Construction and Building Materials 48 (2013) 80–90

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Review

Only tall things cast shadows: Opportunities, challenges and research needs of self-consolidating concrete in super-tall buildings

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HIGHLIGHTS

- Experience with self-consolidating concrete (SCC) in tall building construction is outlined.
- Pumping SCC to high altitude, workability retention and lateral pressure on formwork are examined.
- Elastic, shrinkage and creep shortening of SCC super-tall columns and walls need special care.
- Seismic, fire and wind performance of SCC are analyzed; related design provisions are discussed.
- Research needs and innovations pertinent to SCC in tall buildings are highlighted.

ARTICLE INFO

Article history:
Received 24 January 2013
Received in revised form 13 June 2013
Accepted 24 June 2013

Keywords:
Self-consolidating concrete
Tall building
Pumping
Workability
Hot weather
Modulus of elasticity
Shrinkage
Creep
Fire
Seismic

ABSTRACT

The world's tallest skyscrapers are taking concrete to ever higher altitudes. Indeed, high-strength flowable concrete has become a material of choice for the construction of tall buildings. However, technological challenges associated with using concrete in super-tall buildings are daunting. For instance, Dubai's Burj Khalifa, the world's tallest building completed in 2010 standing 828-m tall with 163 floors, had plans to take concrete higher abandoned somewhere around an altitude of 580-m due to pumping challenges. In 2012, the Holy City of Makah's Royal Clock Tower became the world's second tallest building, standing 601-m tall. This building also experienced the dares of pumping concrete beyond 520-m in height. The City of Jeddah's Kingdom Tower is expected to exceed one kilometer in height upon completion and will take concrete higher than ever before in stringent hot weather conditions. This article discusses the experience with flowable and self-consolidating concrete in skyscrapers, examines the opportunities and technical challenges facing SCC construction in super-tall buildings and highlights needed innovations and technological breakthroughs.

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http://dx.doi.org/10.1016/j.conbuildmat.2013.06.051

1. Introduction

As early as 1956, architect Frank Lloyd Wright unveiled design for a mile-high skyscraper, yet recognized that construction materials available at that time were inadequate for his vision. With advances in high-performance concrete, leaps in elevator technology, integrated approach to the building envelope, mechanical and electrical systems and subsequent reduction in energy consumption, and innovations in safety such as flame-, smoke-, chemical-, and gas-resistant refuge floors, buildings are now soaring taller and taller [1].

When urban development cannot expand laterally, it grows vertically. This is the main thrust for several super-tall buildings in congested urban and pricey land locations. Yet, building taller has also become an expression of economic power and national sovereignty, a statement of "we are here and we are important". Indeed, we have entered an era of super-tall structural concrete buildings. Hence, concrete technology needs to be prepared for the upcoming challenges.

Back in the 1980s, it took more than a decade for the record of tallest reinforced concrete (RC) building to be broken. The Water Tower Place in Chicago (262-m), which had held the title since 1976, has seen two projects topping it out in a single year: The 311 South Wacker Drive (295-m), and the Two Prudential Center (274-m) entitled Chicago to the world's three tallest reinforced concrete buildings in 1989 [2].

The situation has changed considerably since then. Most new super-tall buildings (more than 80 stories tall) will be erected in places other than North America and Western Europe. In 2012, out of the 20 tallest buildings in the world, 18 are in Asia, with 9 in China, 6 in the Middle East, and 3 in Malaysia and Taiwan. Currently, among the world's tallest 100 buildings, 23 are in the City of Dubai alone. The 828-m tall Burj Khalifa, which became in 2010 the world's tallest building, will likely not hold the record for over 5 years.

This haste to build taller and take concrete to greater loftiness escalates technical concrete technology challenges and brings about problems that have not yet been solved. This article discusses the experience gained and the challenges and possibilities of SCC construction in super-tall buildings and highlights needed technological breakthroughs.

2. Experience with SCC in super-tall buildings

According to the Council on Tall Buildings and the Urban Habitat [3], there have been 320 proposed buildings 500-m or taller; with 97 buildings taller than 300-m already under construction around the world in year 2012. The vast majority of these has been or will be constructed primarily with RC [4]. This is because high-performance concrete (HPC) has become vital for the construction of skyscrapers from a structural and economical point of view. Higher mechanical strength is crucial to carry loads and reduce the cross-sections of vertical load-bearing elements, while a high modulus of elasticity is necessary to limit deflections and wind sway. Added to the high early-strength of HPC, prefabricated reinforcing steel cages and advances in slip- and climb-form technology, construction schedules with HPC can be accelerated dramatically. Thus, HPC has become a much stronger contender for super-tall buildings compared to structural steel. Structural concrete is expected to be the material of choice for future tall buildings because concrete systems have twice the dampening effect compared to steel due to increased mass. This has been further bolstered by the perception of better fire resistance in the aftermath of the twin-tower tragic collapse in New York. Arguably, most super-tall buildings in the future will be made of HPC, with a steel or composite spire at the top.

Owing to its inherent advantages, including easier pumping, ability to flow through congested reinforcing steel and fill formwork effectively with little or no vibration, SCC which is a special form of HPC, has become essential for super-tall buildings. For instance, the construction of the 508-m tall Taipei 101 (Fig. 1a), which was the world's tallest building in 2004, and the 85-storey Tungtxt & Chingtai Towers in Taiwan required concrete with a slump flow in the range of 580–620-mm and compressive strength of 56-MPa. In the fall of 2005 during the construction of the 423-m tall Trump International Hotel and Tower (Fig. 1b), a 3-m-thick, 3600-m^3 mat slab was cast at the core of the building using 69-MPa SCC at 56-d. The concrete was placed in a single pour primarily by conveyor over the

Fig. 1. The (a) Taipei 101 (Taiwan), (b) Trump Tower (Chicago), (c) Infiniti Tower (Dubai), and (d) Tower One, World Trade Centre New York all used SCC in their construction (Photos from [3]).