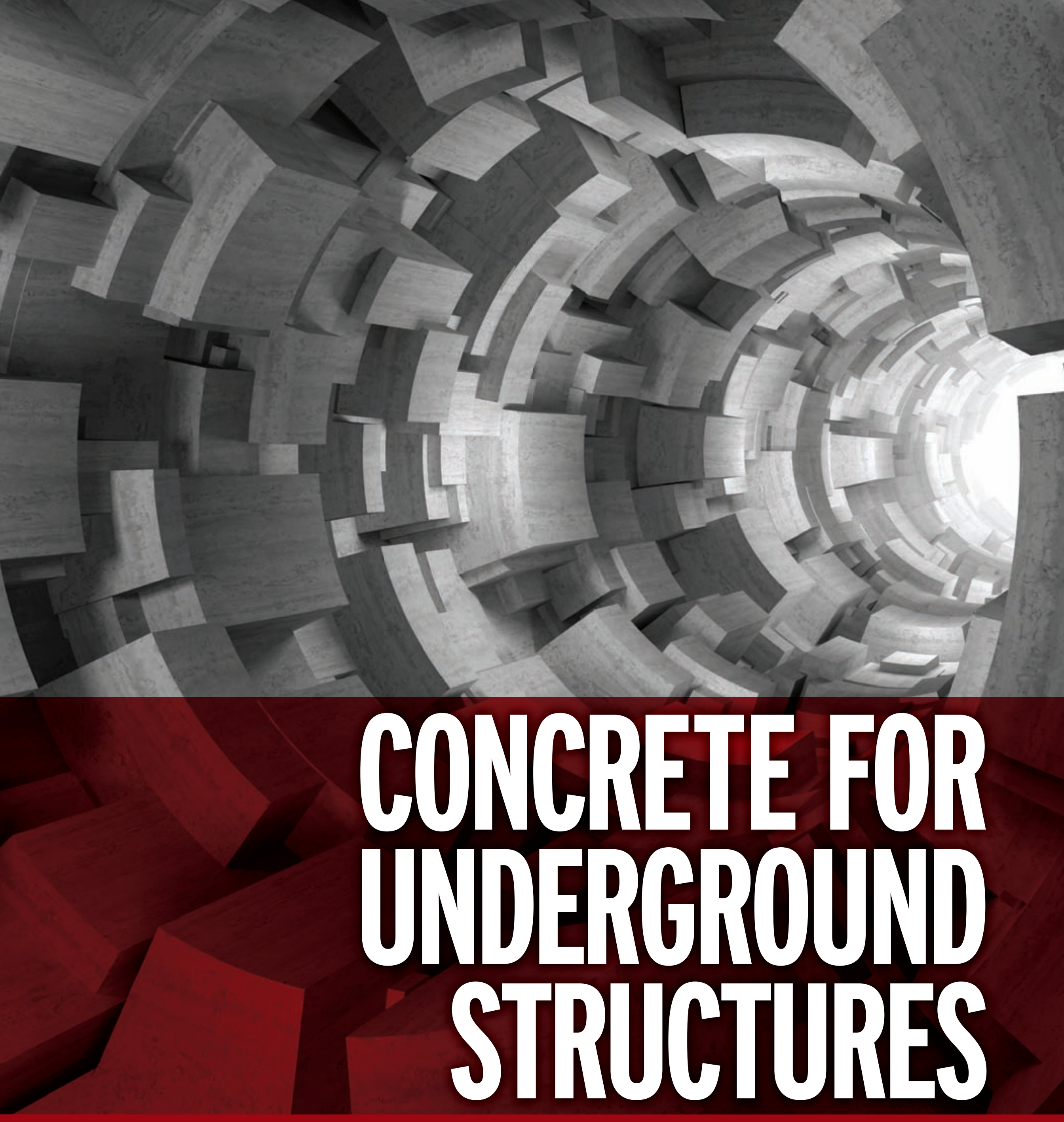

CONCRETE FOR UNDERGROUND STRUCTURES

GUIDELINES FOR DESIGN AND CONSTRUCTION

EDITED BY ROBERT J.F. GOODFELLOW

SME

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Contents

Preface

Concrete is an essential tool of the underground industry and one that has a significant impact on both the durability and capital cost of a constructed project. Concrete is used in almost every project as tunnel support, backfill, or internal structure. As such, all of the parties to a project—owners, designers, and contractors—have an interest in ensuring that concrete is designed and placed in the most cost-efficient way that ensures an appropriate level of quality in the end product.

Because of the importance of concrete to the underground industry, the Underground Construction Association of the Society for Mining, Metallurgy, and Exploration (the UCA of SME) prepared this book to summarize the current best practices of the industry with regard to the design and construction of concrete underground. The intent is to describe key design and construction issues and practices, emerging technologies and solutions, and areas in which improvements are being actively sought by the industry. The book is written as both a source of reference material for industry veterans as well as an educational tool for those new to the industry.

This document was written collaboratively by a committee of authors, and representatives of the tunnel industry provided review and comments. Industry review allowed us as authors to gather input from a wide circle within the industry in order to convey in these pages the industry consensus on design and construction practices as accurately as possible. The industry consensus is reflected in all aspects of this book.

In an accessible, but not overly simplistic manner, the main body of text in this book summarizes the basics of concrete and goes on to describe how the use of concrete underground differs from its use aboveground. Three applications of concrete are considered here: (1) cast-in-place concrete, (2) precast concrete segments, and (3) shotcrete. Each chapter addresses specific applications of these materials, including shafts, tunnels, and caverns. This book specifically does not consider cementitious materials in certain applications, including: grout of any kind, backfill behind pipelines or composite material applications (where concrete is placed behind a structural steel shell), and underwater or tremie concrete placement.

Chapter 5 discusses in detail the different types of concrete admixtures and their impacts on a concrete mixture and Appendices A, B, C, and D contain sample specifications for each type of concrete. While the specifications contain guidelines for language that may be used, it is acknowledged by the authors and by SME that each project has unique aspects, and the specifications should be examined carefully for compatibility with the project's needs and consistency with other contract documents before using this language. Commentary in each guideline specification is provided to help in writing a better concrete specification for each project application.

Acknowledgments

It is inevitable in a guideline document such as this that, although one name appears on the cover, the book is the product of many people's hard work. Among those who had an active and significant role in putting this guideline together, first and foremost is George Yoggy, who was the driving force in initial discussions and a continual inspiration to defining the need and purpose of this book.

The Underground Construction Association (UCA) of SME provided support and motivation to complete the task once begun. A big part of that assistance was given by Jane Olivier and her staff. Kathy Kaiser and Lisa Rode, technical editors of the manuscript, provided professional support, attention to detail, and editing prowess that made us all look good and kept us on our timeline. Black & Veatch provided resources and support when needed, particularly Kyle White and Leslie Sullam, who tirelessly chased down necessary information.

The greatest acknowledgment, as always, goes to my wife, Gina, and our two boys, Julian and Sebastian. Alongside the necessary investment of my own personal time for this venture came an equivalent sacrifice from my family in lost time together. Their unswerving support throughout was an essential component in completing this book.

