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Application of High Performance Concrete in Petronas Twin Tower, KLCC

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Abstract

KLCC(Kuala Lumpur City Center) Petronas Twin Tower, the world's tallest skyscraper, is 452 meters in height, which is 9 meters taller than the Sears Tower in Chicago. This super high rise building has 88 floors plus 6 stories basement and each tower has 200,000 m2 of total floor area. The project required high strength and high performance concrete up to 80 MPa. Utilizing high strength concrete resulted in cost saving, balance of material supply in the Malaysian market, minimized the member cross sectional areas, and maximized the usable space.

This paper will focus on the development of high performance concrete for the highest building in the world, which required careful planning and choice of materials, laboratory and mock-up testing to confirm the mix design, and strict control on the logistic plans to ensure the quality control and quality assurance programs. In addition, this paper will also discuss the means and methods of directly pumping the concrete to 88th floor and 380m high, and the main issues considered in estimating and confirming, by in-situ measurements, the column shortening of the Tower. Estimating the column shortening required due considerations to the condition of the mix, site work, and weather.

Keywords: 80MPa, Mix Design, Direct Pumping, Column Shortening

1. Introduction

KLCC (Kuala Lumpur City Center) Petronas Tower consists of 94 story twin towers, that rises into the sky of Kuala Lumpur at 452 meters above the ground. The twin tower building located in the center of commercial area in Kuala Lumpur, Malaysia. One of the towers is built by Samsung Engineering & Construction Group, Korea and the other tower is constructed by Hazama Corporation, Japan.

The purpose of this project was to build a world's tallest multi-purpose building in the center of Kuala Lumpur's business center. This project not only served the need of the people but it served as a symbol of their growing economic strength and potential toward the advanced country. Figure 1 shows the completed Petronas Twin Tower.

The structure of the building consists of a dual system consisting of reinforced concrete core wall system, and exterior reinforced concrete columns. The floor framing system consists of composite steel framing system. A composite metal deck frames between the steel beams, and acts compositely with them.

Reinforced concrete was selected as the primary structural material for the lateral resisting system as used extensively in the tower because of its availability and availability of skilled labor in Malaysia in particular and South-east Asia in general. In addition, reinforced concrete structures are utilized as primary structural material because of material supply and weather conditions.

Table 1 below provides information related to the project brief, however, Table 2 provides information related to the concrete materials utilized for the project.

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Fig. 1. Photograph of the completed towers

Table 1 Summary of the project brief

Item	Description
Client	Kuala Lumpur City Center Berhad
Contractor	Samsung-Kukdong-Jasatera J/V
Construction Period	1994. 3 ~ 1997. 2
Floor Area	Tower 196,309 ㎡ Wing 30,592 ㎡ Total 216,901 ㎡
Stories	Super Structure 92 Basements 6 Total 98
Structure	Reinforced Concrete & Structural Steel Beam
Formwork	Self Climbing Form Jumping Form
Concrete	High Performance Concrete (40~80 MPa, cubic)
Re-Bar	Pre-fabrication System

Table 2 Summary of the concrete material

Location	Floor	Grade (MPa)
Column	B6~L22 L23~L60 L61~L84M2	80 60 40
Core Wall	B6~L14 L15~L44 L45~L84M3	80 60 40
Ring Beam	B5~L23 L24~L61 L62~L84M3	80 60 40
Slab on Metal Deck	-	30
C.I.P Slab	-	40

2. Production of High Performance Concrete

The British standards are utilized as a basis for the contract documents and high performance concrete was used significantly in the project. The definition of high performance concrete utilized for the project includes high strength concrete, workability, and durability. The definition of high performance concrete might be different country by country, the definition of high performance concrete used for this project is as summarized in Table 3.

Table 3 Definition of High performance Concrete

Item	Description
Strength(MPa)	Age 28day≥700 Age 1day≥350 Age 4 hour≥200
Workability	Water-Binder≤ 35% Excellent Workability No Segregation
Durability	Durability coefficient≥ 80% (300 Freezing and Thawing cycle)

2.1. Selection of Raw Materials

Most of the materials for the high performance concrete were available in Kuala Lumpur and the materials selected for the concrete mix design took into account durability, and workability requirements.

