

Chapter 1

Introduction

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1.1 Historical Development of Construction and Uses of Construction Materials

1.1.1 Stone age habitats

Mankind's earliest ancestors used natural shelters such as caves and rock overhangs for protection purposes. Gradually, they learned to improve their caves with inlaid stone floors, walls at the entrances and fireplaces. Ultimately they began to build entirely new habitats in locations where there had no natural shelter.

Some of the earliest structures built by man were very simple dolmens: by placing two stones vertically and one flat stone spanning them across. Other stone buildings include granaries and temples. The earliest evidence of a man-made habitat was found Olduvai Gorge in Central Africa, which date to about 2,000,000 BCE [1-2]. A small circle of stones was found stacked to hold branches in position. This was clearly the

work of Homo Habilis, our tool-making ancestor. This precursor to Homo Erectus used fire as early as 3,000,000 BCE. They also used tools (more than a tool-maker) and had campsites. They used wooden poles and/or animal bones to erect a framework over which animal hides or leaves were draped. Hides and bones were from hunting. The tent was erected in its crude form by driving a pole in the ground, and slinging animal hides over it. The hide was then held down with stones.

Clay and wood were often used for permanent dwellings, in the so-called wattle-and-daub construction [1]. The walls were made of small saplings or reeds driven into the ground, and tied laterally with vegetable fibers, then plastered over with wet clay for rigidity.

1.1.2 River valley civilizations — *The first steps in permanence*

Once mankind began to settle, the agglomerations of people formed villages, towns and cities, mainly along the riverbanks of the Nile (The Egyptian Civilization), the Tigris and Euphrates (the Sumerian or Mesopotamian Civilization), the Indus (the Harappan Civilization) and the Yellow River (the Yellow River Civilization). Houses were constructed using sun-dried bricks [3]. The bricks were made from mud and straw, which were abundantly found in the river flood plains and were mixed together. This wet mud and straw mixture was formed in a wooden frame. After the mixture had hardened sufficiently through evaporation, the form was removed. The bricks were then left in the sun to be dried completely. The straw acted as reinforcement to hold the mud together when evaporation caused inevitable shrinkage of the mud. Fired bricks were produced and used later for heavy use areas, like pavements and sewers in Mesopotamia.

1.1.3 Construction in ancient Egypt

The main building material used in Ancient Egypt was stone – mainly limestone. Rough stones were used in building interior walls and

foundations, while fine stones, cut out with special care, were used in decorating main walls or erecting colossal temples. Yellow limestone was brought from Al-Silsila Mount, white limestone from Tura, and gray or red granite from Aswan and alabaster from central Egypt. Basalt was often used in paving roads and laying lower courses of buildings. Generally, the above-mentioned stones, in addition to diorite, marble and porphyries were used in making statues and utensils. Convertible diorite was used in making the famous Chephren statue. Many scarabaeuses and other objets d'arte were made of soft steatite. Ancient Egyptians actually reached unmatched high levels in architectural design and construction engineering. Even at present it is still hard to conceive how they could have all these buildings and structures erected with such high level of perfection and precision, using only primitive and naive tools far incomparable with modern machinery and equipment [4]. Some good examples include pyramids and temples. The pyramids have the deepest impression on the whole world's imagination. Edfu Temple is 137-m-long, 79-m-wide and 36-m-high temple and is still exceptionally almost intact, with its hall, columns, stairs and ceiling still maintaining their original state. In addition, its colors and decorations still look fresh.

1.1.4 Construction in the Greek Era

In the Greek Era, Post 1800 B.C., the use of the stone construction continued. The focus, however, was on the ornamentation of the buildings [5]. The heavy stones, once ornamented, were lifted into place by simple machinery. The concealed faces of the columns had grooves and holes that held the ropes to lift the stones. Metal dowels and clamps were employed to fasten the stone pieces together. No mortar was ever used.

The stone surface was carved by master masons to enhance the visual appeal of the buildings. Moldings were used extensively to give each building a profile. "Orders" were developed to create standardized, symmetrical and precise buildings. The buildings were usually painted in

brilliant colors. Majority of Greek temples were built with stone frame. The trabeated building was constructed with stone columns and timber beams. The maximum stone beam span was 5-6 m. Usually wooden beams were supported on the stone columns. Wood was the predominant material for roofs.

1.1.5 Construction in the Romans times

The Romans made great contributions to construction and developed three different construction methods [6]: (1) stone and masonry, (2) concrete construction, and (3) timber and metal.