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After collecting our own thoughts as authors and task force, the author's draft was distributed to all of the above as well as a larger group of industry experts. The following professionals were kind enough to provide comments on the manuscript from their great knowledge and expertise.

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CHAPTER 1

Introduction

Robert Goodfellow

To thoroughly understand the information presented in this book, it is important for the reader to have a basic knowledge of concrete components, how concrete is placed underground, and how the underground environment affects concrete mixture design overall. Many readers will already possess this knowledge, but some may not. This chapter aims to provide a brief and reasonably basic foundation in these topics for readers who are not completely versed in concrete material science. For a more detailed description of concrete basics and concrete mixture design, many textbooks are available, such as *Design of Reinforced Concrete* (McCormac and Brown 2009).

OVERVIEW OF CONCRETE TYPES AND PLACEMENT

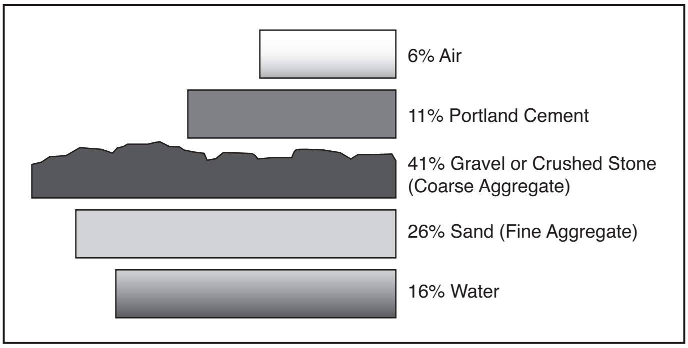
Underground projects such as tunnels, shafts, and caves almost always incorporate concrete elements. The most significant use of concrete underground is as a lining that provides initial and/or final ground support and, if needed, protection from corrosive environments. Initial and final linings may be cast-in-place (CIP) concrete, precast concrete segments, shotcrete, or combinations thereof. CIP concrete uses forms into which the concrete is placed and allowed to set until it attains a specified strength and the forms can be removed. Precast concrete segments are manufactured at a segment manufacturing plant and installed in the tunnel behind tunnel boring machines (TBMs). Shotcrete is transported, similar to CIP concrete, to the point of application before being sprayed directly onto the tunnel surface using a spray nozzle without the need for formwork.

All three applications of concrete raise construction issues underground that differ from considerations aboveground. The biggest differences arise from the confined nature of underground construction, distance from point of delivery to point of placement, and the atmosphere or environment underground. These issues will recur again and again as we discuss in later chapters the construction and specification considerations related to each of the concrete applications.

Different methods of construction require different applications of concrete, whether excavating in rock or soft ground and whether using drill-and-blast or mechanical methods of excavation. Combinations of CIP concrete, shotcrete, and precast concrete segments are applied in almost all underground excavations in either primary or secondary linings or in one-pass lining systems.

UNDERGROUND CONCRETE MIXTURES

The following information about concrete mixture design will not be new to anyone with design or construction experience. Rather, it is intended to provide context for briefly introducing the aspects of concrete mixture design that are specific to the use of concrete underground, which will



Courtesy of Portland Cement Association.

Figure 1.1 Typical volumetric proportions of concrete mixture basic ingredients

be discussed in greater detail in later chapters of this book. It is important to note that in a well-designed concrete mixture all the ingredients are properly proportioned for the specific purpose of the concrete (typical volumetric proportions are shown in Figure 1.1). CIP mixtures are not the same as precast segments or shotcrete mixtures. A simple example of the interrelations of concrete mixtures is the gradation of aggregates. Reducing the maximum size of coarse aggregate—for example, in a shotcrete mixture—requires an increase in the proportion of fine aggregate, consequently requiring a higher proportion of cement to adequately cover the increased surface area of aggregate with paste. This increased surface area of aggregate and more cement means that more energy is required for proper mixing prior to application. There are further consequences of increasing cement content with regard to water content, water-to-cementitious-materials (W/C) ratio, and many other factors. Suffice to say, all aspects of a concrete mixture are related and can rarely be taken in isolation if the most efficient application of concrete is desired. Most frequently, there is more than one correct answer when so many variables exist.

Cement

Portland cement is the most common cement used in concrete. Production of portland cement follows the requirements of the American Society for Testing and Materials (ASTM) standards C150/C150M. There are eight types of portland cement:

1. Type I: normal
2. Type IA: normal, air entraining
3. Type II: moderate sulfate resisting
4. Type IIA: moderate sulfate resisting, air entraining
5. Type III: high early strength
6. Type IIIA: high early strength, air entraining
7. Type IV: low heat of hydration
8. Type V: high sulfate resisting

The various types are more or less available around the United States, depending on where the cement is mined. For example, Type V cement may be difficult to obtain and therefore may be more expensive in some areas. The use of and need for a particular type of cement is dictated by the structure being built. For example, sewer applications typically require at least Type II cement for moderate sulfate resistance, and many specifications demand the use of Type V cement for this application, whereas sulfate resistance may not be necessary for a highway tunnel.

Coarse Aggregate (Stone and Gravel)

Coarse aggregate often makes up more than 40% of the volume of a concrete mixture. As such, selection of appropriate coarse aggregate is critical. The ideal aggregate is chemically inert to the mixture and to the conditions to which it will be exposed, and has adequate strength to resist the load conditions anticipated throughout the life of the structure. In addition to chemical properties and strength, the selection of coarse aggregate is highly influenced by the intended placement method. Different placement methods often call for aggregates with different gradation, shape, and roughness/roundness.

Gradation has a significant impact on pumpability and workability of a concrete mixture, because the gradation of the aggregate determines the amount of cement needed to adequately coat each particle. By affecting pumpability and workability, gradation also impacts the type of equipment needed to pump the mixture.

Shape, roughness, and roundness of coarse aggregate affects the strength of the mixture and, like gradation, affects placement. Elongated aggregate is difficult, if not impossible, to pump long distances because it blocks pump lines. Larger aggregate is not used in shotcrete applications for similar reasons.

One of the most serious issues with aggregate, discussed later in this chapter under "Durability and Degradation," is an alkali–silica reaction (ASR).

Fine Aggregate (Sand)

Fine aggregate is used to fill in holes between the coarse aggregate and provide a more robust mix. A basic concrete mixture may be 25% to 30% fine aggregate by volume. However, some concrete—such as pervious concrete—does not contain any fine aggregate. Pervious concrete is often used to provide drainage pathways.