'MASCRETE', the ready-mix product with OPC(Ordinary Portland Cement) and PFA(Pulverised Fuel Ash) in 80 : 20 ratio were used to improve the workability, long term strength, and to reduce the hydration heat. Silica fume was added to G80 concrete to achieve the high strength requirements. In order to increase the workability of the concrete mix and to achieve 22cm slump in spite of the low water-binder ratio, water reducer P300N and superplasticizer R1000, (both are MASTER BUILDERS' products), were utilized.

2.1.1. Aggregates

The selection of aggregates play a very important role in the production of high performance concrete, therefore careful planning and material investigation was required to select the proper aggregate type, which included at least the aggregate strength, source of aggregate, grading distribution, shape, maximum size, and the percentage of deleterious substances presents in the aggregate.

The maximum size of coarse aggregate used for G80 was 13mm, however, 25mm coarse aggregate was used for G40 and G60 concrete.

2.1.2. Silica Fume

Silica fume was added for G80 to reduce the unit weight of cement and to reduce the heat of hydration of concrete during the curing process. It is reported that most of silica fume particles are adhered to the surface of cement particles, and the remainders mix with cement particle.

2.1.3. Water reducer and Superplasticizer

High performance concrete mix is proportioned on basis of low water-binder ratio, so it was necessary to add water reducer and superplasticizer to get the required workability. For KLCC project, water reducer Pozzolith 300N and superplasticizer Rheobuild 1000 were used, and both are MASTER BUILDERS' products.

Superplasticizer is added only to design high performance concrete in some cases, but for this project, water reducer was used to achieve basic slump and superplasticizer was added to reach to the target slump. This process helped the slump to remain uniform.

The proper dosage of Pozzolith 300N is 0.3% of cement, and that of Rheobuild 1000 is 1.0%, but that will be increased as the quantity of binder is increased. For KLCC project 0.2~0.3% of Pozzolith 300N and 0.2~1.8 Rheobuild 1000 was used in conformity with concrete grade.

2.2. Trial Mix

Despite of the high quality control programs that Samsung planned for the production of high performance concrete, the concrete mix design was targeted to be 15 MPa higher for G40 concrete and below, and 20 MPa for G60 concrete and above.

This strategy was incorporated into the concrete mix design in order to allow for the potential of strength loss in the production process at the batch plant, or during transportation of concrete in the mixer truck, or during the concrete placement at the site.

Table 4 depicts that the actual concrete is higher than the actual design strength.

Table 4 Properties of Concrete

<table>
<tr><th colspan="2">Grade</th><th>G40</th><th>G60</th><th>G80</th></tr>
<tr><td colspan="2">W/B (%)</td><td>44</td><td>30</td><td>27</td></tr>
<tr><td colspan="2">S/A (%)</td><td>44</td><td>44</td><td>40</td></tr>
<tr><td colspan="2">Test Strength (MPa)</td><td>62</td><td>87</td><td>102</td></tr>
<tr><td colspan="2">Age (day)</td><td>28</td><td>56</td><td>56</td></tr>
<tr><td colspan="2">Elastic Coefficient (GPa)</td><td>33.0 (43day)</td><td>36.5 (48day)</td><td>37.0 (28day)</td></tr>
<tr><td colspan="2">Slump (mm)</td><td>175±25</td><td>200-20
200+40</td><td>200-20
200+40</td></tr>
<tr><td colspan="2">Mix Design (MPa)</td><td>55</td><td>80</td><td>100</td></tr>
<tr><td rowspan="2">Admixture (%)</td><td>Water reducer</td><td>0.36</td><td>0.24</td><td>0.17</td></tr>
<tr><td>Superplas-ticizer</td><td>0.24</td><td>1.32</td><td>1.81</td></tr>
</table>

Table 5 provides information about optimum mix design through numerous trial mix design for 3 kinds of high performance concrete for the KLCC project.

