ACI 318-14 CODE EDITION

TENTH EDITION

DESIGN OF REINFORCED CONCRETE

JACK C. McCORMAC • RUSSELL H. BROWN

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Preface

Audience

This textbook presents an introduction to reinforced concrete design. We authors hope the material is written in such a manner as to interest students in the subject and to encourage them to continue its study in the years to come. The text was prepared with an introductory three-credit course in mind, but sufficient material is included for an additional three-credit course.

New to This Edition

Updated Code

With the tenth edition of this text, the contents have been updated to conform to the *2014 Building Code of the American Concrete Institute* (ACI 318-14). Changes to this edition of the code are discussed in Section 1.7 of the text under the heading **Summary of 2014 ACI Code Changes**.

Chapter on Concrete Masonry Updated to ACI 530-13 Code

The new chapter on strength design of reinforced concrete masonry that was added to the ninth edition of the text has been updated to conform to the 2013 issue of ACI 530. Because this code revision involved a lot of reorganization, most of the code references are different. This chapter is available only online (www.wiley.com/college/mccormac). Because strength design of reinforced concrete masonry is so similar to that of reinforced concrete, the authors felt that this would be a logical extension to the application of the theories developed earlier in the text. The design of masonry lintels, walls loaded out-of-plane, and shear walls are included. An example of the design of each type of masonry element is also included to show the student some typical applications. Spreadsheets to assist in the design of these elements are also included on the Wiley website.

Organization

The text is written in the order that the authors feel would follow the normal sequence of presentation for an introductory course in reinforced concrete design. In this way, it is hoped that skipping back and forth from chapter to chapter will be minimized. The material on columns is included in three chapters (Chapters 9, 10, and 11). Some instructors do not have time to cover the material on slender columns, so it was put in a separate chapter (Chapter 11). The remaining material on columns was separated into two chapters in order to emphasize the difference between columns that are primarily axially loaded (Chapter 9) and those with significant bending moment combined with axial load (Chapter 10).

Instructor and Student Resources

The website for the book is located at www.wiley.com/college/mccormac and contains the following resources.

For Instructors

Solutions Manual A password-protected Solutions Manual, which contains complete solutions for all homework problems in the text, is available for download. Most are handwritten, but some are carried out using spreadsheets or Mathcad.

Figures in PPT Format Also available are the figures from the text in PowerPoint format, for easy creation of lecture slides.

Lecture Presentation Slides in PPT Format Presentation slides developed by Dr. Terry Weigel of the University of Louisville are available for instructors who prefer to use PowerPoint for their lectures. The PowerPoint files are posted rather than files in PDF format to permit the instructor to modify them as appropriate for his or her class.

Sample Exams Examples of sample exams are included for most topics in the text. Problems in the back of each chapter are also suitable for exam questions.

Course Syllabus A course syllabus along with a typical daily schedule is included in editable format.

Visit the Instructor Companion Site portion of the book website at www.wiley.com/college/mccormac to register for a password. These resources are available for instructors who have adopted the book for their course. The website may be updated periodically with additional material.

For Students and Instructors

Excel Spreadsheets Excel spreadsheets were created to provide the student and the instructor with tools to analyze and design reinforced concrete elements quickly to compare alternative solutions. Spreadsheets are provided for most chapters of the text, and their use is self-explanatory. Many of the cells contain comments to assist the new user. The spreadsheets can be modified by the student or instructor to suit their more specific needs. In most cases, calculations contained within the spreadsheets mirror those shown in the example problems in the text. The many uses of these spreadsheets are illustrated throughout the text. At the end of most chapters are example problems demonstrating the use of the spreadsheet for that particular chapter. Space does not permit examples for all of the spreadsheet capabilities. The examples chosen were thought by the authors to be the most relevant.

Visit the Student Companion Site portion of the book website at www.wiley.com/college/mccormac to download these spreadsheets.

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Jack C. McCormac
Russell H. Brown

Introduction

CHAPTER 1

1.1 Concrete and Reinforced Concrete

Concrete is a mixture of sand, gravel, crushed rock, or other aggregates held together in a rocklike mass with a paste of cement and water. Sometimes one or more admixtures are added to change certain characteristics of the concrete such as its workability, durability, and time of hardening.

As with most rocklike substances, concrete has a high compressive strength and a very low tensile strength. *Reinforced concrete* is a combination of concrete and steel wherein the steel reinforcement provides the tensile strength lacking in the concrete. Steel reinforcing is also capable of resisting compression forces and is used in columns as well as in other situations, which are described later.