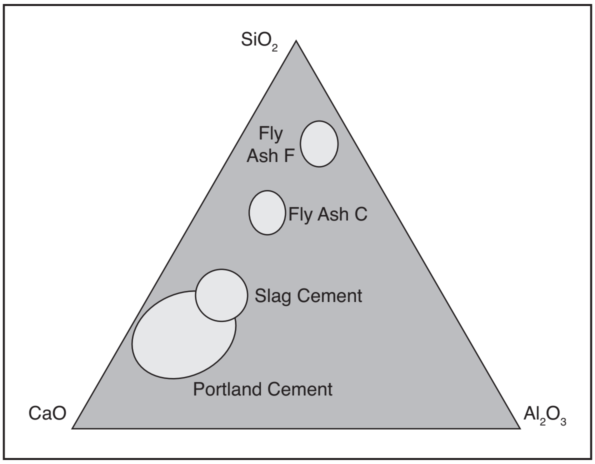
Aggregate for use in concrete should meet the requirements of ASTM C33/C33M. The combined coarse and fine aggregate grading must be smooth without any gaps between particle sizes. ASTM C1436 gives requirements for combined grading for shotcrete mixtures.

Water

The conventional wisdom about the water used in concrete is that if you can drink it, you can make concrete out of it. Excessive chemical pollution of water can interfere in the hydration process, effectively introducing additional unknown "admixtures" that can influence concrete strength gain and durability. Potable water has sufficiently low levels of pollutants to remove this concern. Water for use in concrete should meet the requirements of ASTM C1602/C1602M.

Supplementary Cementitious Materials

The hydration of cement is an exothermic reaction, producing heat. Fly ash and other pozzolans as well as ground granulated blast furnace slag (slag cement) can be added to the mixture to help reduce the heat of hydration and consequently can reduce the incidence of thermal cracking. The chemical composition of these replacement materials is shown in Figure 1.2. Other benefits of these materials include increased resistance to ASR as well as increased fines leading to better pumpability of the mixture.



Courtesy of Slag Cement Association.

Figure 1.2 Ternary diagram for cementitious materials. Note the chemical similarity allowing a higher level of cement replacement using slag cement as compared with fly ash.

Microsilica, or silica fume, is a particle many times smaller than cement, and, as a consequence, microsilica fills the gaps in the matrix between the cement particles on hydration. Adding microsilica to a mixture increases density and reduces permeability. Using microsilica has great benefits in applications where increased durability, strength, and reducing water infiltration are important, such as water and wastewater conveyance projects.

Supplementary cementitious materials added directly to concrete mixtures are governed by ASTM C618 (fly ash and natural pozzolans), ASTM C989 (slag), or ASTM C1240 (silica fume).

Admixtures and Entrained Air

Air is naturally entrained in the concrete mixture during mixing. ACI 318 states that air content for concrete exposed to freeze–thaw cycles may vary between 3.5% and 7.5%, depending on exposure and size of aggregate with allowable variation of ±1.5%.

Air-entraining admixtures are chemical admixtures that are added to concrete to introduce microscopic air bubbles into the concrete during mixing to improve its fresh and hardened properties. Entrained air can also enhance the workability and pumpability of concrete. Air-entraining admixture should meet the requirements of ASTM C260. See Chapter 5 for details.

Chemical admixtures are chemical compounds that create variations in the properties and behavior of fresh and hardened concrete. These variations may be desirable for many reasons. Admixtures are also discussed in detail in Chapter 5.

QUALITY OF UNDERGROUND CONCRETE MIXTURES

The quality of concrete in underground construction is determined by several factors:

- W/C ratio
- Workability
- Mixing

- Placement
- Hydration and curing

W/C Ratio

The W/C ratio is the most important single measure of the quality of a mixture and is defined as the ratio of water used (by mass) to cementitious materials used (by mass). If supplementary cementitious materials are used, such as fly ash and silica fume, these are added to the cement content to provide the total cementitious materials by mass. With all the other many variables being equal, a lower W/C ratio generally results in a stronger and more durable concrete.

Workability

As will be discussed in some detail in later chapters, workability is defined as the ability of a mixture to be conveyed, placed, and consolidated without segregation. Workability of the mixture is closely related to the W/C ratio. Adding more water without adding more cement can improve workability but reduces strength. As such, the degree of workability required for adequate placement is weighed against the required structural strength and durability to select an appropriate W/C ratio.

Mixing

Mixing concrete ingredients requires that energy is imparted to the mixture such that all ingredients become evenly distributed. Traditionally in North America, CIP concrete is mixed inside a drum equipped either with fins or paddles, which mix the cement. When a normal to large aggregate mixture (0.75 to 1.5 in. or 20 to 35 mm) is prepared, the shear energy required to homogenize the components is provided by the coarse aggregate tumbling through the fine particles of the mixture. Precast concrete plants use horizontal paddle mixers that directly apply energy to the mixture through the action of those paddles. In general, the smaller the aggregate, the more energy required to mix the cement.

A high-shear modern mixing system such as a ring-pan or twin shaft system is appropriate for underground construction applications as high-performance mixtures are generally used with demanding specifications. Without proper mixing, the concrete mixture will not perform up to its maximum level of performance.

Management plans for concrete projects should address mixing procedures and mixture monitoring. This is especially critical if shotcrete or other small aggregate mixtures are being used. Batching and mixing procedures should result in a mixture that at least meets the requirements of ASTM C94/C94M for ready-mixed concrete, ASTM C1116/C1116M for fiber-reinforced concrete, and ASTM C685/C685M for volumetric batched and mixed concrete.

Placement

The success of an underground project is often determined by the efficiency of the concrete placement cycle. For example, where CIP concrete is being used as a lining, the production and construction cycle of place concrete, strip forms, reset forms, and place again is the lifeblood of the contractor. It can literally make or break a project. Where precast concrete segments are being used as lining, a similar cycle is equally important, both at the segment manufacturing plant and when installing the ring behind the TBM. Though it doesn't involve forms, shotcrete also relies on efficient delivery of a constant volume of concrete for placement, because an interruption in supply can be catastrophic when immediate ground support is required within an excavation cycle.

Put simply, the underground industry has taken concrete, a basic and ancient construction material, and applied it in difficult-to-access underground spaces in relatively small volumes that require very efficient placement to be commercially viable. Accordingly, major considerations in concrete mixture design are those that influence the ability of concrete to be

- Pumped long distances,
- Dropped from the surface to the tunnel elevation, and/or
- Cured in a moist and hot environment.

These factors are discussed in greater detail in the chapters that follow.

Hydration and Curing

Curing concrete involves limiting loss of moisture from the concrete (hydration) and keeping the mixture above approximately 40°F (4°C) throughout the hydration process. Curing is generally easier underground than curing aboveground due to the confined, hot, and moist atmosphere underground. This type of atmosphere is the exact condition that often must be artificially created aboveground for better curing.

The speed of the curing process relates directly to concrete strength gain, which is, of course, a central concern in any underground project. Both the designer and contractor have a stake in determining how quickly the mixture will achieve an initial set and then how quickly it will gain additional strength. The ultimate specified strength for the mixture is typically a 28-d strength measurement. However, strength tests are carried out on the mixture at several stages during construction at time intervals that depend on the method of placement. Shotcrete may be tested several times in the first 24 h to determine initial set and ground support characteristics before it is tested to see if it has achieved its 28-d specified strength. CIP concrete is generally tested for early stripping strength and then at 28 d for quality control purposes.