Table 5 Optimum Mix Design

<table>
<tr><th colspan="2">Grade</th><th>G40</th><th>G60</th><th>G80</th></tr>
<tr><td colspan="2">W/B (%)</td><td>44</td><td>30</td><td>27</td></tr>
<tr><td colspan="2">S/A (%)</td><td>44</td><td>44</td><td>40</td></tr>
<tr><td colspan="2">C (kg)</td><td>400</td><td>500</td><td>184</td></tr>
<tr><td colspan="2">M (kg)</td><td>-</td><td>-</td><td>345</td></tr>
<tr><td colspan="2">S/F (kg)</td><td>-</td><td>-</td><td>35</td></tr>
<tr><td colspan="2">W (kg)</td><td>180</td><td>150</td><td>152</td></tr>
<tr><td colspan="2">Coarse Agg.</td><td>1000</td><td>1000</td><td>1040</td></tr>
<tr><td colspan="2">Fine Agg.</td><td>775</td><td>785</td><td></td></tr>
<tr><td rowspan="2">Admix-ture</td><td>P300N</td><td>1.2</td><td>1.0</td><td>0.8</td></tr>
<tr><td>R1000</td><td>0.8</td><td>5.5</td><td>8.5</td></tr>
</table>

3. Mock-up Test

Since the exterior concrete frame columns were 2.4m diameter, required high strength concrete, and ambient temperature was 30℃, special precaution and measures needed to be taken into account in order to verify the concrete quality from the batch plant to concrete placement.

Therefore, concrete mock-up tests with actual size members were performed before construction stared in order to get the actual behavior of the high performance concrete, which includes production at batch plant, properties of fresh concrete, characteristics of hardened concrete, heat of hydration, and strain in the concrete members resulting the heat of hydration.

The potential for thermal crack of due to temperature variation in large concrete members is one of the major issues that needed to be considered. Since a 2.4m diameter concrete column with G80 concrete was required, a mock-up test for columns was performed in order to address the following issues.

- QA/QC program to produce the uniform concrete quality
- Early striking of form panels
- Curing method for sound concrete when it is hardened
- Method of preventing from excess hydration heat and thermal cracks

Two(2) of 2.4m diameter column mock-up test were performed. These mock-up are an actual representation of typical concrete columns in the towers. The reinforcing steels in the columns were laid as per the design drawing and thermal sensors were positioned at each part of column to measure the heat of hydration and the thermal strains

3.1. Mix design of concrete

Ordinary portland cement with silica fume were used for the first column mock-up test, a pulverised fuel ash was used in the second mock-up in addition to ordinary portland cement and silica fume. MASCRETE , mixture of ordinary portland cement and pulverised fuel ash with 80 : 20 mix ratio was available in the Malaysian market.

Table 6-1 and 6-2 summarize the mix design utilized for G80 mock-up tests for the columns.

Table 6-1 G80 Concrete Mix Design for Mock-up Column

	Mock-Up Column 1	
	Design Mix	Actual Mix
OPC (㎏/㎥)	505	503
Mascrete (㎏/㎥)	-	-
Silica Fume (㎏/㎥)	30	29
Water (ℓ)	134	133
C. Agg. (㎏/㎥)	1000	990
F. Agg. (㎏/㎥)	750	738
P300N (㎏/㎥)	1	1
R1000 (㎏/㎥)	9.06	9.08
Slump (㎜)	220	195
Conc. Temp (℃)	-	32

Table 6-2 G80 Concrete Mix Design for Mock-up Column

	Mock-Up Column 2	
	Design Mix	Actual Mix
OPC (㎏/㎥)	184	185
Mascrete (㎏/㎥)	345	343
Silica Fume (㎏/㎥)	35	34
Water (ℓ)	152	152
C. Agg. (㎏/㎥)	1006	1003
F. Agg. (㎏/㎥)	728	715
P300N (㎏/㎥)	0.8	0.8
R1000 (㎏/㎥)	8.48	8.49
Slump (㎜)	220	220
Conc. Temp (℃)	-	33

3.2. Measuring the heat of hydration and strains

Thermal sensors were positioned at each of the mock-up columns in order to measure the heat of hydration and strains. Maximum measured temperature reached 91.6℃ at 29 hours after casting for the first column mock-up test occurred, the second column mock-up test reached 87.0℃ for the second mock-up at 26.5 hours after casting.