Stone and Masonry Construction: Stone construction in the Roman Times was a carryover of the techniques used by the Greeks. The Romans understood the concept of the true arch and used it to its full extent. Stone arches of large spans were used extensively in the construction of aqueducts and buildings. Many of the Roman stone buildings became models for medieval European construction. Stone construction soon gave way to brick construction. Lime mortar, constituted of lime, sand and water, used until the 2nd Century B.C. The best-known example of brick technology developed by the Romans is the Hagia Sophia, with its brick dome spanning 32.6 m.

Concrete Construction: The Romans started to mix pozzolana with lime to make strong lime-pozzolana mortar and concrete in the 3rd Century B.C. The use of lime-pozzolan cement mortar and concrete in construction was a landmark as it altered the interior space of buildings. The crowning example of concrete technology is the Pantheon, a massive structure with brick-faced concrete walls 6 m thick, spanned by a concrete dome 1.5 m thick, 43.2 m above the floor level.

Timber and Metal Construction: Timber technology was also highly developed, evident from the advanced timber form required for the brick

and concrete construction. The Romans also developed the concept of the truss. A truss is a beam with some portions of it hollowed out. The areas, which are hollowed out are redundant in supporting loads but only increase the dead weight of the structure supporting these beams. The Romans used it extensively in their buildings and bridges. Bronze trusses were used where durability and longevity was desired.

Metals were also used extensively in Roman buildings for non-structural purposes. Roman introduced lead and gilded bronze tiles as roofing materials [6]. Lead was very popular as it was waterproof and could be used on low pitch roofs as well. Lead also made pipes to supply fresh water to buildings and to discharge wastewater from buildings. Another material used was glass. Although the Egyptians had discovered it, the Romans were the first to use it in their buildings. Various kinds of colored glass were used as mosaics for interior decorations. The Romans also made the first recorded clear window glass. Glazed sun porches became very popular in villas. It was also used in public buildings and middle-class housing. Thin slabs of colored stone were employed for decoration of interior surfaces in buildings. These stone slabs were fastened to concrete walls with metal fasteners.

1.1.6 *The early industrial age (18th–19th Century)*

The construction activity in the initial stages of the Industrial Age, that is, in the latter half of the 18th century, can be summarized by one single term – mass production [7]. Unforeseen innovation in technology made new building prototypes possible during this period. The methods used by these prototypes were Iron members as the structural frame, and the balloon frame.

With the advent of steam engine and the knowledge of the smelting and puddling process, iron could be made easily for construction purposes at a large scale. Many different forms and members, such as hollow

tubular columns, wrought iron trusses, tension beams, and rivets were standardized and mass-produced in factories. Although initially iron beams were supported by the masonry, soon iron was being used for the entire structure.

Brick was also being mass-produced in factories using the mechanical extrusion method and the fired beehive kilns. This reduced the cost of bricks and led to extensive use in buildings as infill with the iron members as the structure.

Glass was used extensively with the iron frame - the best and most known example being the Crystal Palace in London. The Crystal Palace was made entirely of prefabricated materials, which were simply assembled together on the site. The plate glass panels let in light like never before. The concept of construction underwent a major change. The same prototype was employed for train stations all across western Europe. The biggest one is the St. Pancras Station in London with the iron trusses spanning 74 m.

In the 18th century a big efforts started in Europe to understand why some limes possess hydraulic properties. In 1756, John Smeaton discovered that cement made from limestone containing a considerable proportion of clay would harden under water [8]. Based on his discovery, he rebuilt the Eddystone Lighthouse in 1759, which stood for 126 years before replacement was necessary.

Several other people, including L. J. Vicat and Lesage in France, Joseph Parker and James Frost in England, investigated hydraulic cement during the period from 1756 to 1830. In 1824, Joseph Aspdin, a bricklayer and mason in Leeds, England, took out a patent on a hydraulic cement that he called portland cement because its color resembled the stone quarried on the Isle of Portland off the British coast [8]. Aspdin's method involved the careful proportioning of limestone and clay, pulverizing them, and burning the mixture into clinker, which was then ground into finished cement.