1.2 Advantages of Reinforced Concrete as a Structural Material

Reinforced concrete may be the most important material available for construction. It is used in one form or another for almost all structures, great or small—buildings, bridges, pavements, dams, retaining walls, tunnels, drainage and irrigation facilities, tanks, and so on.

The tremendous success of this universal construction material can be understood quite easily if its numerous advantages are considered. These include the following:

1. It has considerable compressive strength per unit cost compared with most other materials.
2. Reinforced concrete has great resistance to the actions of fire and water and, in fact, is the best structural material available for situations where water is present. During fires of average intensity, members with a satisfactory cover of concrete over the reinforcing bars suffer only surface damage without failure.
3. Reinforced concrete structures are very rigid.
4. It is a low-maintenance material.
5. As compared with other materials, it has a very long service life. Under proper conditions, reinforced concrete structures can be used indefinitely without reduction of their load-carrying abilities. This can be explained by the fact that the strength of concrete does not decrease with time but actually increases over a very long period, measured in years, because of the lengthy process of the solidification of the cement paste.
6. It is usually the only economical material available for footings, floor slabs, basement walls, piers, and similar applications.
7. A special feature of concrete is its ability to be cast into an extraordinary variety of shapes from simple slabs, beams, and columns to great arches and shells.
8. In most areas, concrete takes advantage of inexpensive local materials (sand, gravel, and water) and requires relatively small amounts of cement and reinforcing steel, which may have to be shipped from other parts of the country.
9. A lower grade of skilled labor is required for erection as compared with other materials such as structural steel.

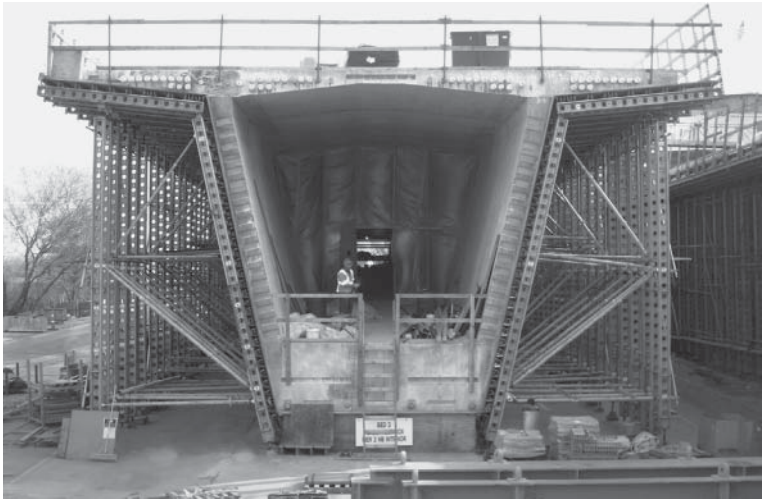
Courtesy of Portland Cement Association.

NCNB Tower in Charlotte, North Carolina, completed 1991.

1.3 Disadvantages of Reinforced Concrete as a Structural Material

To use concrete successfully, the designer must be completely familiar with its weak points as well as its strong ones. Among its disadvantages are the following:

1. Concrete has a very low tensile strength, requiring the use of tensile reinforcing.
2. Forms are required to hold the concrete in place until it hardens sufficiently. In addition, falsework or shoring may be necessary to keep the forms in place for roofs, walls, floors, and similar structures until the concrete members gain sufficient strength to support themselves. Formwork is very expensive. In the United States, its costs run from one-third to two-thirds of the total cost of a reinforced concrete structure, with average values of about 50%. *It should be obvious that when efforts are made to improve the economy of reinforced concrete structures, the major emphasis is on reducing formwork costs*.
3. The low strength per unit weight of concrete leads to heavy members. This becomes an increasingly important matter for long-span structures, where concrete's large dead weight has a great effect on bending moments. Lightweight aggregates can be used to reduce concrete weight, but the cost of the concrete is increased.
4. Similarly, the low strength per unit volume of concrete means members will be relatively large, an important consideration for tall buildings and long-span structures.


Courtesy of EFCO Corp.

Pre-cast segments for the I-35W St Anthony Falls Bridge, Minneapolis, Minnesota.

