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Burj Khalifa – a new high for high- performance concrete

The world's tallest structure – the 828 m high Burj Khalifa building in Dubai – has set a new benchmark for engineering super-tall buildings. In particular, it significantly raised the bar for high-performance-concrete construction, with its massive reinforced-concrete core and wings extending nearly 600 m above ground level. This paper describes the how the extreme concreting challenges were overcome on the project, including successfully pumping and placing high-performance concrete to unprecedented heights as well as preventing excessive cracking and shrinkage in the hot and arid conditions. Practical advice is provided for future projects.

The 828 m high Burj Khalifa (formerly known as the Burj Dubai) in Dubai, United Arab Emirates opened in January 2010 as the world's tallest structure. Its Y-shaped, 586 m high reinforced-concrete core also represented a step-change for high-performance concrete construction (Figure 1).

The project is the latest and largest manifestation of the world's increasing appetite for super-tall buildings. According to the Council on Tall Buildings and the Urban Habitat (CTBUH, 2010), there were 82 buildings of 300 m or greater under construction in January 2010, the vast majority of which were being constructed primarily with reinforced concrete. At least four buildings of around 1000 m are currently at the detailed proposal stage and others with heights of 1400–1600 m are on drawing boards.

High-performance concrete is a crucial part of the viability of super-tall buildings, both structurally and economically. The stiffness provided by high-modulus

concrete has significant benefits in terms of limiting movement, and high strength is necessary to reduce the cross-section of vertical elements. Furthermore, the pumpability and high early strength of high-performance concrete coupled with prefabrication of reinforcing cages and advances in slip- and climb-form technology mean that large, complex reinforced-concrete structures can be constructed at rates of two to three levels per week. Properly designed reinforced concrete is thus becoming far more competitive with structural steel in terms of construction speed.

For the many super-tall structures and other major infrastructure projects under construction in the Middle East, the durability of high-performance concrete also helps to ensure the required service life will be achieved in a hot, chemically aggressive environment. However, such concrete can be more sensitive than conventional concrete during the plastic and early hardening phase, particularly in a harsh drying environment.

Figure 1. The 828 m tall Burj Khalifa dominates the Dubai skyline and is the world's tallest structure by far – the first 586 m of the building is constructed from high-performance reinforced concrete (www.imresolt.com)

This paper discusses the issues encountered with using high-performance concrete on Burj Khalifa and how they were overcome.

Pumping high-performance concrete

The suitability of reinforced-concrete construction for super-tall buildings is entirely dependent on the ability to pump the concrete. The material may not be viable if large quantities need to be placed by crane, which would not only limit the casting rate but also significantly delay other works. However, whereas the literature contains a great deal of information on many characteristics of high-performance concrete, there is little information on pumping.

It was originally planned to conduct staged pumping at Burj Khalifa, which would have involved a separate set of problems and possible delays. However, following mixture development, procedural modifications, pressure monitoring and the advent of powerful

pumps such as the Putzmeister 14000 SHP-D, a world-record pumping height of 601 m was achieved during the final part of the core wall casting in November 2007 (Figure 2). The previous record was 448 m at Taipei 101 Tower in 2003.

It was also considered economic to pump relatively small quantities of C50 concrete for metal deck composite slabs above the 586 m concrete core rather than use cranes, adding a further 5 m to the record in April 2008. For a 48 m³ slab using 3 m³ skips with a 30 min transit time, the maximum casting rate would be 12 m³/h and would require two cranes full time for 4 h. For pumping, the time in the pipeline was approximately 30 min at this elevation but resulted in a relatively uninterrupted casting rate of 20 m³/h or more thereafter. The 11 m³ of concrete evacuated during cleaning the pipeline was used in other applications.

Mixture proportions

One of the challenges to designing pumpable concrete in the Middle East

is the use of crushed aggregate for both coarse and fine aggregate. Two principal types of aggregate are used in the region: gabbro and a high-quality limestone, principally from the Emirates and Oman, though the quality of the fine aggregate can vary significantly around the Gulf.

