracks in the concrete. Keeping the number of cracks and joints to a minimum, helps to reduce slab maintenance.

There are four (4) types of construction joints that should be considered when designing a concrete slab-on-grade or concrete pavement.

1. Construction Joints
2. Expansion Joints
3. Contraction/Control Joints
4. Isolation Joints

Construction joints are used to ensure that concrete displacement occurs horizontally and not vertically or rotationally. This is most important when compensating for thermal and shrinkage movement. Construction joints are the full depth of the slab or pavement and can be as simple as a butt joint or more complex, such as a butt joint with dowels. Construction joints are used, for example, when the concrete pour cannot be completed in a single pour.

Expansion joints are used to accommodate for concrete that is subject to volume change for a number of reasons, including temperature and moisture. The joints are formed by providing a full gap between constructed members. For a slab-on-grade, the gap itself is typically ¾ inches to 1 inch wide filled with an appropriate joint filler (e.g. asphalt-impregnated fiber board or cork).

A contraction joint or control joint is a saw cut in the slab or pavement that creates a vertical weakness in the slab or pavement. This is done in “control” where cracks occur. Uncontrolled cracks can result in rough surfaces and infiltration of water as deep as the base, subbase or subgrade. Contraction joints are generally ¼ to ⅓ the depth of the slab and are typically spaced every 3 to 15 m.

Isolation joints are used to isolate other constructed members from the slab. For example, columns and walls have their own foundations, isolating them from the slab ensures that objects can move independently. Isolation joints are the full depth of the slab and make use of joint material (e.g. asphalt-impregnated fiber board or cork).

Slab Reinforcement

Steel reinforcement of a slab-on-grade, using either rebar or welded wire fabric (WWF; also called welded wire reinforcement, WWR), can accomplish a number of objectives.

1. Control cracking due to drying shrinkage, temperature changes, moisture content or applied loads (moment capacity).
2. Increase spacing or negate the need for control joints.
3. Span soft spots in the subgrade.
4. Reduce curling of the slab edges.
5. Improves impact loading handling.

There are now a number of different calculation procedures that can be used to calculate the steel area required. These methods include:

1. Subgrade Drag Procedure
2. Confirmed Capacity Procedure
3. Temperature Procedure
4. Equivalent Strength Procedure
5. Crack Restraint Procedure

From the list above, the only procedure discussed is the Subgrade Drag Procedure; based on the Subgrade Drag Theory (SGDT). This method of calculation was used for years by slab designers and today it is considered to provide reasonably good results for slabs that are less than 6 inches in thickness in residential and light commercial applications. Please find the subgrade drag formula below.

$$A_s = \frac{\text{FLW}}{2f_s}$$

Where: A_s = cross-sectional area in square inches of steel per lineal foot of slab width

f_s = allowable stress in reinforcement, psi, use 0.75 f_y, where f_y is the yield strength of steel (e.g. 65,000 psi for WWF)

F = friction factor, without detail - use a range of 1.5 to 2

L = distance in feet between joints

W = dead weight of the slab, psf, typically 12.5 psf per inch of thickness

The steel area for WWF is available from cut-sheets provided by various WWF suppliers. Note that the new designation for WWF is by W-Number. For example, 6 x 6 - W1.4 x W1.4, which is equivalent to the old steel wire gauge designation, 6 x 6 - 10 x 10. The new designation system is explained below.

6 x 6 – W1.4 x W1.4

Longitudinal wire spacing in inches	Transverse wire spacing in inches	Longitudinal Plain Wire Cross Sectional Area (100^{th} in^2)	Transverse Plain Wire Cross Sectional Area (100^{th} in^2)

Using the above nomenclature it is easy to see that the steel cross sectional area is 0.014 in^2 and since the calculated steel required is based on one lineal foot of width the above WWF would provide 2 x 0.014 in^2 or 0.028 in^2 per lineal foot.

The SGDT has a number of pitfalls which can result in too little steel reinforcement. A number of countries have suggested that the minimum reinforcement percentage should be 0.10%, with a typical minimum yield strength of 65,000 psi. The percentage of reinforcement is defined as the ratio of the cross sectional area of the reinforcement to the cross sectional area of concrete. For example an 8 inch thick concrete slab would require .001 x (8 inches x12 inches) or 0.096 square inches per lineal foot of slab width. While it is true that the increase in steel usage will cost more, it is the labor cost that is usually the larger of the two costs (i.e. material vs. labor) and this case the labor cost will remain the same for both scenarios (application of SGDT vs. 0.10% reinforcement).

To properly address cracking due to shrinkage, temperature variations, moisture content and moment loading, steel reinforcement should be placed at or above the mid-depth of the slab – never below mid-depth. Typically for slabs that are 5 inches thick or less, the steel reinforcement would be at mid-depth. For 6 inch thick slabs or greater, reinforcement would be above mid-depth, but deep enough to provide 1.5 to 2 inches of concrete cover. Typically, steel reinforcement is placed at one-third the depth from the top of the slab. If the reinforcement can be placed to avoid interfering with the installation of contraction joints, all the better.

One of the key reasons for poor slab-on-grade construction is the lack of support for the steel reinforcement. The method of “hooking” or pulling the WWR into place as the concrete is being poured or, “walking-in” the steel after the concrete has been poured; both of these antiquated methods simply fail to properly position the steel reinforcement in the finished slab. Modern placement of steel reinforcement require the use of any one of a variety of supports, including chairs (or “high chairs”), wire and welded wire supports, concrete blocks and bolsters with plates. The type of base materials used will help determine which type of support is most appropriate. The type and size of the steel reinforcement will help to determine support spacing. Ultimately, the choice of the supports and their spacing must, in large part, be determined by the types of construction loads the reinforcement will have to survive.