Joseph Monier invented Reinforced concrete in 1849 and received a patent in 1867 [9]. Reinforced concrete combines the tensile or bendable strength of metal and the compressive strength of concrete to withstand heavy loads. Joseph Monier exhibited his invention at the Paris Exposition of 1867. Besides his pots and tubs, Joseph Monier promoted reinforced concrete for use in railway ties, pipes, floors, arches, and bridges, and four years later, he registered another patent to use it in beams and columns [9]. An American mechanical engineer, W. E. Ward, built the first landmark building in reinforced concrete near Port Chester, New York in 1875 [10]. It used reinforced concrete for walls, beams, slabs and staircase. A reinforced concrete system was patented in the United States by Thaddeus Hyatt in 1878 [11]. Later on, there were parallel developments of reinforced concrete frame construction by Ernest L. Ransome in the United States, by Francois Hennebique in France, and by G. A. Wayss in Germany/Austria. Ernest L. Ransome first used reinforcing in 1877 and patented a system using twisted square rods to help the development of bond between the concrete and reinforcing in 1884 [12]. His largest work of the time was the Leland Stanford, Jr. Museum at Stanford University, the first building to use exposed aggregate. He was also responsible for several industrial buildings in New Jersey and Pennsylvania, such as the 1903-1904 construction of the Kelly and Jones Machine Shop in Greensburg, Pennsylvania.

On the other side of the Atlantic, Francois Hennebique, a successful mason turned contractor in Paris, started to build reinforced concrete houses in the late 1870s. He took out patents in France and Belgium for the Hennebique system of construction and proceeded to establish an empire of franchises in major cities. He promoted the material by holding conferences and developing standards within his own company network. Most of his buildings (like Ransome's) were industrial. In 1879 G. A. Wayss, a German builder, bought the patent rights to Monier's system and pioneered reinforced concrete construction in Germany and Austria, promoting the Wayss-Monier system [12].

In 1903 Perret, designed and built a multi-storey building in Paris using reinforced concrete: this structure deeply influenced architecture and concrete constructions for decades, since it was built without load-bearing walls, replaced by columns, beams and slabs. Perret also built museums, churches, garages and theatres, such as the Theatre Champs Elysées.

1.1.7 Constructions in the 20th century — High rise steel structures/buildings

The construction during the late 19th up to the mid-20th Century can be identified by one predominant structural form - the High Rise [13]. This type of structure was usually constructed with either concrete or steel.

1.1.7.1 High rise steel structures/buildings

The first tall structure using steel as its principal building material was the Eiffel Tower in Paris. It was 300 m tall. Its height was not challenged until 1929. But the major innovation was the development of the steel frame, as a structural element. The home of the high rise is Chicago, where the first metal structure was built - the 10-story Home Insurance Company Building in 1885. The metal framing used in this building was completely encased in brick so as to render it fireproof. The Manhattan Building was the first to use vertical truss bracing to resist wind forces. The first all-steel building was the Ludington Building in 1891 [13].

Soon standard construction practice for high rise structures included the steel frame of rolled steel I-beams, riveted and/or bolted connections, diagonal wind bracing, brick or clay tile fireproofing and the caisson foundation. Vertical transportation was by electric-powered hydraulic elevators. But climate control within the structures was still through natural ventilation.

In the years after World War II, glass was used extensively in high-rise structures, culminating in the curtain-walled skyscraper. But the efficiency of such high-rise structures was possible only after the development of rubber as a sealant, artificial climate control, and through the use of aluminum as a building material. One of the major landmarks in curtain walled structures was the United Nations Secretariat Building (1949) in New York City

1.1.7.2 High rise concrete buildings

The major developments of reinforced concrete have taken place since the year 1900. The Ingalls Building, built in 1903 in Cincinnati, Ohio, was the world's first reinforced concrete skyscraper, as shown in Fig. 1.1 [14]. The 16 story building was designed by the Cincinnati architectural firm Elzner & Anderson and was named for its primary financial investor, Melville Ingalls. The building was considered a daring engineering feat at the time,



Fig. 1.1 The Ingalls Building built in 1903 in Cincinnati, Ohio [15].

But its success contributed to the acceptance of concrete construction in high-rise buildings in the United States. Notre Dame du Raincy, built in 1922, was an important breakthrough (especially compared with previous concrete buildings) and is regarded as a masterpiece of architectural design: the lofty arched ceiling and the slender columns bear witness to the exceptional features of this new building material.