The strain for the first column mock-up was 146 micrometer, and for the second column mock-up, it was 118 micrometer. Micro cracks were observed on mock-up due to the thermal temperature difference between the column core to exterior surface of the column.

Table 7 provides information about the results of measurement of internal temperature and strain for the first and second column mock-up.

Table 7 Internal temperature and strain for the first and second column mock-up

	Mock-Up Column 1	Mock-Up Column 2
Peak Temp.	91.6℃ at 29.0 hours	87.0℃ at 26.5 hours
Bulk temp. Max	82.7℃ at 14.5 hours	79.7℃ at 22.0 hours
Diff. Temp. (Max)	57.5℃ at 27.5 hours (center to corner)	52.9℃ at 33.0 hours (center to corner)
R (Max)	0.27	0.24
Strain (Max)	146 micro strain (center to corner)	118 micro strain (center to corner)

3.3. Compressive Strength Test

In order to shorten the tower construction period, it was necessary to remove the column formwork system after 12 hours of casting. Therefore, the column mock-up tests were utilized as a basis to understand the behavior of the concrete under these conditions.

The concrete strength of mix design was correlated with the actual in situ behavior of the column mock-up tests. Comparison of the compressive strength of the cored sample from the column mock-up tests(1 and 2) to the concrete test samples are shown in table 8 and 9 below.

Table 8 Concrete compressive strength comparison between the cored sample and cube specimens for the first column mock-up test

	No.	Compression Test		Average Strength	
		Date	Time	Age	Strength
Core	1	2/9	02:00	14 hrs	37.8
	2	2/9	12:50	1 day	66.5
	3	2/12	12:10	4 days	71.8
	4	2/15	15:15	7 days	77.8
	5	3/25	16:00	45 days	79.0
Cube	1	2/9	00:00	12 hrs	25.8
	2	2/9	12:00	1 day	45.0
	3	2/12	12:15	4 days	72.7
	4	2/15	-	7 days	82.9
	5	3/8	-	28 days	104.2
	6	3/25	-	45 days	102.3

Table 9 Concrete compressive strength comparison between the cored sample and cube specimens for the first column mock-up test

	No.	Compression Test		Average Strength	
		Date	Time	Age	Strength
Core	1	2/9	03:00	13.5 hrs	30.25
	2	2/9	16:40	1 day	68.0
	3	2/12	14:10	4 days	77.0
	4	2/15	16:30	7 days	82.0
	5	3/25	16:00	45 days	85.8
Cube	1	2/9	1:30	12 hrs	19.3
	2	2/9	13:30	1 day	40.0
	3	2/12	13:45	4 days	71.5
	4	2/15	13:45	7 days	83.8
	5	3/8	13:00	28 days	105.5
	6	3/25	13:00	45 days	107.6

3.4. Mock-up Test Results

The utilization of the column mock-up was very critical in identifying all the critical issues that are required in mass production the very large columns with high strength concrete. The following conclusions can be derived from the column mock-up tests :

- The compressive strength of cored specimen was higher than the cube specimen at the early stage (4 days and below).
- The compressive strength of cored specimen was lower than that of cube specimen by 23% for first column mock-up and 20% for second column mock-up at 46 day strength.
- The thermal crack due to excess heat of whereas no cracking occurred at the second column mock-up. This indicated that the pulverised fuel ash mixed MASCRETE have reduced the heat of hydration and thus eliminated the potential for thermal cracking.
- Removal of the form panels at 8 hours after concrete placement can be achieved since the concrete strength was higher than the specified 15 MPa. This also satisfied the 12 hour construction planning requirement for this project.

4. Quality control of High performance concrete

The quality of high performance concrete for KLCC project was controlled at each stages of concrete production, transportation, site testing, placing, and curing that is required by project strict specification requirements.

4.1. Concrete Production

PIONEER was selected as concrete supplier through strict pre-qualification process. Batch plants were built on site for easier and shorter transportation, which minimized the potential risk of producing the quality of concrete required

However, outside batch plants were arranged in case PIONEER's on site batch plants was not operational

4.2. Transportation

To minimize the slump loss of high performance concrete due to high ambient temperature in Malaysia, the shortest transportation time was the optimal choice. Therefore, the batch plants were established on site.