The abrasion characteristics of coarse aggregate are an important consideration for pumping: the rate of wear of the pipeline is a significant cost consideration, particularly at high pressure. The lifespan of a pipeline when using highly abrasive gabbro can be as low as 10 000 m³. For Burj Khalifa, approximately 40 000 m³ of a suitably designed mix containing a dolomitic limestone was pumped through the central pipeline with only minor local replacement.

Another crucial consideration in mixture proportioning is the pipeline diameter and the maximum aggregate size. A 150 mm pipeline was used on Burj Khalifa, which enabled a 20 mm maximum aggregate size to be used up

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Figure 2. A world record concrete pumping height of 601 m was achieved on 8 November 2007

to level 100 (346 m). There are issues with weight, cost and concrete volume associated with the use of larger diameter pipes for high-pressure pumping. As such, use of a smaller diameter pipeline with a smaller maximum aggregate size may be more practical in many applications.

There is a tendency today to use a high proportion of fine aggregate in high-performance concrete, particularly when it is designed to have a slump flow exceeding 500 mm. However, even with higher fines, these concretes were found to have low shrinkage and creep characteristics. In the Emirates, a fine dune sand ($<600\ \mu\text{m}$) is also used to increase the finer fraction and the improve cohesion of the mixture, while in other areas such as Qatar – where dune sand contains high quantities of gypsum – viscosity-modifying admixtures can be used to improve cohesion and segregation resistance.

In the case of Burj Khalifa, the fine-aggregate percentage for tower mixes was approximately 50% and fly ash was used at a replacement level of 13–20% together with silica fume at 5–10%. A specially modified superplasticiser was developed for the project by BASF to achieve greater workability retention with early strength development. Indicative mixture proportions are given by Aldred (2007).

Pumping trials

Concrete pumping trials were conducted before the Burj Khalifa tower construction using a Putzmeister BSA 14000 HP-D stationary pump with a maximum hydraulic pressure of 310 bar. A length of 600 m of high-pressure ZX 125 delivery pipe was laid out horizontally with transducers to measure concrete pressure after pumping through distances of 250, 450 and 600 m (Figure 3). The pipeline was in direct sunlight, but during one of the cooler months of the year.

Five different concrete mixtures were tested, and fresh and hardened concrete properties were measured before and after pumping. This procedure provided useful data, indicating that single-stage pumping would be possible as well as highlighting certain practical problems which reduced possible blockage during construction. However, there were

changes in a number of parameters that meant friction factors calculated for the pumping trial were different from in situ pumping.

An alternative procedure to horizontal trials is the use of in situ pressure transducers at the hopper, at the end of the horizontal section of the pipeline and at various elevations to establish the friction factor in situ. The limitation of this procedure is that blockage of the pipeline cannot be allowed, which tends to inhibit pushing the limits.

Appropriate positioning of pumps and planning of concrete-truck flow on and off site will help ensure smooth operation of pumping. Equipment and tools necessary to clear the pipeline in the event of blockage should be kept in a locked area near the point of discharge to enable immediate action by the pumping team if required. A seminar with the concrete supplier, pump operators, contractor's supervisors and consultant's representatives should be conducted, with an interpreter if necessary, so that all parties know the procedure and their role. This should be repeated regularly: a problem with pumping concrete on a super-tall tower is that the degree of difficulty is always increasing but the team can become blasé.

Effect of pumping on concrete properties

Concrete in the Middle East has a potential for blockage during pumping due to temperature effects and delays. If practically possible, all pumping of concrete, particularly in summer months, should be conducted at night. The batching plant should be as close as possible to the project to reduce transit time and disruptions to supply – a site plant is best.

Careful consideration should be given to the maximum allowed concrete placement temperature. To achieve the common limit of 32°C with high-performance concrete, and depending on the moisture content of the fine aggregate, the added water content could be almost completely composed of flake ice during the summer months, when shade temperatures can exceed 50°C. Limited variation in rheology and concrete temperature through summer will help minimise pumping problems.