DURABILITY AND DEGRADATION OF CONCRETE

Reinforced concrete is generally a highly durable material in most environments but is inherently vulnerable to some forms of deterioration. These can be either chemical or physical attack of the concrete itself or corrosion of embedded reinforcement. Special precautions may be needed to ensure the required performance.

External Degradation

Chemical. Underground concrete may encounter aggressive chemicals through contact with groundwater, both natural and contaminated, or in materials that are being contained or transported. Mobility of water can have a large influence through its ability to continually refresh the aggressive ions. Static groundwater will generally be much less aggressive.

Sulfates. Sulfates are commonly present in groundwater and can react with the concrete matrix to form ettringite, gypsum, and/or thaumasite, depending on prevailing conditions such as temperature. This can result in progressive damaging expansion or softening of the concrete surfaces. Water containing very high concentrations of sulfates should be prevented from contact with concrete through the use of a suitable barrier. Lower concentrations can usually be adequately resisted through the use of well-compacted concrete with a low free water/cement ratio and dense surface, and through selection of cement type (secondary cementitious materials or portland cement with low tricalcium aluminate, C_3A, content).

Acids. Concrete can be attacked by acids with pH less than 6.5, although generally the attack is not severe until less than 5.5, and potentially very severe below pH 4.5. The type of acid (mineral or organic) is also influential. Attack occurs through gradual dissolution of the concrete matrix and any soluble aggregates, leading to weakening and loss of section. Portland cement–based concrete (including that containing secondary cementitious materials) is inherently vulnerable to strong acid, and direct contact should be avoided. Weaker acids can be resisted through the use of well-compacted concrete with a low free water/cement ratio and dense surface. The choice of cement type is less important, although the use of silica fume may be beneficial.

Seawater. Seawater contains many different species of ion, but its effect on concrete is mainly through the action of magnesium sulfate, although the sulfate action is modified by the presence of chlorides, and damaging expansion does not generally occur. Indeed, the magnesium can cause the formation of a layer of brucite, which, if not eroded by abrasive actions, can be protective. The choice of cement type to resist seawater attack is less important than the use of a low free water/cement ratio and the achievement of a dense surface. Nevertheless, portland cement with tricalcium aluminate content greater than about 8% should be avoided because of the risk of sulfate attack.

Leaching. Flowing soft water, low in calcium, in contact with concrete will gradually dissolve calcium compounds from the concrete matrix until eventually all that remains is an incoherent silica gel. Nevertheless, this action is generally very slow for concrete with a low free water/cement ratio and a dense surface. No-fines concrete used for drainage may be especially vulnerable to this type of attack.

Sewage. Sewage is not, in itself, aggressive to concrete but if sludge is allowed to build up—wherein hydrogen sulfide is produced by anaerobic bacteria and subsequently oxidized by aerobic bacteria to sulfuric acid—severe attack can occur rapidly. Because it is not possible to produce portland cement–based concrete to resist such conditions, they must be avoided by design or a barrier provided to prevent contact. The implications for wastewater tunnels are self-evident.

Other Chemicals. Other chemicals particularly aggressive to concrete include aluminum chloride and most ammonium salts. Such chemicals are likely to be encountered only in solutions associated with industrial processes. Ammonium nitrate may be present in groundwater through its use as fertilizer, but a concentration sufficiently high to be dangerous to concrete would not normally be expected.

Influential Factors. Chemical attack of concrete will be affected by many factors, including

- Concentration of aggressive ions,
- Temperature (most chemical reactions are accelerated by heat),
- Presence and mobility of water (to replenish the aggressive ions),
- Composition of concrete (cement type, free W/C ratio),
- Quality of concrete surface, and
- Hydrostatic head.

Physical Degradation

Freezing and Thawing. Concrete surfaces subjected to freezing while saturated experience large stresses within the pores as the water expands to form ice. This can cause cracking and loss of the concrete surface. Freeze–thaw resistant concrete can be produced through the inclusion of a suitable entrained air-void system or, in moderate freeze–thaw conditions, by use of concrete with sufficient strength to resist the expansion forces. Partially saturated surfaces do not generally suffer freeze–thaw damage.

Salt Weathering. Concrete in contact with water containing salts on one face and subject to strong drying conditions on the other can suffer disintegration of the internal face. Recrystallization of salts in the surface pores, as permeating pore water evaporates at the free surface, can destroy the pore structure. This can be prevented by the use of an external barrier or an integral pore-blocking admixture to prevent absorption.

Abrasion. Flowing water containing hard solids can abrade concrete surfaces. Improved abrasion resistance can be achieved through increased strength, good finishing and curing, and by the use of silica fume as a secondary cementitious material. Cavitation can occur where flowing water undergoes a change of pressure such that bubbles form and subsequently collapse, causing a shock wave that can be very aggressive to concrete surfaces. This should be avoided by design.

Internal Degradation

Alkali-Aggregate Reaction. Certain types of aggregates contain materials that are potentially reactive with alkalis in concrete under wet conditions; a subset of this type of degradation is ASR where silica in aggregate is reactive. The reaction can be expansive and may result in damaging deformation and cracking of concrete elements (Figure 1.3). ASR is caused by a reaction between ions in the alkaline cement and reactive forms of silica in the aggregate (e.g., chert, quartzite, opal, strained quartz crystals). In areas where ASR is possible with the proposed aggregate source, this must be checked by chemical testing before approval of the aggregate. Potentially reactive aggregates are best avoided, but, where this is not possible, risk can be minimized through specification measures including limiting alkali content and inclusion of certain secondary cementitious materials.

Delayed Ettringite Formation. In wet conditions, delayed ettringite formation (DEF) is a potential risk if excessive temperature is developed during hydration because ettringite cannot form normally during hydration. Ettringite is a large, needle-like crystal and cannot be readily accommodated if it forms later within the structure of the hardened concrete matrix, and damaging expansion, similar to ASR, may result. The risk of DEF increases with peak hydration temperature above about 158°F (70°C) or higher for certain secondary cementitious materials. It can be avoided altogether by keeping the hydration temperature below this critical level at all stages of the curing process.

Reinforcement Corrosion

Reinforcement in concrete can corrode if the alkaline protection is reduced by carbonation or if the chloride level at the reinforcement depth builds up to beyond the corrosion threshold level, provided there is adequate moisture and oxygen available.

Carbonation-induced Corrosion. Carbon dioxide in the atmosphere will react with the concrete matrix, reducing its alkalinity to near neutral pH. If the carbonated zone reaches the reinforcement, the protective oxide layer will be broken down and corrosion will be initiated. This process is normally slow in good-quality concrete, and required design lives can normally be achieved by provision of adequate depth of cover. Heavily trafficked road tunnels and industrial processes can result in greatly elevated atmospheric carbon dioxide (CO_2) levels and proportional increases in carbonation rates. Resistance to carbonation-induced corrosion can be enhanced by increased concrete quality, increased cover depth, and anticarbonation surface treatments. In

Courtesy of Portland Cement Association.

Figure 1.3 Examples of alkali–silica reaction between cement paste and reactive aggregates

relatively dry environments, corrosion rates may be very slow, and it may be several decades after initiation before cracking or spalling damage occurs.