Curing of a Slab-On-Grade

The topic of curing has been previously discussed above under the **Concrete Installation** section. However, when discussing the proper installation of slabs-on-grade that are exposed to freeze thaw cycles and chlorides (i.e. a C-2 Exposure Classification) it is important to note that the CSA prescribes a "Level 2" curing. Level 2 curing requires that the slab be held at a temperature of greater-than-or-equal-to 10 ºC for a period of 7 days and for a time necessary to attain 70% of 28 day strength.

Cold Weather Conditions

Cold weather conditions have already been discussed at some length, but this topic cannot be over emphasized. Under no circumstance show concrete be allowed to freeze before it has reached a compressive strength of 3.5 MPa (500 psi). At normal temperatures and concrete-to-water ratios of less-than 0.60, this usually occurs within 24 hours (at-or-above 10 ºC). Pouring concrete at ambient temperatures below 10 ºC is not normal practice, so one must adjust the timing accordingly. The bottom line is that freezing concrete leads to its being permanently weakened. Strength reductions of up to 50% can occur if concrete is frozen within the first few hours of placement.

Concrete must be delivered at the specified temperature; some jurisdictions require that concrete from the cement truck must be between 10 and 28 ºC. Concrete must not be placed on frozen ground or frozen concrete. All form work, reinforcement and embedded fixtures must be free and clear of ice and snow. The use of thermometers is standard practice when considering both cold and hot weather conditions.

In addition, concrete must be allowed to fully cure before the first winter. The use of various "tricks" such as using heated mixing water or the use of accelerators (to produce high-early strength), such as calcium chloride, do not replace proper curing and frost protection. The use of antifreeze, for example, ethylene glycol (used in automobiles), is a complete waste of time and must <u>not</u> be used. The quantity of antifreeze necessary to affect the freezing point of concrete would be huge and, at the same time, have a very negative affect on the properties of the concrete mixture. And, just throwing an insulated blanket over freshly laid concrete in the middle of winter is simply a waste of time.

All of this being said, concrete that experiences <u>one</u> freeze thaw cycle at an early age, can regain its ability to meet its specified compression strength if it is exposed to favorable curing conditions. However, it will never be as weather resistant or impermeable as it otherwise would have been if it had not been frozen.

Hot Weather Conditions

Hot weather conditions include the following conditions.

- High ambient temperature – typically, at or above 28 ºC (75 ºF)
- High concrete temperature – typically, at or above 28 ºC (75 ºF)
- Low relative humidity
- Wind
- Sun exposure

The above conditions can result in a myriad of challenges (e.g. having to increase mixing water), ultimately leading to:

- Decreased compressive strength;
- Decreased durability; and,
- Increased permeability.

The ability to manage hot weather conditions can be very challenging especially if the need is to regulate the temperature of the concrete itself, or even worse still, somehow trying to mitigate high ambient temperatures. For example, mass pours that are critical may justify the cost of adding liquid nitrogen directly to the mix truck at the ready mix plant. Other more economical methods such as cooling the aggregate with sprinklers in order to take advantage of evaporative cooling is one way to significantly affect the overall temperature of the concrete. For every 1ºC (1.8 ºF) reduction in aggregate temperature, the temperature of the concrete mixture will be reduced by approximately 0.5 ºC (1 ºF).

In short, there are a whole host of techniques that have been developed to address the aforementioned list of hot weather conditions. Many of these approaches are straight forward and just require some forethought and planning prior to starting the project.

Finishing of a Slab-On-Grade

The type of exposure will determine the type of equipment that can be used to finish the surface of the slab. In the case of the C-2 exposure classification, steel trowels and power trowels are <u>not</u> allowed; using these types of finishing tools will negatively affect air entrainment of the concrete. One can use magnesium floats and concrete brooms.

Slab-on-Grade Defects

The following is a list of common slab-on-grade defects. This list is just a sampling of some of the more common problems encountered when a concrete project is not managed professionally.

Defect Description	Typical Cause	Typical Fix
Scaling	• Exposer to deicing compounds too soon • Improper air entrainment	• Insure air entrainment meets exposure classification specification • Properly cure concrete
Cracking due to Shrinkage	• Improper placement of joints • Sub-grade not proper inspected and compacted	• Implement proper joint plan • Properly characterize sub-grade and insure proper compaction
Popouts	• Inadequate curing and air-dry time • Aggregate includes soft, porous material	• Properly cure and air-dry concrete • Change aggregate supplier

Table 5.1 – Concrete Defects and Remediation

Defect Description	Typical Cause	Typical Fix
Heaving	• Failure of the subgrade and/or base materials • Failure of expansion joint(s) • Freeze thaw cycle	• Properly specify and prepare base and subgrade • Implement a proper joint plan
Structural Failure	• Failure of base and/or subgrade • Freeze thaw cycle • Over loaded	• Properly specify and prepare base and subgrade • Redo project based on new load specification
Subsidence	• Failure of the subgrade and/or base materials • Installation of utility line(s) underneath slab	• Properly specify and prepare base and subgrade • Do not run utility lines underneath slab

Table 5.1 – Concrete Defects and Remediation (continued)

Conclusion

In this chapter we have reviewed:

- The history of cement and concrete;
- Modern cement manufacturing;
- The types of cement;
- The types of concrete;
- Concrete as a construction material; and,
- Things to consider when constructing a slab-on-grade.

Cement and concrete have been around for a long time as building materials and as a consequence, countless books have been written on the subject. Add to this, the volumes of information provided by various organizations, associations and regulatory agencies, all of which provide invaluable testing and specification documentation.

Hopefully, one of the takeaways from this chapter is, even the simple slab-on-grade isn`t so simple if the goal is to construct something that will last for generations.