SUSTAINABLE DEVELOPMENT FOR CONCRETE INFRASTRUCTURE IN CHINA

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ABSTRACT: The growing concern over global warming and other significant ecological changes have made sustainable development become hot topic in all fields of science and technology. Concrete is the most popular and widely used construction material in the world. It not only consumes huge amount of energy and natural sources, but also emits large amount of CO$_2$, mainly due to the production of cement. In China, the annual consumption of concrete has reached 7 billion tons in 2008. It is evident that such large amount of concrete production has put significant impact on the energy, resource, environment, and ecology of the society. Hence, how to develop the concrete technology in a sustainable way has become an urgent issue for the nation. In this paper, the scientific strategies for the sustainable development of concrete infrastructure in China are presented, including deterioration mechanism and damage model of concrete under coupling effect of both loading and environmental factors, as well as the loading-carrying and durability scientifically unified service life design theory. Moreover, the sustainable features of several important concrete infrastructures in China, such as Su-tong Bridge and Qinghai-Tibet Railway, are briefly introduced.

1 INTRODUCTION

In 1987, the world commission on environment and development defined sustainable development as the development that meets the need of the present without comprising the ability of further generation to meet their own needs, and later in 1992 earth in Rio de Janeiro as economic activity that is in harmony with the earths ecosystem [Mehta (1999)]. Concrete is the widely used construction material. Presently, the annual concrete production in China is about 7 billion tons, consuming approximately 1.4 billion tons of Portland cement, 5.2 billion tons of sand and rock, and 0.7 billion tons of water. The principal binder in concrete is Portland cement, the production of which is a major contributor to greenhouse gas emissions. Thus, concrete industry significantly impacts the ecology of our planet. How to develop concrete technology in a sustainable way becomes an urgent issue in China [Bhatty (1984), Bhatty (1986)]. Currently, the research on sustainable development on the concrete has been carried out on the following aspect: low-carbon cement development for concrete, utilization of solid wastes or other environmental material as aggregate in concrete and durability improvement for concrete. There are some evident achievements on the first and the second area, such as wide fly ash application, new type cement development [Li et al (2004)], recycled-aggregate, and recycled-rubber chips as filler...
in concrete [Schimizze(1994), Topcu(1997)]. However, as understanding on concrete microstructure and its effect on macro-scope properties of concrete is very limited, it is difficult to improve concrete durability hence enhance the service life in a more scientific manner. Lack of durability is still a significant issue in concrete technology. For instance, in USA, bridges with designed service life of 75 years only last about 40 years. According to statistics in 2004, 27.5% of bridges in US has durability problem (FHA, USA2006). In China, the number of bridges in danger has increased significantly from 5000 in year 2000 to 15,000 in year 2005 (Transportation Ministry, China, 2007). The economic loss due to corrosion in reinforced concrete structure has reached 1 trillion RMB per year (CAE report 2002). Thus, there is a pressing need to help prolong the service life of structures and buildings in China. To enhance and prolong the service life of concrete infrastructures, basic research should be carried out to better understand the hydration mechanism of concrete materials and the effects of the microstructure on the performance of concrete, and build up microstructure-based constitutive model. Finally, the way to overcome the fetal weakness of concrete and develop a new generation of concrete with super properties shall be developed.

2 SCIENTIFIC STRATEGIES FOR CONCRETE SUSTAINABLE DEVELOPMENT

In year 2009, the ministry of Science and Technology of China has funded a project for the basic research on environmentally friendly contemporary concrete. The objectives of the project are to develop scientific strategies for concrete sustainable development. To achieve the objectives, the following focuses have to be investigated:

2.1 Hydration mechanism of cementitious materials

An effective way of saving energy and natural resources in concrete industry is to reduce the usage of Portland cement in the concrete compositions, as the production of cement requires high energy consumption accompanied by harmful gas emission. Therefore, a large amount of different kinds of supplementary cementitious materials and chemical admixtures are utilized in the concrete mixtures. This, however, will further complex the formulation of concrete mixtures. To better understand the behaviors and control the quality and durability of concrete materials, it is required to fully investigate the hydration dynamics of contemporary concretes. Concrete has a complex hydration process and microstructure, varying in time and depending on its chemical compositions, admixture incorporation and working temperature. The degree of hydration describes the process of hydration, and directly relates to the fraction of the hydration products or porosity in a hydration system that governs the properties of cement based materials.