5. The properties of concrete vary widely because of variations in its proportioning and mixing. Furthermore, the placing and curing of concrete is not as carefully controlled as is the production of other materials, such as structural steel and laminated wood.

Two other characteristics that can cause problems are concrete's shrinkage and creep. These characteristics are discussed in Section 1.12 of this chapter.

1.4 Historical Background

Most people believe that concrete has been in common use for many centuries, but this is not the case. The Romans did make use of a cement called *pozzolana* before the birth of Christ. They found large deposits of a sandy volcanic ash near Mt. Vesuvius and in other places in Italy. When they mixed this material with quicklime and water as well as sand and gravel, it hardened into a rocklike substance and was used as a building material. One might expect that a relatively poor grade of concrete would result, as compared with today's standards, but some Roman concrete structures are still in existence today. One example is the Pantheon (a building dedicated to all gods), which is located in Rome and was completed in 126 CE.

The art of making pozzolanic concrete was lost during the Dark Ages and was not revived until the eighteenth and nineteenth centuries. A deposit of natural cement rock was discovered in England in 1796 and was sold as "Roman cement." Various other deposits of natural cement were discovered in both Europe and America and were used for several decades.

The real breakthrough for concrete occurred in 1824, when an English bricklayer named Joseph Aspdin, after long and laborious experiments, obtained a patent for a cement that he called portland cement because its color was quite similar to that of the stone quarried on the Isle of Portland off the English coast. He made his cement by taking certain quantities of clay and limestone, pulverizing them, burning them in his kitchen stove, and grinding the resulting clinker into a fine powder. During the early years after its development, his cement was used primarily in stuccos.[1] This wonderful product was adopted very slowly by the building industry and was not even introduced in the United States until 1868; the first portland cement was not manufactured in the United States until the 1870s.

The first uses of concrete are not very well known. Much of the early work was done by the Frenchmen François Le Brun, Joseph Lambot, and Joseph Monier. In 1832, Le Brun built a concrete

[1] Kirby, R. S. and Laurson, P. G., 1932, *The Early Years of Modern Civil Engineering* (New Haven: Yale University Press), p. 266.

Itar-Tass Photos/NewsCom.

Installation of the concrete gravity base substructure (CGBS) for the LUNA oil-and-gas platform in the Sea of Okhotsk, Sakhalin region, Russia.

house and followed it with the construction of a school and a church with the same material. In about 1850, Lambot built a concrete boat reinforced with a network of parallel wires or bars. Credit is usually given to Monier, however, for the invention of reinforced concrete. In 1867, he received a patent for the construction of concrete basins or tubs and reservoirs reinforced with a mesh of iron wire. His stated goal in working with this material was to obtain lightness without sacrificing strength.[2]

From 1867 to 1881, Monier received patents for reinforced concrete railroad ties, floor slabs, arches, footbridges, buildings, and other items in both France and Germany. Another Frenchman, François Coignet, built simple reinforced concrete structures and developed basic methods of design. In 1861, he published a book in which he presented quite a few applications. He was the first person to realize that the addition of too much water to the mix greatly reduced concrete's strength. Other Europeans who were early experimenters with reinforced concrete included the Englishmen William Fairbairn and William B. Wilkinson, the German G. A. Wayss, and another Frenchman, François Hennebique.[3,4]

William E. Ward built the first reinforced concrete building in the United States in Port Chester, New York, in 1875. In 1883, he presented a paper before the American Society of Mechanical Engineers in which he claimed that he got the idea of reinforced concrete by watching English laborers in 1867 trying to remove hardened cement from their iron tools.[5]

Thaddeus Hyatt, an American, was probably the first person to correctly analyze the stresses in a reinforced concrete beam, and in 1877, he published a 28-page book on the subject, entitled *An Account of Some Experiments with Portland Cement Concrete, Combined with Iron as a Building Material*. In this book he praised the use of reinforced concrete and said that "rolled beams (steel) have to be taken largely on faith." Hyatt put a great deal of emphasis on the high fire resistance of concrete.[6]

E. L. Ransome of San Francisco reportedly used reinforced concrete in the early 1870s and was the originator of deformed (or twisted) bars, for which he received a patent in 1884. These bars, which