Batching plants in the Middle East generally use pan mixers or similar where the ingredients are well mixed before discharge into a truck. At large replacement levels, most of the flake ice needs to melt to lubricate the mix before discharge. Monitoring the ammeter in the plant provides a good indication of the workability of the concrete in the pan, and workability should be measured at the plant and site regularly to confirm full melting before pumping.

If there is no ice facility at the batching plant, an alternative is to use a high-volume fly ash mixture to limit the heat of hydration. This was done for the 4 m thick raft of the 412 m Al Hamra Tower in Kuwait, where the casting was scheduled in August and a peak temperature of 71°C was specified, and the batching plant did not have an ice plant.

At various elevations on the Burj Khalifa project, concrete was tested for rheological properties, using an Icar rheometer, and temperature both before and after pumping. The sampling included C80-20, C80-14 and C60-14 concretes. There was some variation in the results but the average effects of pumping to elevations from 350 m to

580 m was a 2–3°C rise in temperature and a 10% reduction in slump flow. Pumping was found roughly to halve the plastic viscosity of the concrete and double the dynamic yield stress. The results appear related to the increase in temperature during pumping.

The significantly lower plastic viscosity after pumping will reduce the segregation resistance of the concrete, and should be considered during mix design and when deciding on placement procedures. On the other hand, pumping will tend significantly to increase early-age compressive strength. The greater strength after pumping combined with the significant concrete volume within typical structural elements means that the in situ compressive strength can greatly exceed that of compliance cube/cylinder specimens, particularly if taken before pumping.

Where demanding early-age strength targets are required, the in situ maturity should be assessed using appropriate methods to avoid possible unnecessary modification to the mixture, such as reduced retardation, that may compromise pumpability. While sampling at the point of discharge would be more representative of the concrete

Figure 3. A 600 m, 125 mm diameter concrete delivery pipe fitted with transducers was laid out on the ground near the site to help assess pressures due to pipe friction

in the actual structure, it can create significant logistical and safety problems, especially on a confined climb form. On Burj Khalifa, samples were taken at a site laboratory with periodic assessment of the effect of pumping by sampling concrete after it was pumped.

Practical pumping applications

At Burj Khalifa there were three stationary concrete pumps positioned in parallel on the ground floor slab adjacent to the tower: two Putzmeister BSA 14000 SHP-Ds with maximum hydraulic pressure of 360 bar (equivalent to a concrete pressure up to 240 bar) and one Putzmeister BSA 14000 HP-D with a maximum hydraulic pressure of 310 bar (Figure 4). The pumps were connected to 150 mm diameter high-pressure pipes servicing the three wings and the central core, all with separate delivery pipelines. This configuration meant that concrete could be placed at up to three separate locations simultaneously.

Free-standing Putzmeister placing booms with a reach of 28 m were located on each of the three wings while a larger placing boom with a reach of 32 m was used for the central core (Figure 5). The booms were secured to the Doka climb-form system and were raised along with the formwork. The delivery pipelines were connected to reducers several floors below the formwork to connect to the

125 mm diameter booms.

The general trend of increasing pumping pressure with elevation and the effect of different concrete types are shown in Figure 6. At floor 101, the concrete for the core walls changed from C80-20 to C80-14, with a noticeable reduction in pumping pressure. The increased water/cement ratio of the C60-14 mixture appeared to reduce pumping pressure slightly compared to C80-14.

All the potential benefits of pumping high-performance concrete can be lost if blockage occurs and therefore preventing blockage must be a vital consideration. Blockage can be caused by priming with a wet slurry, excessive delay, inadequate retardation and incompatibility of admixtures. Measurement of fresh concrete properties at the site can be a useful guide to the suitability of the delivered concrete before pumping. Temperature, slump flow and visual inspection for segregation after slump flow should be tested both at the plant and on site. Good practice is to measure the first three trucks and then regularly thereafter. On Burj Khalifa, detailed rheological properties of the core concrete were assessed at every fifth level.

With the extreme ambient temperatures that can occur in the Middle East, blockage due to setting is a particular concern. On a super-tall structure, the substantial volume within

the pipeline and the time for the concrete to reach the point of discharge need to be fully understood before attempting to push 'old' concrete through. The old adage of 'better safe than sorry' is especially true of evacuating a pipeline in which a problem has occurred or when the concrete in the pipeline has exceeded an agreed time since batching.