Electrical conduction in fresh concrete occurs primarily due to ion transport through the pore solution in a cement based system. It is strongly dependent on both pore solution conductivity and porosity. Electrical measurement methods have been applied
to study the microstructure evolution in hydrating cement based concrete materials. However, the direct contact between electrodes and fresh mixtures leads to electrochemical reactions and shrinkage gap, which in turn affect the test results. Recently, a non-contact electrical resistivity method, which eliminates the conventional contact problems, has been developed to measure the resistivity development of fresh concrete and of the pore solution within the concrete mixes. The non-contact electrical resistivity method is used to investigate the hydration dynamics of contemporary concrete materials.

The numerical simulation methods at atomic and molecular scale include quantum chemical and molecular potential based methods. Quantum (first principles) approaches involve solution of the Schrödinger equation describing the interaction of electrons and atomic nuclei. The electrons are described by their wave functions, and the challenge is to adequately describe these functions in a computationally accessible way. The Schrödinger equation cannot be solved exactly except in the most limited cases. Hence, some approximate methods are needed. The Hartree-Fock approach involves an approximate solution of the exact solution to an approximate Schrödinger equation.

With the advancement of technology, a wide range of experimental and computational tools are available in recent decades for discovering of the nature of hydrate of cementitious materials. The experimental methods such as Atomic Force Microscopy (AFM), Small angle neutron and X-ray scattering, Nuclear Magnetic Resonance (NMR), Nanoindentation and High resolution scanning and transmission electron microscopies can be used to reveal at least the part of C-S-H at different scales. For example, AFM can be utilized to examine the aggregation shape of C-S-H at tens of nanometer scale and to determine the cohesive force nature of the hydration products. Small angle neutron and X-ray scattering can be applied in probing “gel” porosity of C-S-H. NMR can be utilized to determine the C-S-H structure and the pore structure of cementitious materials. Nanoindentation can be used to measure the modulus of C-S-H and other hydrates. And high resolution scanning and transmission electron microscopies coupled with chemical microanalysis can be used to determine microstructural development and microchemistry of hydration phases.

2.2 Constitutive model containing characteristics of microstructure

One of the most important elements in the design and analysis of service life of concrete structures is the constitutive modeling of concrete materials. Constitutive modeling is the mathematical description of how concrete materials respond to various loading conditions. The studies of constitutive modeling of concrete can be categorized into two basic types, namely, macroscopic phenomenological modeling and multiscale modeling. For the first type of macroscopic modeling, relationship between quantified parameters and responses of the materials is established largely based on observations and experimental results. Such kind of constitutive modeling does not
consider seriously the physical meaning of those parameters, not mention the characteristics of microstructure of concrete materials. Moreover, it usually assumes concrete as an isotropic and single phased which is not true in the reality. Such kind of simplifications in the macroscopic constitutive modeling of concrete leads to lacking of flexibility and difficulties in simulation of concrete members under complex stress conditions. The second type of constitutive modeling, multi-scale modeling, is suitable to simulate complex composite materials, such as concrete, which have important features at multiple spatial scales. Multi-scale modeling is aimed at calculation of concrete properties or structural behavior of concrete members on one level using information or models from different levels. On each level particular approaches are used for the description of concretes. Following levels are usually distinguished: level of molecular dynamics models (information about individual atoms is included), meso-scale or nano level (information about groups of atoms and molecules is included), level of continuum models, level of device models. Each level addresses a phenomenon over a specific window of length and time. Multi-scale modeling is particularly important since it can predict concrete behaviors based on the knowledge of characteristics of microstructure and hydration dynamics of concrete mixtures.

2.3 High toughness Concrete

The fetal weaknesses of contemporary concrete are their low tensile strength, low toughness, and low ductility. To fundamentally improve concretes performance, an organic-inorganic system is needed. Hence, an organic-inorganic polymer needs to be developed.

Considering that C-S-H gel contributes the most to the strength of hydration product, it will benefit to strength the link between the layers of C-S-H. Also, the voids, especially at the interface, are responsible to low tensile strength. Thus, the admixture to be developed shall have two poles. One pole of the admixture can generate a hydrolysis-bond with hydrated cement, especially C-S-H, and another pole can self polymerize or co-polymerize. The self polymerized chains can fill the voids among the hydration products of cement as well as aggregates and thus form a continuous network inside a concrete. The microstructure of concrete formed in this way will have many connected ductile polymer chains. When concrete is stretched, the polymer chains can provide more deformation and hence the concrete looks “ductile”. In additional, the modified concrete microstructure has much better bond that can increase the tensile strength of concrete. The development of hybrid organic-inorganic polymer dispersion will be based on emulsion polymerization of polyacrylate, polyurethane, acrylatres and siloxane molecular precursors. Hybrid organic-inorganic particles are functionalized with siloxane molecules R’nSi(OR)4-n, where R’ can polymerize or copolymerize. Terminal trialkysiyil groups undergo hydrolysis-bonds with mineral matrix of concrete (cement or aggregates). The parameters such as raw materials amount, ratio, synthesis procedures, synthesis temperature and additives will be studied.
2.4 Load carrying capability-durability unified service life design theory