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[2] Ibid., pp. 273–275.
[3] Straub, H., 1964, *A History of Civil Engineering* (Cambridge: MIT Press), pp. 205–215. Translated from the German *Die Geschichte der Bauingenieurkunst* (Basel: Verlag Birkhauser), 1949.
[4] Kirby and Laurson, *The Early Years of Modern Civil Engineering*, pp. 273–275.
[5] Ward, W. E., 1883, "Béton in Combination with Iron as a Building Material," *Transactions ASME*, 4, pp. 388–403.
[6] Kirby and Laurson, *The Early Years of Modern Civil Engineering*, p. 275.

were square in cross section, were cold-twisted with one complete turn in a length of not more than 12 times the bar diameter.[7] (The purpose of the twisting was to provide better bonding or adhesion of the concrete and the steel.) In 1890 in San Francisco, Ransome built the Leland Stanford Jr. Museum. It is a reinforced concrete building 312 ft long and 2 stories high in which discarded wire rope from a cable-car system was used as tensile reinforcing. This building experienced little damage in the 1906 earthquake and the fire that ensued. The limited damage to this building and other concrete structures that withstood the great 1906 fire led to the widespread acceptance of this form of construction on the West Coast. Since the early 1900s, the development and use of reinforced concrete in the United States has been very rapid.[8,9]

1.5 Comparison of Reinforced Concrete and Structural Steel for Buildings and Bridges

When a particular type of structure is being considered, the student may be puzzled by the question, "Should reinforced concrete or structural steel be used?" There is much joking on this point, with the proponents of reinforced concrete referring to steel as that material that rusts and those favoring structural steel referring to concrete as the material that, when overstressed, tends to return to its natural state—that is, sand and gravel.

There is no simple answer to this question, inasmuch as both of these materials have many excellent characteristics that can be utilized successfully for so many types of structures. In fact, they are often used together in the same structures with wonderful results.

The selection of the structural material to be used for a particular building depends on the height and span of the structure, the material market, foundation conditions, local building codes, and architectural considerations. For buildings of fewer than 4 stories, reinforced concrete, structural steel, and wall-bearing construction are competitive. From 4 to about 20 stories, reinforced concrete and structural steel are economically competitive, with steel having been used in most of the jobs over 20 stories in the past. Today, however, reinforced concrete is becoming increasingly competitive for buildings over 20 stories, and there are a number of reinforced concrete buildings of greater height around the world. The 74-story, 859-ft-high Water Tower Place in Chicago is the tallest reinforced concrete building in the world. The 1465-ft CN tower (not a building) in Toronto, Canada, is the tallest reinforced concrete structure in the world.

Although we would all like to be involved in the design of tall, prestigious reinforced concrete buildings, there are just not enough of them to go around. As a result, nearly all of our work involves much smaller structures. Perhaps 9 out of 10 buildings in the United States are 3 stories or fewer in height, and more than two-thirds of them contain 15,000 sq ft or less of floor space.

Foundation conditions can often affect the selection of the material to be used for the structural frame. If foundation conditions are poor, using a lighter structural steel frame may be desirable. The building code in a particular city may favor one material over the other. For instance, many cities have fire zones in which only fireproof structures can be erected—a very favorable situation for reinforced concrete. Finally, the time element favors structural steel frames, because they can be erected more quickly than reinforced concrete ones. The time advantage, however, is not as great as it might seem at first because, if the structure is to have any type of fire rating, the builder will have to cover the steel with some kind of fireproofing material after it is erected.

Making decisions about using concrete or steel for a bridge involves several factors, such as span, foundation conditions, loads, architectural considerations, and others. In general, concrete is an excellent compression material and normally will be favored for short-span bridges and for cases where rigidity is required (as, perhaps, for railway bridges).

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[7] American Society for Testing Materials, 1911, *Proceedings*, 11, pp. 66–68.
[8] Wang, C. K. and Salmon, C. G., 1998, *Reinforced Concrete Design*, 6th ed. (New York: HarperCollins), pp. 3–5.
[9] "The Story of Cement, Concrete and Reinforced Concrete," *Civil Engineering*, November 1977, pp. 63–65.

1.6 Compatibility of Concrete and Steel

Concrete and steel reinforcing work together beautifully in reinforced concrete structures. The advantages of each material seem to compensate for the disadvantages of the other. For instance, the great shortcoming of concrete is its lack of tensile strength, but tensile strength is one of the great advantages of steel. Reinforcing bars have tensile strengths equal to approximately 100 times that of the usual concretes used.

The two materials bond together very well so there is little chance of slippage between the two; thus, they will act together as a unit in resisting forces. The excellent bond obtained is the result of the chemical adhesion between the two materials, the natural roughness of the bars, and the closely spaced rib-shaped deformations rolled onto the bars' surfaces.