The giants and midgiants of the 1930s were all of steel construction. The Johnson Wax Tower, however, provided the impetus for Bertrand Goldberg's twin towers of Marina City, though on a vastly different scale. The Chicago 60-story high-rise, erected in 1962, heralded the beginning of the use of reinforced concrete in modern skyscrapers and with it, competition for the steel frame. Place Victoria in Montreal, constructed in 1964, reached height of 190 m utilizing 42 MPa concrete in the columns. Concretes of higher strength proved to be the key to increased height, permitting as they do a reasonable column size on the floors below. One Shell Plaza in Houston topped out at 218 ft in 1970 using 42 MPa concrete. The Chicago area, with its plentiful supply of high quality fly ash (which helps to achieve a more workable concrete at lower water/cement ratios), has spawned the greatest concentration of tall reinforced concrete buildings. The 70-story Lake Point Towers used 52 MPa concrete to reach 197 m in 1968. Water Tower Place reached 859 feet in 1973 with concrete strengths as high as 63 MPa [10].

The developments during this period have led to construction practices that have become standard for buildings and continue to be so even today. Skyscrapers are the expression of architectural and construction expertise of this century.

1.2 Recent Construction — High Performance Construction Materials

Since the 1980's, the design and construction use more and more high performance materials. High performance construction materials

provide far greater strength, ductility, durability, and resistance to external elements than traditional construction materials, and can significantly increase the longevity of structures in the built environment and can also reduce maintenance costs for these structures considerably. These most significant high performance construction materials include high performance concrete, high performance steel, fiber reinforced cement composites, FRP composites, etc.

The United States, the Strategic Highway Research Program (SHRP) sponsored a project on High Performance Concrete in 1987. In an effort to improve and extend the service life of bridges, the Federal Highway Administration (FHWA) initiated a national program in 1993 to implement high-performance concrete (HPC) in bridges [16]. Also, FHWA initiated a program to develop high-performance steels (HPS) for bridges. A 485 MPa grade of HPS was the first developed, and is specified in ASTM A709 as grade HPS-70W (HPS 485W) (the designation “W” stands for “weathering”). High Performance Steel, grade 70 (HPS-70W) became available for use in early 1996 for fabrication and testing in bridges. Fiber reinforced cement composites and FRP composites are also becoming more and more popular because their unique mechanical properties and corrosion resistance (see Chapters 3 and 5 for detailed discussions).

The other trend is the combined use of several different types of high performance materials in one structure. The combination or composite structures made of several high performance materials could maximize the advantages of these components. High strength steels and high strength concretes have been tested or used in composite construction [17,18]. It has been found that in addition to strength and serviceability, stability, local buckling and ductility are also important effects in the design of composite members incorporating high strength materials [17].

In addition to these technical advantages, the use of high performance materials can have very significant economic advantages as well. The materials cost of high performance materials is usually higher than

conventional materials due to the special requirements for raw materials and manufacturing processes. However, these materials maybe only one component in construction, and the total cost of the finished construction is more important than the cost of an individual material. According to a study by Moreno [19], the use of 41 MPa compressive strength concrete in the lower columns of a 23-story commercial building requires a 865-mm square column at a cost of \$9.90/m². The use of 83 MPa concrete allows a reduction in column size to 610 mm square at a cost of \$5.60/m². In addition to the reduction in initial cost, a smaller column size results in less intrusion in the lower stories of commercial space and, thereby, more rentable floor space.

In addition to increasing the duration of structures, high-performance materials are also valuable because they can improve the efficiency of design and construction practices. For instance, sustainable design and construction, an innovative building approach that incorporates high standards of environmental protection with an emphasis on life-cycle cost considerations, often uses high performance materials because these substances are more environmentally friendly and possess greater recyclable capability than conventional construction materials. The use of high performance materials to increase service life of a structure from 50 years to 100 years will save far more than the amount of money for the original construction cost of the structure. Also, it will conserve natural resources and reduce negative impacts on the environment. Moreover, many of these materials are often much easier and faster to install than conventional construction materials, a key advantage for the many fast-track projects delivered using design-build.

More and more people have been harnessing the advancement in smart materials technology for structural engineering applications. Specifically, the use of smart sensors and actuators as well as advanced signal processing and computational techniques are explored and adapted for structural health monitoring and control of structures. One good example is the Confederation Bridge, which was completed in 1997 and