Chloride-induced Corrosion. Where concrete is in contact with waterborne salt from brackish groundwater, seawater, industrial processes, or de-icing chemicals (including spray from vehicles), chloride ions will ingress toward the reinforcement by diffusion through water-filled pores. Initially dry surfaces may suffer more rapid ingress through capillary absorption. Conditions may be particularly onerous where one face is in contact with chloride-bearing water and the other is exposed to air, such as an immersed tunnel. If the chloride ion concentration at the reinforcement or other corrodible embedded metal reaches the so-called threshold or critical level, corrosion will be initiated. Rates for chloride-initiated corrosion are generally much greater than for carbonation-induced corrosion, and the period between initiation and manifestation of damage may be only a few years.

Influential Factors. Both carbonation and chloride-induced corrosion processes are influenced by many factors, including

- Temperature: Both ingress and corrosion rates will be increased by heat but may be very low in very cold conditions.
- Moisture: Optimum internal relative humidity ranges for the initiation processes may differ from those for corrosion.
- Oxygen availability: Completely and deeply buried concrete may have an insufficient supply of oxygen to support significant corrosion rates.
- Depth of cover.
- Composition of concrete (cement type, free W/C ratio).
- Concentration of chlorides or CO_2 at the surface of the concrete.

Corrosion-resistant Reinforcement. For long design lives in particularly aggressive conditions or where cover depth is constrained by other considerations, the use of corrosion-resistant reinforcement may be the most effective solution. It should be noted that corrosion-resistant reinforcement is not considered appropriate for conventional application underground. Where it is considered necessary, stainless steel is the most suitable. Fusion-bonded epoxy and galvanized reinforcement are generally less reliable in chloride-bearing environments where corrosion-resistant reinforcement is most likely to be considered.

CONCLUSION

The information presented in this chapter is important because the rest of the book is based on this knowledge. The following chapters build on this knowledge with in-depth discussion of the three applications of concrete underground: CIP concrete, precast concrete segmental linings, and shotcrete.

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CHAPTER 2

Cast-in-Place Concrete

Shane Yanagisawa and Leon Jacobs

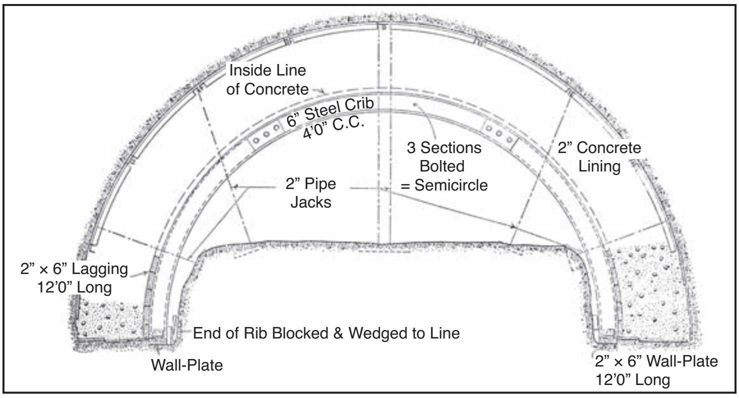
Cast-in-place (CIP) concrete may be placed directly against rock, shotcrete, or a waterproofing membrane or slip sheet. As in construction aboveground, forms are used to place the concrete and are removed when the concrete has gained sufficient strength. However, there are many differences between aboveground and belowground applications of CIP. The concrete mixture, the factors involved in placement, the forms, and a variety of other design and construction factors all differ in underground construction.

INTRODUCTION

During the late 1800s, most tunnels requiring linings for long-term stability used brick or cast-iron segmental plates. CIP tunnel linings started being placed in the early 20th century. The Colorado River Siphon Tunnel near Yuma, Arizona, was driven and lined from 1909 to 1912. The siphon had cast concrete caisson sunk shafts 90 ft (27 m) deep and a 900-ft (274-m) long tunnel with a 14-ft (4-m) finish diameter. The circular section tunnel was driven under compressed air in a top heading and bench manner. The ground was temporarily supported by thin steel segmental plates that bolted together to make a ring 1 ft (0.3 m) wide. After the top heading was advanced 14 ft (4 m), a form with steel ribs and wood lagging was set up, and a 2-ft (0.6-m) thick concrete lining was placed (Figure 2.1). The concrete was delivered by small railcars through the pressure locks and was hand shoveled behind the forms. The bench was then excavated and concreted using the same formwork rotated 180 degrees. The concrete had the proportions by weight of 1 part cement, 2½ parts sand, and 5 parts crushed rock.

By the 1930s concrete had become an essential component of tunnel linings. During the construction of Hoover Dam, which borders Arizona and Nevada, four 56-ft (17-m) diameter tunnels were driven through the rock to divert the Colorado River. These tunnels, totaling 16,000 ft (4.8 km) in length, were lined with a 3-ft (0.9-m) thickness of concrete to a finished diameter of 50 ft (15 m). The concrete was placed in three lifts (invert, sides, and top arch) using steel forms for the sides and arch. The top arch concrete was placed using a pneumatic concrete placer. In 1932, the tunnel linings were completed. At the conclusion of dam construction, two of the tunnels were permanently plugged with 400 ft (122 m) of concrete.

The pneumatic placer operated by dumping a fixed amount of concrete (somewhere between ½ yd^3 (0.38 m^3) and 1 yd^3 (0.76 m^3) into a sealable pot. The pot was closed and pressurized with air forcing the concrete through a 6-in. (152-mm) steel line into the annular space between the form and the ground. The steel pipe, called a slickline, was situated at the 12 o'clock position and was retracted as the space filled with concrete. The force of the concrete did a better job of filling



Source: Schobinger 1914, reproduced with permission from ASCE.

Figure 2.1 1914 drawing of concrete placement and formwork scheme for Colorado River Siphon

the top arch of the form with concrete than could be done by hand shoveling. Placement rates for pneumatic placers were in the range of 30 yd^3/h (23 m^3/h) compared to the 1-to-1½ yd^3/h (0.76-to-1 m^3/h) possible with hand shoveling. Although concrete pumps began placing concrete in the late 1930s, they did not have much power. Concrete could be placed at rates of 25 to 40 yd^3/h (19 to 31 m^3/h) but required the assistance of an air slugger to pack the concrete into the forms.

Separate invert, sidewall, and arch forms gave way to combined wall and arch forms filled by a pneumatic concrete placer. By the 1940s, small tunnels were still formed with wood but steel-skinned forms were being used for large tunnels. Lack of suitable retarders made delivery of concrete to the tunnel form within 45 min to 1 h essential. For shallow tunnels, the favored method was to drop the concrete through shafts spaced 1,000 to 1,500 ft (305 to 456 m) apart. Batching of concrete inside large tunnels was also done.

The first hydraulic-powered twin cylinder concrete pump was introduced in 1957. Since the 1970s, modern concrete pumps sped up the placement of tunnel concrete, and placement rates of 100 yd^3/h (76 m^3/h) are now commonplace. The advent of modern concrete admixtures in the 1990s, most notably superplasticizers (e.g., high-range water-reducing admixtures such as a polycarboxylate) and long-term hydration stabilizers, radically improved the ability of the tunnel builder to place high-quality concrete on a high-production basis. Example specifications for CIP concrete linings are provided in Appendix A.