Reinforcing bars are subject to corrosion, but the concrete surrounding them provides them with excellent protection. The strength of exposed steel subjected to the temperatures reached in fires of ordinary intensity is nil, but enclosing the reinforcing steel in concrete produces very satisfactory fire ratings. Finally, concrete and steel work well together in relation to temperature changes because their coefficients of thermal expansion are quite close. For steel, the coefficient is 0.0000065 per unit length per degree Fahrenheit, while it varies for concrete from about 0.000004 to 0.000007 (average value: 0.0000055).

1.7 Design Codes

The most important code in the United States for reinforced concrete design is the American Concrete Institute's *Building Code Requirements for Structural Concrete* (ACI 318-14).[10] This code, which is used primarily for the design of buildings, is followed for the majority of the numerical examples given in this text. Frequent references are made to this document, and section numbers are provided. Design requirements for various types of reinforced concrete members are presented in the code along with a commentary on those requirements. The commentary provides explanations, suggestions, and additional information concerning the design requirements. As a result, users will obtain a better background and understanding of the code.

The ACI Code is not in itself a legally enforceable document. It is merely a statement of current good practice in reinforced concrete design. It is, however, written in the form of a code or law so that various public bodies, such as city councils, can easily vote it into their local building codes, and then it becomes legally enforceable in that area. In this manner, the ACI Code has been incorporated into law by countless government organizations throughout the United States. The International Building Code (IBC), which was first published in 2000 by the International Code Council, has consolidated the three regional building codes (Building Officials and Code Administrators, International Conference of Building Officials, and Southern Building Code Congress International) into one national document. The IBC Code is updated every 3 years and refers to the most recent edition of ACI 318 for most of its provisions related to reinforced concrete design, with only a few modifications. It is expected that IBC 2015 will refer to ACI 318-14 for most of its reinforced concrete provisions. The ACI 318 Code is also widely accepted in Canada and Mexico and has had tremendous influence on the concrete codes of all countries throughout the world.

As more knowledge is obtained pertaining to the behavior of reinforced concrete, the ACI revises its code. The present objective is to make yearly changes in the code in the form of supplements and to provide major revisions of the entire code every 3 years.

Other well-known reinforced concrete specifications are those of the American Association of State Highway and Transportation Officials (AASHTO) and the American Railway Engineering Association (AREA).

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[10] American Concrete Institute, 2014, *Building Code Requirements for Structural Concrete* (ACI 318-14), Farmington Hills, Michigan.

1.8 Summary of 2014 ACI Code Changes

Because this is an introductory textbook on the subject of reinforced concrete design, most readers are seeing the material for the first time. For those readers, this section would not be of much interest. However, for readers who may be familiar with older versions of the ACI 318 Code, this section may be helpful in understanding the changes that have been introduced in the 2014 issue.

Reorganization

ACI 318-14 has been totally reorganized into six categories: General, Systems, Members, Joints and Connections, Toolbox, and Construction. Each category contains several chapters. For example, the Members chapters include separate chapters for One-Way Slabs, Two-Way Slabs, Beams, Columns, and Walls. The Toolbox chapters have provisions that are common to many types of elements including Strength Reduction Factors, Sectional Strength, Strut-and-Tie, Serviceability, and Reinforcement Details. An example of sectional strength is the nominal moment capacity of beam, which is determined in essentially the same way as that of a one-way slab, a two-way slab, a footing, or a wall.

New Chapters

ACI 318-14 has new chapters including Structural Systems (Chapter 4), Joints and Connections (Chapter 16), including beam/column and slab/column joints, connections between members and anchoring to concrete (formerly an appendix to the code). The new Construction chapter (Chapter 26) is written for the designer, not for the contractor, and includes what must be communicated via construction documents to the contractor. A new chapter on diaphragms (Chapter 12) is now included.

Tables

Many new tables have been added to ACI 318-14. Such tables are much clearer than verbiage in earlier codes.

Other Changes

Concrete mix design has been removed from ACI 318-14, and ACI 301 is simply referenced. The designer of a reinforced concrete structure is often not the same person who proportions that concrete mix. The essential requirements of the concrete, such as specified compressive strength and exposure classes, which the designer must specify, remain in the code.

Finite element analysis is now recognized and discussed in some detail. Guidance and limitations on the use of finite elements modeling are now included in the code.