connects the Provinces of Prince Edward Island (PEI) and New Brunswick (NB) on the east coast of Canada (Fig. 1.2) [20]. The 12.9 km long Confederation Bridge is the world's longest prestressed concrete box girder bridge built over salt water. With 45 main spans of 250 m each and a 100-year design life, the design criteria of the Confederation Bridge are not covered by any code or standard in the world. With a design life of 100 years, the use of high performance concrete and careful attention to production and construction practices were imperative. Over 400,000 cubic meters of concrete was used for the structure. The proposed high-performance concretes were extensively tested for durability, especially through freeze-thaw cycles, sulfate resistivity and chloride diffusivity testing, checking of alkali content and alkali/aggregate reactivity, evaluation of curing regimes for the huge components, etc. Precasting was chosen for improved quality, as well as reduced construction time. A comprehensive monitoring and research program is being carried out to monitor and study the behavior and performance of the bridge under ice forces, short-and long-term deformations, thermal stresses, traffic load and load combinations, dynamic response due to wind and earthquake, and corrosion, and to obtain critical information that engineers now lack in these areas [21].



Fig. 1.2 Confederation Bridge built in Canada, 1997 [20].

1.3 Design Codes and Specifications for Use of High Performance Construction Materials

While the benefits of using high performance construction materials are numerous, many building practitioners are unfamiliar with the behavior and characteristics of these materials. The design and construction community often lacks information about the use of these materials, limiting their capability of achieving the highest possible standards in quality assurance and control construction projects.

High performance construction materials may be derived in two ways: modified existing materials or complete newly developed materials. As for these high performance materials from modification of existing materials, the current design code or regulations may be still applicable. However, for these newly developed high performance materials, new codes or specifications are usually required to be developed for the purpose of design, construction and testing purpose.

For different applications or different construction procedures, different professional associations or committees may need to get involved in the development of specifications or guidelines for design, testing and construction. For example, a number of committee activities from professional organizations are addressing the recommended use and specification of FRP composites. Many organizations have published codes, standards, test methods and specifications for FRP composites and their products for the respective products. Table 1.1 lists some American professional associations and technical committees working on FRP. American Society of Civil Engineers (ASCE) has a technical committee called Structural Composites and Plastics (SCAP) to address the design and implementation of composites. This committee published a design manual in the early 1980's and is currently working to update this manual to address the many FRP composite products developed over the years.

Table 1.1 American professional associations and committees working on FRP.

Organization	Committee
American Society of Civil Engineers (ASCE)	Structural Composites and Plastics
American Concrete Institute (ACI)	440 – Composites for Concrete 440C – State-of-the-art-Report 440D – Research 410E – Professional Educations 440F – Repair 440G – Student Education 440H – Reinforced Concrete (rebar) 440I – Prestressed Concrete (tendons) 440J – Structural Stay-in-Place Formwork 440K – Material Characterization 440L – Durability 440M - Repair & Strengthening of Masonry Structures
American Society of Testing and Materials (ASTM)	ASTM D20.18.01 – FRP Materials for Concrete ASTM D20.18.02 – Pultruded Profiles ASTM D30.30.01 – Composites for Civil Engineering
AASHTO Bridge Subcommittee	T-21 - FRP Composites
Transportation Research Board	A2C07 – FRP Composites

The American Concrete Institute has a Committee 440 – Fiber Reinforced Polymer Reinforcement to develop and report information on fiber reinforced polymer for internal and external reinforcement of

concrete. The committee consists of 13 subcommittees and has published several state-of-the-art review and guides for the use of FRP.

Several ASTM committees are currently working on consensus test methods for the use of rebars, repair materials, and pultruded structural profiles. ASTM D20.18.01 (FRP Materials for Concrete) committee is developing standard test methods for FRP rebar and repair materials. ASTM D20.18.02 focuses on the development of test methods for FRP pultruded profiles and shapes. ASTM D30.30.01 addresses FRP composites products used construction.

The American Association of State Highway and Transportation Officials (AASHTO) Bridge Committee established a subcommittee in 1997 called “T-21 Composites”. This committee has an ongoing effort to develop design guidelines for of the use of composites in bridge applications including FRP reinforced concrete, concrete repair, and vehicular bridge deck panels.

1.4 Organization of This Book

This book is intended to provide some recent progresses and applications of several most commonly used high performance construction materials. Chapter 2 discusses high performance concrete; Chapter 3 discusses high performance fiber reinforced cement composites; Chapter 4 discusses high performance steel; Chapter 5 discusses fiber reinforced Polymer; Chapter 6 discusses masonry materials. Chapter 7 discusses geosynthetics; Chapter 8 discusses coatings and Chapter 9 discusses several smart materials and structures and presents several applications of these materials and structures.

This book can be used as a textbook for advanced courses in civil engineering, or a reference book for students, laboratory workers, engineers and scientists.

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