DIFFERENCES BETWEEN ABOVEGROUND AND UNDERGROUND APPLICATIONS OF CAST-IN-PLACE CONCRETE

The differences fall under five categories: concrete mixture, placement, formwork, schedules, and testing. These differences highlight the logistical challenge of concrete material delivery to one location at the surface and placement of the material into a confined area in a reasonably small quantity and a potentially long distance from the point of surface delivery.

Concrete Mixture

The differences between aboveground and belowground application of CIP concrete begin with the concrete itself. The concrete mixture must have a well-balanced combination of short- and long-term characteristics. In the short term, tunnel concrete is usually placed on a 24-h cycle because the lining is on the project schedule's critical path, and most projects carry substantial liquidated damages for late completion. The concrete must gain strength quickly enough to allow for timely form stripping and resetting. The concrete should have enough cementitious material to achieve the required early strength but no more than what is necessary to reliably meet the long-term design requirements. Excessive cementitious material added to gain early strength will increase heat generation and thermal expansion, causing cracks.

From a long-term perspective, tunnel-lining concrete must typically provide a service life of up to 100 years while requiring minimal maintenance. Tunnel portals have to resist freeze and thaw cycles. Concrete must resist attack by aggressive groundwater or road salts. Sewer tunnels must resist corrosion from gases and impact loads at the base of drop shafts from inflows into the tunnel. Water tunnels must resist abrasion from rocks and grit in the invert. Hydropower tunnels must resist high velocities and cavitation. Transportation tunnel linings must resist intense fire. Depending on the application, the lining must resist internal or external water pressure. The lining must withstand ground-induced loads of all kinds, including ground pressures and earthquake loads.

Placement

Tunnel construction is notable for restricted access. The portals and shafts are the only means of supplying labor, materials, and supplies—all of which must be brought to the heading in a carefully coordinated fashion. Access to many tunnels is by small-gauge rail systems, often with only single-track access.

The access limitations affect concrete placement as well. The final point of concrete placement may be far from the point of conventional delivery. Concrete may be pumped thousands of feet and may encounter substantial vertical drops or increases in height via a shaft or incline. It may also be transferred multiple times from one method of conveyance to another. For example, concrete might be sent by truck from a batch plant to the job site, transferred to railcars, and then pumped into the forms. The long supply chain required to deliver a time-critical material (fresh concrete) to the point of placement requires that the entire chain work in a well-coordinated fashion. Otherwise the risk of plugged concrete lines, disrupted schedules, and rejected concrete is high.

Tunnel liner concrete is typically placed via a slickline (an assembly of steel pipe that is continuously smooth on the outside to allow easy withdrawal of the pipe from the space between the form and the excavated tunnel wall) over the top of the concrete form or by injecting the concrete through the form using a special injector car and ports built into the form. Concrete may also be placed through close-fitting hatches fitted to the side of the form.

Formwork

Typical modular panel formwork systems used aboveground don't work in a tunnel, where the arch is a predominant feature. Specialized forms are required. The formwork is typically one-sided and has no form ties to resist loads from freshly placed concrete. Because the cavity to be filled with concrete is narrow and often occupied with reinforcement, access to the space for introducing internal vibrators is limited. External vibrators are usually bolted to the steel formwork to consolidate the concrete by vibrating the form skin (as shown in Figure 2.2). The vibrators and the concrete liquefied by the vibrators place high loads on the form. When the pump forces concrete into the cavity between the form and the excavated tunnel, the form must resist the gravity load of

Courtesy of Shane Yanagisawa.

Figure 2.2 Typical steel form interior with window, with form vibrator at right and positioning spuds at top

the concrete and the pumping pressures. The form also must resist lateral loads caused by differential heights of concrete on opposite sides of the form. The forms are also exposed to dynamic loads caused by the activation of vibrators bolted to the form framework. Full-round forms (circular forms that allow concrete to be placed around the entire 360-degree envelope at once) must resist strong uplift forces. In tunnels where the arch is cast separately from the invert, the form must resist uplift if the portion below springline has inclined sides, as is typical with New Austrian Tunneling Method (NATM) style tunnels. Tunnel form design loads are typically in the range of 1,500 psf (70 kPa) for the invert and sides and up to 3,000 psf (140 kPa) for the top quarter arch.

Tunnel forms must resist cyclic loading, deformation, and wear caused by multiple reuses, sometimes for hundreds of cycles. The form must provide a high-quality finish even after these repeated cycles of use. Concrete forms for long tunnels are generally constructed with a steel skin and integrally welded steel bracing. They come with carriers designed to help with stripping and moving the form. If the form is a full-round form, the rails will be built into the form invert section. Arch-only forms normally have sections of track that must be advanced with the form. The form may range from hundreds of feet long in the case of a tunnel bored by a tunnel boring machine (TBM) to just 30 ft (9 m) long in the case of a drill-and-blast excavated tunnel or a soft ground tunnel. Steel tunnel forms are generally designed to be collapsed and moved in sections. Telescopic forms have the additional feature that the collapsed form section can be advanced through a long series of erected forms and be erected at the other end (see Figures 2.3 and 2.4).

Wood forms are also used for casting tunnel linings but only for unusual geometries or one-time uses where a steel form would not be economical (e.g., the intersection of two arched tunnels at a subway station; see Figure 2.5). The wood forms have to resist the same forces as steel forms and involve the added complication that they cannot be externally vibrated; special provisions have to be made for the introduction of internal vibrators, or a self-consolidating concrete mixture must be used. Wood forms with complicated geometries or large dimensions are typically shop-built in modules for shipping purposes and for easier handling underground. Restricted

Courtesy of Shane Yanagisawa.

Figure 2.3 Telescopic formwork—collapsed arch and invert form on carrier inside expanded full round form

Courtesy of Shane Yanagisawa.

Figure 2.4 Telescopic formwork—expanded full-round tunnel form with concrete injector in place

access to the tunnel normally prevents the final assembly of steel or wood forms with an overhead crane. The forms must be designed with the final assembly location in mind.

It is becoming more common for waterproof membranes to be placed between the initial ground support and the final lining. In such cases, the centering pins that are usually used to brace the form against uplift and shifting cannot be used. Instead, the forms must be internally braced against movement (as shown in Figure 2.6).

Schedules

Tunnel projects normally have tight schedules and high daily operating costs. Tunnel lining installation typically takes place 24 h a day, using multiple shifts of workers. When long (100 to

Courtesy of Shane Yanagisawa.

Figure 2.5 Modular wood forms shop-built for subway station

Courtesy of Shane Yanagisawa.

Figure 2.6 Waterproofing membrane in place with sealed dowels to support template bars

300 ft, or 30 to 91 m) reinforced sections of tunnel are placed using multiple form sections, work takes place on a three-shifts-a-day basis. The first shift places the concrete; the second shift cleans up the next placement area and places reinforcement; and the third shift strips and resets the form for the next placement.