1.9 SI Units and Shaded Areas

Most of this book is devoted to the design of reinforced concrete structures using U.S. customary units. The authors, however, feel that it is absolutely necessary for today's engineer to be able to design in either customary or SI units. Thus, SI equations, which are different from those in customary units, are presented herein, along with quite a few numerical examples using SI units. The equations are taken from the American Concrete Institute's metric version of *Building Code Requirements for Structural Concrete* (ACI 318M-14).[11]

[11] Ibid.

For many people it is rather distracting to read a book in which numbers, equations, and so on are presented in two sets of units. To try to reduce this annoyance, the authors have placed a shaded area around any items pertaining to SI units throughout the text.

If readers are working at a particular time with customary units, they can completely ignore the shaded areas. It is hoped, however, that the same shaded areas will enable a person working with SI units to easily find appropriate equations, examples, and so on.

1.10 Types of Portland Cement

Concretes made with normal portland cement require about 2 weeks to achieve a sufficient strength to permit the removal of forms and the application of moderate loads. Such concretes reach their design strengths after about 28 days and continue to gain strength at a slower rate thereafter.

On many occasions it is desirable to speed up construction by using *high-early-strength cements*, which, although more expensive, enable us to obtain desired strengths in 3 to 7 days rather than the normal 28 days. These cements are particularly useful for the fabrication of precast members, in which the concrete is placed in forms where it quickly gains desired strengths and is then removed from the forms, and the forms are used to produce more members. Obviously, the quicker the desired strength is obtained, the more efficient the operation. A similar case can be made for the forming of concrete buildings floor by floor. High-early-strength cements can also be used advantageously for emergency repairs of concrete and for *shotcreting* (where a mortar or concrete is blown through a hose at a high velocity onto a prepared surface).

There are other special types of portland cements available. The chemical process that occurs during the setting or hardening of concrete produces heat. For very massive concrete structures such as dams, mat foundations, and piers, the heat will dissipate very slowly and can cause serious problems. It will cause the concrete to expand during hydration. When cooling, the concrete will shrink and severe cracking will often occur.

Concrete may be used where it is exposed to various chlorides and/or sulfates. Such situations occur in seawater construction and for structures exposed to various types of soil. Some portland cements are manufactured that have lower heat of hydration, and others are manufactured with greater resistance to attack by chlorides and sulfates.

In the United States, the American Society for Testing and Materials (ASTM) recognizes five types of portland cement. These different cements are manufactured from just about the same raw materials, but their properties are changed by using various blends of those materials. Type I cement is the normal cement used for most construction, but four other types are useful for special situations in which high early strength or low heat or sulfate resistance is needed:

Type I—The common, all-purpose cement used for general construction work.

Type II—A modified cement that has a lower heat of hydration than does Type I cement and that can withstand some exposure to sulfate attack.

Type III—A high-early-strength cement that will produce in the first 24 hours a concrete with a strength about twice that of Type I cement. This cement does have a much higher heat of hydration.

Type IV—A low-heat cement that produces a concrete that generates heat very slowly. It is used for very large concrete structures.

Type V—A cement used for concretes that are to be exposed to high concentrations of sulfate.

Should the desired type of cement not be available, various admixtures may be purchased with which the properties of Type I cement can be modified to produce the desired effect.

One Peachtree Center in Atlanta, Georgia, is 854 ft high; built for the 1996 Olympics.

1.11 Admixtures

Materials added to concrete during or before mixing are referred to as admixtures. They are used to improve the performance of concrete in certain situations as well as to lower its cost. There is a rather well-known saying regarding admixtures, to the effect that they are to concrete as beauty aids are to the populace. Several of the most common types of admixtures are listed and briefly described below.

- *Air-entraining admixtures*, conforming to the requirements of ASTM C260 and C618, are used primarily to increase concrete's resistance to freezing and thawing and provide better resistance to the deteriorating action of deicing salts. The air-entraining agents cause the mixing water to foam, with the result that billions of closely spaced air bubbles are incorporated into the concrete. When concrete freezes, water moves into the air bubbles, relieving the pressure in the concrete. When the concrete thaws, the water can move out of the bubbles, with the result that there is less cracking than if air entrainment had not been used.
- The addition of *accelerating admixtures*, such as calcium chloride, to concrete will accelerate its early strength development. The results of such additions (particularly useful in cold climates) are reduced times required for curing and protection of the concrete and the earlier removal of forms.