It has been long realized that concrete structure is carrying out the load while being exposed to various environmental conditions. The mechanical load and environmental condition influence each other during service period of concrete. The property degradation of concrete is caused by the coupling effect of loading and environment. However, traditionally, the design of concrete structure only considers the loading carrying capability of the structure. Moreover, the design code treats the mechanical properties of concrete at both material and structure level as a constant and no variation with time. Since 1990s’, durability issue has caused more and more attention and some design code with consideration of concrete durability has been developed. However, in these preliminary attempts, the durability of concrete structure is taking care only by the detailing described in the code such as the cover thickness of a structure under a certain environmental condition. There is no scientific formulation to quantify the effect of environmental condition. In addition, the code has not considered the dynamic changes of the properties and performances of concrete as either material or structure with time. Thus, the code can not reflect the true service conditions of concrete structure.

It attempts to develop a brand new design philosophy in which the safety, durability and serviceability of concrete structure can be considered in a scientific unified way and hence overcome the limitation of current design code. The service life design theory has to resolve two fundamental issues. The first one is how to introduce factors that influence concrete durability such as environmental issues into a design code quantitively and couple it with mechanical loading effect? The second one is how to consider the material properties and structure behavior dynamically as a function of time?

For the first issue, one solution is to develop a method that can transfer the environmental effect into an equivalent force or stress effect. This can be done by utilizing a plate-form of thermodynamics and porous media theory.

For the second issue, one approach to solve the problem is to find the mechanism and the regularity of material and structure degradation with time. It can be achieved through the study on the deterioration of material and structure under the coupling effect of loading and environmental conditions, the study on structure exposed to real environmental condition under the loading, the computer simulation of structural behavior under different combinations of loading and various environmental factors. Through these studies, the properties and behavior of concrete shall be able to be described as function of time. With such function, the performance of concrete structure at different service period can be predicted and incorporated into the design accordingly.
3 RECENT CONCRETE INFRASTRUCTURES IN CHINA

Currently, a lot of concrete infrastructures are under construction in China, which includes large bridges, high-speed railways, and high-rise buildings. The following are five recent large-scale concrete infrastructures in China.

3.1 Su-tong Bridge

3.1.1 Brief information

The Su Tong Bridge located in Jiangsu province, which is the longest cable-stayed bridge in the world. The construction began in June 2003, linked up in June 2007, and opened in May 2008. It wins 2010 Outstanding Civil Engineering Achievement award from the ASCE. The total bridge length is 8,206 m (26,923 ft) with a main span of 1,088 m, the first whose main span exceeds 1,000 m. A new kind of zinc-galvanized-steel strand that reduces the diameter of its cables was utilized. The total width of the bridge deck is 41 meters including the fairing noses. Su-tong Bridge replaces a cumbersome and potentially dangerous 4-hour ferry ride between Nantong and Shanghai with a 1-hour drive. The dosage of high performance concrete in Su-tong Bridge is 1.10 million m$^3$.

![Su-Tong bridge in Jiangsu province](image)

Figure 1: Su-Tong bridge in Jiangsu province

3.1.2 The sustainable features of Su-Tong Bridge

One evident sustainable feature of Su-Tong Bridge is that the durability improvement of reinforced concrete. In Su-tong Bridge construction, the concrete mix was optimized to improve the durability of concrete in following aspects: (a) the cement with low C3S content was adopted and the cement usage per cubic concrete was reduced...
about 130-170 kg, so the hydration heat of concrete was largely deceased and crack resistance of the concrete was improved; (b) the water usage per cubic concrete was decreased about 10-35 kg, which can decrease porosity and permeability of concrete; (c) the fly ash proportion was carefully calculated for different structure positions of bridge. The experimental results on the concrete durability of S-T Bridge were shown in Table 1. It shows that the expected service life from experimental results of Su-tong Bridge is over 100 years [Wang (2009)].