Concrete quality control

There have been significant advances in many aspects of concrete technology in the Middle East, with great increases in strength, modulus and durability. However, a serious limitation in the region has been the lack of systematic quality control. This has often been exacerbated by high test errors of cube samples as well as sometimes unreliable reporting of compliance data. Production standard deviations of greater than 7 MPa have been common as are within-test standard deviations of 3 MPa or more based on 28-day pair differences.

Significant sources of error are the quality of the cube moulds, sampling, curing and testing. Samples for compressive strength or other hardened properties should be taken at a properly controlled testing facility. Attempting to take samples at the point of discharge often results in poor to non-existent initial curing and early mechanical damage during transport.

Figure 4. A total of 165 000 m³ of concrete for the Burj Khalifa tower was delivered by three Putzmeister pumps on the ground floor with up to 240 bar capacity

Figure 5. MX32 Putzmeister concrete placing boom on the core, seen here with its operator, had a 32 m reach and was mounted on a 20 m high steel column attached to the Doka climbing formwork

Compliance data are often used for quality assurance but not in a timely manner to influence production, which has led to over-design of concrete mixtures. Aside from reduced economy, the variability in compressive strength indicates an underlying variability in mixture proportions, which may also influence rheology and pumpability.

Due to the high production and testing variability, it is prudent to include an in situ testing programme to confirm design assumptions.

Placing and finishing

High-performance concrete in the Middle East is often designed with high workability and would be considered self-consolidating concrete in many parts of the world. However, it is often placed and vibrated using the same techniques as traditional concrete, which can lead to segregation.

High-workability, high-performance concrete should be allowed to flow from the point of discharge and stop moving before any limited vibration (Figure 7). In the case of vertical elements, small portable tremie pipes can be placed at the approximate flow distance apart to reduce the time to position the placing boom or pump outlet. Such modifications to construction practices can be very helpful in super-tall structures, enabling contractors to keep the concrete pumping at a constant rate and thereby avoid blockages due to excessive articulation of placing booms containing static concrete, particularly when the weather is hot. Any blockage in a placing boom is difficult to clear and the piping is expensive to replace.

The installation of a reducer near the pump can be a good precaution so that any concrete with a high segregation potential blocks at that location rather than elsewhere in the pipeline. This will not necessarily prevent blockage caused by a wet slurry, or stop viscosity reduction during pumping, but it is a good precaution against variability in the delivered concrete.

High-performance concrete in the Middle East typically contains 5–10% silica fume with a high cementitious content and has a tendency rapidly to

Figure 6. Graph showing how pumping pressure increased with height up to around 200 bar – and the reduction due to changing from 20 mm to 14 mm aggregate above 346 m

Figure 7. Placing high-workability concrete in the core walls at night – minimal movements of the boom between placing points helped to avoid blockages

form a 'skin' under the harsh drying conditions. The skin can limit the melding of cast layers, but can be reduced by retaining moisture in the concrete surface by the use of evaporation retarders and other methods to reduce evaporation.

The thixotropic nature of self-consolidating concrete can also induce distinct layer casting of the material. The first consequence of this is often only visual but reductions in mechanical strength of more than 40% have also been reported by Coussot and Roussel (2006). A dramatic reduction in strength following a critical delay between casting a subsequent layer is also shown by Roussel and Cussigh (2008). This can be a particular concern in casting self-consolidating-concrete rafts or other elements where the delay between layers can be substantial and no vibration is conducted.

High-performance concrete usually has negligible bleed and can be quite cohesive. Therefore finishing works require operatives to develop a feel for material. Trial applications should be conducted early to enable the finishers to become familiar with the concrete's properties and to confirm an acceptable finish. Evaporation retarders facilitate finishing by retaining moisture in the upper layer helping to eliminate sprinkling of water on the concrete during finishing, which reduces surface quality.