Testing

The objectives of testing underground concrete, including CIP concrete, are similar to the objectives of testing aboveground concrete. They are

- To ensure that the mixture and application perform according to specifications under real conditions and on-site with the actual equipment that will be used;

- To verify that these tests meet the requirements of the design and function of the facility; and
- To ensure that the adequacy and consistency of both the material and its application are maintained by continuing to test throughout construction.

However, in underground placement of concrete, producing representative concrete samples for testing is often more challenging than for aboveground concrete. The location of concrete placement changes every day, and there is often no place underground to store test cylinders, even for a day. A compromise often has to be reached between the engineer and the contractor about the best place to take the samples and the best way to store and transport them for testing.

MATERIAL CHARACTERISTICS

The characteristics of CIP concrete are the typical underground concrete characteristics described in Chapter 1. Unique characteristics and mixture considerations are discussed where appropriate in the following sections related to design and construction.

KEY DESIGN ISSUES

The two key issues in the design and specification of tunnel concrete linings are (1) how to minimize concrete cracking and (2) when to allow stripping of the tunnel formwork. For serviceability reasons, the designer wants to minimize cracking by limiting thermal expansion, early shrinkage cracks, and long-term shrinkage. For schedule and cost reasons, the contractor wants to have enough early strength to strip the formwork as soon as is prudent. Both parties want to guarantee achievement of the specified minimum compressive strength. These issues are more closely related than they would appear at first glance.

North American building codes and the American Concrete Institute (ACI) code and guidelines give little guidance on the subject of tunnel-lining concrete. Fortunately the Germans, Austrians, and Swiss have developed codes, guidelines, and model specifications that provide ample advice on the subject. European codes, reviewed in this chapter, provide good guidance on what strength the concrete should have before the tunnel form can be stripped and how to avoid cracks in the fresh concrete but don't describe well how to predict temperature differentials and strength gain or how to verify these properties in the field. This section also discusses a method to predict temperature differentials and strength gain using a semi-adiabatic calorimeter with the appropriate software.

In drill-and-blast and soft ground tunnels, sections of concrete can be thicker than 3 ft (914 mm). Drill-and-blast tunnels can have substantial overexcavation (overbreak) from the blasting process. Soft ground tunnels can have inverts 4 to 6 ft (1 to 2 m) thick. Concrete thicker than 3 ft (914 mm) is often called out in North American specifications as "mass concrete," and special requirements are invoked to minimize cracking due to high thermal differentials within the concrete. But the method to analyze the thermal stresses is left to the contractor. The methods described in this chapter can also be used to model temperature differentials and strength gain in thick concrete sections commonly found in tunnels.

Other issues tend to lie in wait until touched upon at the worst time. These items are brought up for discussion later in the "Other Common Problems" section of this chapter.

Early Form Stripping and Crack Formation Prevention

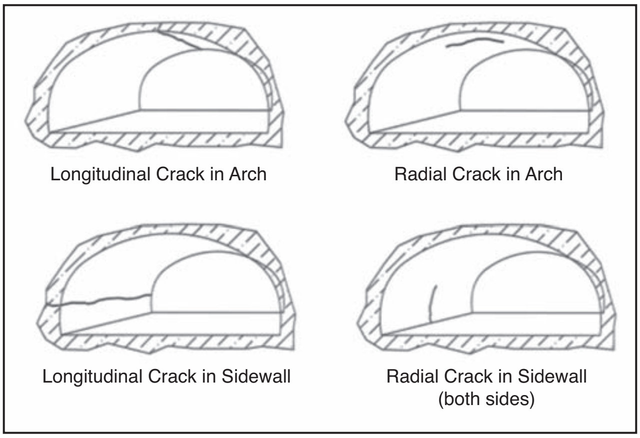
In the classic book *Practical Tunnel Driving* (Richardson and Mayo 1941), the authors note, in the "Time of Stripping" section, that specifications are "often based on open cut practice, where the arch must have gained sufficient strength to resist the distortion before the support is removed," but that in a rock tunnel the concrete cannot distort. Further on, they note that specifications for the 28½-ft (8.5-m) wide Pennsylvania Turnpike tunnels allow the arch forms to be stripped when the concrete attains a compressive strength of 600 psi (4 N/mm^2). Arguments about when to strip tunnel forms are still common on job sites today.

Designers' concrete mixture proportioning specifications often specify the maximum amount of cement permitted. This is an attempt to limit the heat of hydration and thermal differential expansion—and thereby cracking. Occasionally, designers specify slow-setting cements in an attempt to minimize thermal gradients. Sometimes the designer specifies the minimum amount of cement as a means of ensuring that the concrete will achieve the required strength. However, specifications often require concrete strengths from 1,000 to 2,500 psi (7 to 17 N/mm^2) or a percent of ultimate design strength (such as 50%) before a tunnel form can be stripped. With normally proportioned concrete, these requirements are not practically achievable within 12 to 14 h.

Often, such stripping strength requirements are borrowed from specifications for above-ground elements such as elevated slabs and beams, and the borrowers do not consider that they may be inappropriate for underground construction. Stripping strength requirements should take into account the shape of the cast concrete, the boundary conditions of the lining, and the common knowledge of the tunnel industry. CIP tunnel linings are installed after the tunnel excavation is complete and the ground support has already been installed. The time elapsed between ground support and tunnel lining installation is normally long enough to allow the ground to redistribute stresses and cease short-term movement. The circular, parabolic, and horseshoe cross sections common in tunnel linings show very low internal bending stresses when analyzed for self support. Shotcrete sprayed arches support themselves immediately, despite the low initial strength of the accelerated shotcrete. Contractors' experience is that they can set, place, and strip tunnel forms on a daily basis in tunnels with diameters 30 ft (9 m) or larger, but their ability to prove this on an analytical basis is lacking.

From the designer's perspective, as previously noted, the key issue is to minimize cracking by limiting thermal expansion and long-term shrinkage.

The ACI 318 Building Code does not provide specific direction on minimum stripping times for tunnel forms. The only relevant guidance in the ACI literature is publication 347R *Guide to Formwork for Concrete*, Section 6.6.4, which recommends that "at the start of a tunnel arch concreting operation, the minimum stripping time be 12 h for exposed surfaces and 8 h for construction joints." If the specifications provide for a reduced minimum stripping time based on site experience, such reductions should be in time increments of 30 min or less and should be established by laboratory tests, visual inspection, and surface scratching of sample areas exposed by opening the form access covers. In Austria, Germany, and Switzerland, designers have produced extensive codes, guidelines, and model specifications that emphasize crack control in CIP linings without requiring high early concrete strengths for form stripping. A common theme of these specifications is that certain types of cracks form at very early stages of concrete curing and can be minimized (Figure 2.7). Cracks are limited by removing the tunnel form about 10 to 12 h after concrete placement when the concrete has only 218 to 435 psi (1.5 to 3 N/mm^2) compressive strength. The form must be stripped before the concrete reaches 725 psi (5 N/mm^2). German



Source: Wilhelm and Grube 2000.