Table 4: Experiments results on concrete durability

<table>
<thead>
<tr>
<th>Structure position</th>
<th>Freeze-thaw cycles (experiment/design)</th>
<th>Carbonation depth for 28d (mm)</th>
<th>Chloride diffusivity coefficient (m²/s)</th>
<th>Expected service life years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile cap</td>
<td>120/80</td>
<td>10.9</td>
<td>$9.3 \times 10^{-12}$</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>Cable Support Tower</td>
<td>210/80</td>
<td>6.0</td>
<td>$4.3 \times 10^{-12}$</td>
<td>100</td>
</tr>
<tr>
<td>Pier</td>
<td>150/80</td>
<td>8.9</td>
<td>$9.4 \times 10^{-12}$</td>
<td>100</td>
</tr>
<tr>
<td>Box girder</td>
<td>250/80</td>
<td>3.5</td>
<td>$4.4 \times 10^{-12}$</td>
<td>100</td>
</tr>
</tbody>
</table>

3.2 Hangzhou Bay Bridge

3.2.1 Brief information

Hangzhou Bay Bridge located in Zhejiang Province, China. The total length of it is 35.673 km, and the longest span of Hang Zhou Bay Bridge is 448m. It is the longest trans-sea bridge in the world. The construction was five years (2003-2007), and it was opened in 2008. The Hangzhou Bay Bridge has 6 lanes of expressway, with a speed limit of 100 km/hr. The bridge reduced the travel time between Ningbo and Shanghai from 4 to 2.5 hours. The dosage of high performance concrete in Hangzhou Bay Bridge is 2.45 million m³.

3.2.2 The sustainable features of Hangzhou Bay Bridge

Hangzhou Bay Bridge is marine engineer, so the challenge to sustainable development is the durability of the bridge under corrosive environment. A lot of measures were adopted to protect the bridge. First, the concrete cover thickness was carefully designed for different structural positions of bridge. Theoretically, the thicker the concrete cover, the less the chloride reaching steel. But in practical, excessive concrete cover thickness may increase the self weight of structure and is easy to form cracks under bending. Hence, the careful consideration on the determination of cover thickness is a must. The concrete cover thickness for different structure position in Hangzhou Bay Bridge is listed in Table 2.
Figure 2: Hangzhou Bay bridge in Zhejiang province

Table 5: Concrete cover thickness for different structure positions

<table>
<thead>
<tr>
<th>Structure position</th>
<th>environments</th>
<th>Concrete cover thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile</td>
<td>Underwater</td>
<td>75</td>
</tr>
<tr>
<td>Pile cap</td>
<td>air</td>
<td>90</td>
</tr>
<tr>
<td>Pier</td>
<td>Under water</td>
<td>75</td>
</tr>
<tr>
<td>Box girder</td>
<td>air</td>
<td>40</td>
</tr>
</tbody>
</table>

Secondly, the concrete mix was optimized according to the following principles: (a) the cement with low hydration heat and alkali contend was adopted; (b) high efficiency water reducer was adopted to reduce the water usage per unit volume concrete; (c) the proportion of fly ash and mineral powder were determined according the requirements of different structure positions; (d) the contend of chloride ion was strictly limited in raw materials selection. Concrete mix was shown in table 3. The experimental results showed that the concrete used in Hangzhou Bay Bridge has good durability [Zhang, et al (2006)].

3.3 Qinghai-Tibet Railway

3.3.1 Brief information

The total length of Qinghai-Tibet Railway is 1,956 km. The Construction of the 815 km section between Xining and Golmud was completed by 1984; The 1,142 km section between Golmud and Lhasa was inaugurated in July 2006. It is the highest and
longest high-altitude railway that connects Xining and Lhasa. More than 960 km, or over 80% of the Golmud-Lhasa section, is at an altitude of higher than 4,000 m. The Tanggula pass, which is at 5,072 m above sea level, is the world’s highest rail track. The 1,338 m Fenghuoshan tunnel is the highest rail tunnel in the world at 4,905 m above sea level.