To prevent from confusion of delivery places which was adjacent to each other, the channel for radio communication was open always to get the information to the places where the concrete was poured among truck drivers. The drivers were allowed to depart from the plant only after they have correct information of the concrete placing area.

4.3. Site Test

The slump test was performed as the truck arrived at concrete placing area. For every truck, visual inspection was performed and for every two truck, slump test was performed. In case the slump was too low, admixture was added and mixed, but in case the slump was too high, the truck was forced to returned with the comments on delivery order sheet not to make same mistakes.

4.4. Placement

Concrete pumps were used for most of concrete placement, and tower cranes were used partially. The concrete was directly pumped up a non stop reaching to 380m at the 88th floor without intermediate pump station, this renewing the world record. The direct concrete pumping has resulted time and cost saving without loss in concrete quality.

For the direct vertical pumping of concrete, quality control of concrete itself is essential along with regular concrete pump and pipe line tests and cleaning. Two(2) BP 8000 pumps, made in Germany, were used for the Tower area and one(1) BP 3000 pump was used for the Bustle area.

The concrete was pumped to the top level where it was finally poured into the designated areas with concrete pipe placing booms attached to both sides of core wall. The placing booms were self- climbing type device supported by the brackets, which were installed at the outside of core wall had a working radius of 27 meters.

4.5. Concrete Curing

A simple curing method was utilized in the Tower and it was considered in the concrete mix design that complies with the ambient temperature and moisture conditions.

The curing compound was applied on the surface of columns and the core wall as soon as formwork was removed, and moisture curing was performed for the slabs and beams.

5. Column Shortening

In design and construction of super high-rise buildings, one of the most important factors is to predict and plan for the decreasing aspect of the building height caused by the deformation of the vertical structure.

The tolerance value and detailed design solutions against deformation of the vertical structure should be prepared at early design stage.

In the case of Petronas Tower, we anticipated 610mm deformation due to the elastic contraction, creep and shrinkage of concrete. A compensation program for each floor was adopted as the construction progressed to get a designed floor elevation after 20 years.

Figure 2 provides information about the comparison between the actual-measured values and pre-calculated values, and shows that this tower was so properly designed and built that the time-dependent shortening and differential movements do not affect the strength and serviceability of the structure.

5.1. Details against Deformation

In order to account for the effect of relative deformation between the exterior columns and the core wall, the following details were incorporated in the final construction of the project, which included at least :

- Long slot holes are adopted on the joint area of beams connecting the core wall and column. Beams are movable to the extent of the camber angle.
- The vertical joint area of the curtain-wall was designed with 28mm spare space for construction work and 20mm space for transformation.
- Ball joint, mechanical coupler, telescoping sleeve, etc were designated to prevent a damage of vertical pipes.
- Copper plate film inserted between elevator rails and a clip tied system for the rail allowed the rail well to operate vertically for each floor.