Early protection and curing

The low bleed characteristics of high-performance concrete and the strong drying conditions in the Middle East make the concrete particularly susceptible to plastic shrinkage cracking. In the warmer months, high-performance concrete will often have a placement temperature less than ambient and moisture will tend to condense on the fresh concrete surface. However, after the surface has heated to ambient temperature, the formation of plastic cracks can be rapid and dramatic if appropriate measures are not taken to limit evaporation.

An evaporation retarder is a very practical and inexpensive method to reduce plastic shrinkage cracking. Wind breaks and sun shades are also helpful. Effective fogging is the best method as it

can actually keep a high humidity layer at the concrete surface, though wind breaks may be necessary to confine the body of air above the concrete.

For flatwork, concreting and finishing in the heat of the day should be avoided with pours planned so that curing can commence before 10 a.m. at the latest. The general guideline as given in ACI 305-99 (ACI committee 305, 1999) is that the rate of evaporative loss which exceeds the rate of bleeding (i.e. when plastic cracking would occur) is approximately 1.0 (kg/m²)/h (NRMCA, 1960). However, some agencies in the USA require that pouring of high-performance concrete bridge deck overlays be postponed until the rate of evaporation is less than 0.25 or 0.50 (kg/m²)/h (VDT, 2002; Hover, 2006).

If plastic cracks do develop, the cracks concerned should be vibrated if the concrete has not reached initial set. Attempts to close plastic cracks by trowelling will generally only cover over the cracks, which may influence structural performance and provide pathways for chlorides to the reinforcement.

The optimum curing for high-performance concrete is ponding with water. This provides water to replace that used in hydration, improving concrete properties and helping to reduce early autogenous shrinkage. The latent heat of evaporation helps release the heat of concrete hydration, which can markedly reduce peak temperature – especially in concrete containing fly ash, slag and natural pozzolans. The use of polythene over wet hessian will help keep water in contact with the concrete surface but does not allow evaporative heat loss from the surface. Ponding is best for thicker elements.

Early-age autogenous shrinkage can be particularly significant in high-performance concrete containing high replacement levels of slag (Aldred and Lim, 2004). Even limited periods of water curing immediately after finishing can thus provide significant reductions in autogenous shrinkage. However, the immediate application of a curing membrane may increase early autogenous shrinkage by blocking the pores, which causes greater tensile stresses within the concrete. In applications where

prolonged water curing is difficult, liquid water curing for the first day or so before application of a curing membrane would still have considerable benefits.

For vertical surfaces, the use of a controlled-permeability form liner is a good technique for improving the density and appearance of the concrete surface. The water that collects in the liner is also sucked into the hydrating concrete, providing excellent early curing for vertical surfaces – traditionally the most difficult to cure effectively. Alternatively, the formwork should be kept in place for as long as possible. On Burj Khalifa, where the formwork could be set back within 12 h, a sprayed curing compound was used.

Due to widespread use of crushed limestone aggregate with a low coefficient of thermal expansion and the relatively warm climate, the use of insulation on formwork is rarely required in the Middle East to control internal thermal restraint cracking.

Conclusion

High-performance concrete offers immense benefits to developers, consultants and contractors working on the hundreds of super-tall structures under construction and planned in the Middle East and elsewhere in the world.

The material's high strength and modulus mean that super-tall buildings can have more slender vertical elements. Also, as has been proved on the Burj Khalifa project in Dubai, single-stage pumping to over 600 m is now possible and this, together with high early strengths, allows rapid cycle times to meet today's demanding construction schedules.

However, appropriate care and attention to mix design, placing, protection and curing is vital to minimise potential problems with pump blockage, segregation, autogenous shrinkage and cracking.

Burj Khalifa shattered all previous world construction records by a considerable margin and required an enormous effort by all parties involved to overcome its many construction challenges – not least with regard to using high-performance concrete (Figure 8). In the quest to build the world's next tallest structure, the lessons learned at Burj Khalifa must not be overlooked.

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Figure 8. Burj Khalifa set new standards for reinforced-concrete construction but there is no room for complacency in future projects (www.imresolt.com)