Table 6: Concrete mix for different structure positions

<table>
<thead>
<tr>
<th>Structure Position</th>
<th>Usage of raw materials per cubic meter concrete (Kg)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>water/ cement</td>
<td>Mineral powder</td>
</tr>
<tr>
<td>Piles</td>
<td>0.36</td>
<td>165</td>
</tr>
<tr>
<td>Sea piles</td>
<td>0.31</td>
<td>264</td>
</tr>
<tr>
<td>Pile caps</td>
<td>0.36</td>
<td>170</td>
</tr>
<tr>
<td>at sea</td>
<td>0.33</td>
<td>162</td>
</tr>
<tr>
<td>Pier at sea (cast in-situ)</td>
<td>0.345</td>
<td>126</td>
</tr>
<tr>
<td>Pier at sea (precast)</td>
<td>0.31</td>
<td>180</td>
</tr>
<tr>
<td>Box girder</td>
<td>0.32</td>
<td>212</td>
</tr>
</tbody>
</table>

Figure 3: Qinghai-Tibet Railway

3.3.2 The sustainable features of Qinghai-Tibet Railway

The concrete property improvement under low temperature and corrosive ground water is the most evident sustainable feature of the Qinghai-Tibet. The Qinghai-Tibet railway lies in the west area of China at an altitude of more than 4000 meter. About 576 kilometers of the railway is laid on permafrost. The low temperature and corrosive groundwater demand the concrete used in this project must satisfy following
requirements: (a) the early strength of concrete must be high enough to meet the design requirements; (b) the hydration heat of concrete must be low enough to avoid the melting of permafrost; 3. enough resistance ability to corrosive water. According mentioned above, the concrete mix was determined base on the following principles: (a) adopting moderate heat and high sulfate-resistant Portland cement; (b) deceasing the usage of cement; (c) adopting high quality aggregate; (d) adding compound admixture, whose function should include: reducing water usage, increasing early strength and anti-freezing. High performance concrete used in Qinghai-Tibet railway reach following standard: the minimum cast temperature is -20°; the ability of anti-freezing cycle is F300; the value of chlorine anion penetration is smaller than 1000 Coulomb [Xie(2003)].

3.4 Shanghai Tower

3.4.1 Brief introduction

Shanghai Tower will be the tallest building in china when it is completed in 2014, which is under construction in Pudong district. It will have 128 stories (632 m), containing an area of 380,000 m² and can accommodate more than 30,000 people working together in the tower. It is with 955 piles underneath, the pile cap is a one piece disc of 121 m diameter and 6m thick, and will have an inside-outside transparency and is the only super high-rise building wrapped in public spaces and sky gardens.

Figure 4: Shanghai Tower
3.4.2 The sustainable features of the tower

The skyscrapers twisting, asymmetrical envelope features a carefully considered structure and texture that work together to reduce wind loads on the building by 24%, saving building materials and construction costs. The buildings spiraling parapet collects rainwater to be used for the towers heating and air conditioning systems, and wind turbines situated below the parapet generate on-site power. Additionally, the gardens nestled within the building’s double-skin facade create a thermal buffer zone while improving indoor air quality.

3.5 The Third terminal in Beijing Airport

3.5.1 Brief information

Construction of Capital airport Terminal 3 started on 2004, and took 4 years to build. Capital airport Terminal 3 is the single largest airport expansion project in the world. The two passenger terminal buildings have a roof area of over 80 acres. These structures have a larger surface area than all of Heathrow’s five terminals put together. The terminal 3 was constructed to satisfy the fast increasing Beijing’s air traffic and requirement of the Beijing Olympics. The addition of terminal 3 and the third runway will increase the airport’s capacity from 35 million to over 80 million passengers per year.

![Figure 5: The third terminal of capital airport](image)

3.5.2 The sustainable features of the third terminal

Terminal 3 is one of the world’s most sustainable buildings. Its soaring, aerodynamic roof uses south-east orientated skylights to make the most of natural heat and light.
Water consumption is minimized by adopting separate water systems for drinking and non-portable use, such as flushing toilets. Carbon emissions of the building have been reduced by minimizing energy consumption with integrated environmental control systems, incorporating shading into the design to reduce the need for cooling, and combining natural daylight with intelligent use of artificial lighting.

Figure 6: The south to east skylight of terminal 3

4 SUMMARY

The massive infrastructure construction programs are carrying out in China, which make the sustainable development of concrete industry become a national urgent need. In this paper, scientific strategies for concrete sustainable development in China has been introduced with emphases on the modeling of nano-scale material structure of concrete, microstructure-based constitutive relationship, development of high toughness concrete, and development of load-carrying and durability unified design theory. The achievements of these basic studies have contributed to the durability enhancement of concrete infrastructure. Five typical infrastructures have been introduced with clear descriptions on their sustainable development features.

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REFERENCES