Figure 2.7 Typical cracks in tunnel linings

specifications require that forms be stripped before the concrete compressive strength exceeds 435 psi (3 N/mm^2) above the minimum for stripping strength. Early form removal prevents heat from accumulating in the early stages of cement hydration and allows the green concrete to expand and contract with less restraint. The Austrian guidelines recommend a slip sheet behind the final lining if additional crack reduction is desired. A waterproof membrane between the initial and final lining can serve as this slip sheet. The smoothing shotcrete and compressible fleece behind the membrane further reduce the interlock between the irregular substrate and the concrete.

Under these circumstances, the concrete is very green, so the specifications require curing at a constant temperature in a high-humidity environment, with protection from high air velocities and excessive cooling during the initial cure. For tunnels with large cross sections and short forms, a framework assembled to fit within the tunnel profile that is draped with insulated curing blankets is sometimes suggested to protect the green concrete. Curing using water mist or curing compounds is also normally required, although Austrian specifications do not require curing compounds or mists if the humidity can be maintained at higher than 90% and air velocities can be kept below 200 ft/min (1 m/s).

These model specifications recommend that concrete batch temperatures not exceed 64°F (18°C) with a maximum temperature of 77°F (25°C). Cement should also be the minimum required to limit long-term shrinkage and is suggested in the range of 474 to 540 lb/yd^3 (280 to 320 kg/m^3). Fly ash in the range of 85 to 135 lb/yd^3 (50 to 80 kg/m^3) is recommended to reduce the heat of hydration while providing long-term strength. Aggregates should not exceed 1.25 in. (32 mm). Water-to-cementitious-materials (W/C) ratios are suggested to be in the 0.50–0.55 range, much higher than typical American practice. The concrete mixture ultimate compressive strength should not be significantly higher than the strength required for loads and serviceability.

Finally, Austrian, German, and Swiss model tunnel specifications require that a method be used to determine the in-place concrete strength prior to form removal. One suggestion is to strip the bulkhead as soon as possible and use a Schmidt hammer to determine the compressive strength. The Austrian specifications suggest that the bulkhead be stripped after 4 to 5 h for strength checks. Another approach is to cast test cylinders with integral caps and individually cure the cylinders in insulated compartments. The cylinders are to be broken prior to stripping

Courtesy of Christian Neumann.

Figure 2.8 European-style form for NATM tunnel

the form. These specifications state that tunnel linings with concrete radii up to 19 ft (6 m) can be stripped when concrete strengths reach 290 psi (2 N/mm^2). Special analysis is required in cases of concrete liners that have unusual cross sections, large radii, or nonuniform thicknesses. It is recommended that niche formwork and reveals be detachable from the main form to allow early stripping without breaking off sharp edges.

By using the early form stripping criteria combined with a modern form, European contractors have been able to strip, set, and pour the CIP tunnel linings for a highway tunnel in one 12-h shift with minor cleanup work being performed on the second shift. The single section combined wall and arch form had a span of 43 ft (13 m), a length of 33 ft (10 m), and required 324 yd^3 (248 m^3) of concrete to fill the form (a typical example of European style formwork is shown in Figure 2.8).

In summary, the overall approach of the Austrian, German, and Swiss concrete tunnel lining codes, guidelines, and specifications is to strip the concrete at very low compressive strengths to allow expansion and contraction of the concrete in a temperature- and humidity-controlled environment. The heat buildup of the concrete is minimized because there is less need to add more cement to meet the form stripping strengths commonly called for in the United States. The ultimate concrete strength is closer to the design strength because the compressive strength target for stripping the formwork is lower. This approach is recommended.

One of the author's experience is that the amount of cement required to meet the stripping strength requirement of 600 psi (4 N/mm^2) in 12 h has always resulted in a concrete mixture that exceeded the 4,000-psi (27-N/mm^2), 28-d strength requirement. This observation is limited to conventional mixtures with fly ash or slag cement at a 20% replacement rate and no accelerator usage.

Identifying and Addressing Potential Thermal Problems

For large or extensive tunnels, structural analysis should be done to establish the minimum concrete strength required for form removal. The contractor should show that the selected concrete mixture can meet the time and strength criteria. The rate of strength gain for the proposed concrete mixture can be established by using a combination of modeling software and test cylinders of the proposed concrete. The concrete test cylinders are instrumented and placed in a drum calorimeter to detect the heat generation and loss. Test cylinders broken as part of the program establish a heat/strength curve. The modeling software can take into account the mixture design and the thermal characteristics of the surrounding environment—including the form, tunnel air temperature, and ground temperature—and provide heat generation and strength curves for various ground conditions. This modeling can establish the performance of the concrete before any fieldwork begins. Examples of this software would be the Quadrel system by Digital Site Systems (Pittsburgh, PA) and the 4C-Temp&Stress system by Germann Instruments (Evanston, IL). The contractor should select the mixture design and model the strength development. The software can also model the temperature differentials in thick concrete sections and check for the possibility of thermal cracking.

The model will show that ground temperature has a substantial effect on concrete strength gain when the concrete is placed directly against shotcrete or rock substrate. The substrate usually has a temperature in the 50°–60°F (10°–15°C) range and acts as a large heat sink. Concrete placed directly against rock will drop in temperature before rising again as the cement begins to hydrate. A temperature profile across the concrete section is highest in the middle and drops toward the rock and the form skin. Because waterproofing membranes with fleece have an insulating effect on the concrete, the concrete will not cool down much before the hydration process kicks in and raises the concrete temperature. The temperature profile is more uniform across the concrete section with the lowest temperatures at the form skin. Consequently, strength gain is faster for the same tunnel concrete mixture placed against waterproof lining membranes with fleece than against bare rock or shotcrete. Shotcrete smoothness criteria for waterproofing membranes tend to reduce thickness differences occurring within short distances and therefore reduce sharp temperature differentials in curing concrete. If a sudden change in lining thickness is unavoidable, a construction joint at the thickness change will be better than a continuous placement to avoid cracking.

The very early stages of concrete strength development are reduced by air entrainment in the normal ranges of 3% to 5%. Non-air-entrained concrete shows earlier strength gain in the 0–1,000 psi (0–7 N/mm^2) range because the mixture is more compact. The impact of air entrainment can be countered by reduction in W/C or adding other admixtures.

The maturity meter is a recognized method (ASTM C1074) to determine the strength of in-place concrete from thermocouples placed in the concrete. This method does not predict concrete performance but provides a real-time estimate of in-situ concrete strength and is further discussed in the "Quality Control" section later in this chapter.

Other Common Problems

Concrete mixture design should follow normal good practices but should also consider the limitations of tunnel forms. Access to the freshly placed concrete is limited. The tunnel concrete is usually placed by injection through the form or by placement via a slickline over the form. The concrete needs to flow as a plastic mass toward its final location without segregation. The form is usually externally vibrated, with about 30 ft^2 (2.8 m^2) of area serviced by each vibrator. Internal vibrators are limited to application below the springline because of the form window locations. Tightly spaced reinforcement blocking the form windows may also limit the use of internal