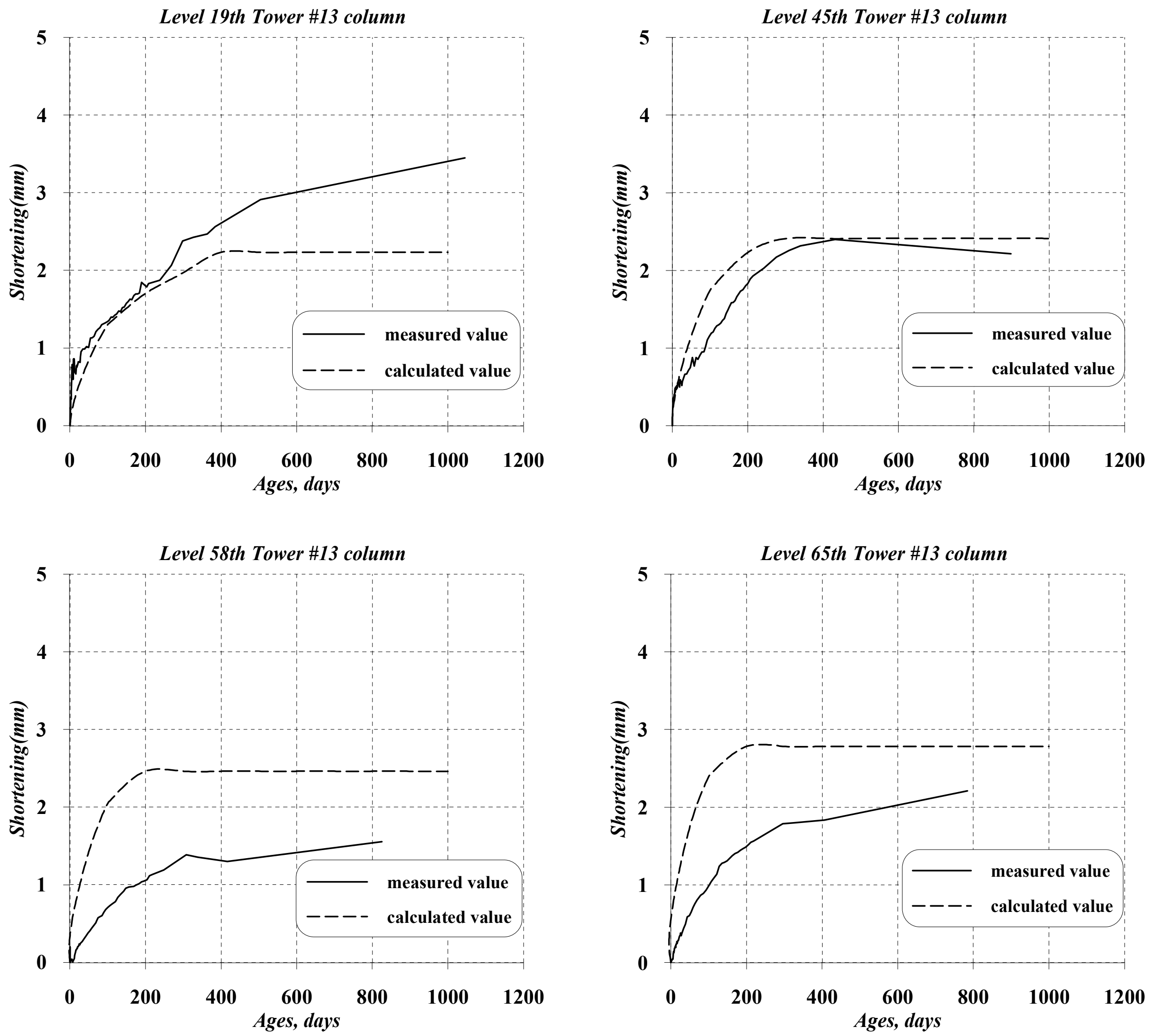

Fig. 2. Measured and calculated values

5.2. Monitoring

It is important to compare the pre-calculated/predicted deformation values, which based on theory, with actual measurements. In the KLCC Project, the pre-calculated values were exemplified and monitored by 100 measuring gauges where placed on total six floors, periodically.

Conclusion

High performance concrete used in KLCC project satisfied the following project requirements and renewed the world record for direct concrete pumping to a new height.

- Design cube compressive strength of 80 MPa (11,600 psi)
- Use the local product as much as possible
- Select the aggregates available in close proximate to the site as much as possible
- Reduce heat of hydration to prevent thermal cracking
- Concrete direct pumping up to 380m without intermediate pumps
- Achieve early strength within 12 hours thus allowing for early formwork removal
- Minimize the slump loss for the smoother pumping
- Simpler curing method that was considered in design

While the above requirements may be considered in every project in the world where the high performance concrete is required. The ways of approach to satisfy the requirements are different by project requirements, location, and market situations.

Therefore, precise study and review must be necessary at every single stage of construction planning, material selection, production, placement and curing, in order to satisfy the project requirements before the application of high performance concrete.

And all of the results of study and review must be recorded as a part of QA/QC program of the project and must be made available to all parties involved in the project.

References

1) K.S. Yom et al. (1998) A study of monitoring and compensation for column shortening. Journal of The Korea Concrete Institute