



Quality Assurance and Control of the Largest and Longest Continuous Concrete Pour in Sudan

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ABSTRACT

This paper aims to document the largest and longest continuous concrete pour in hot weather in Sudan which had been carried during the casting of the raft foundation of the National Club Project in Khartoum. The paper describes the planning and logistics management taken before, during, and after the pour in addition to the adopted quality control and quality assurance processes. Moreover, the paper assesses the quality of the produced concrete in 7 and 28 days age using different codes. The results shows that the concrete strength is satisfied the project requirements. Also, the paper present the spatial distribution of concrete strength over the raft foundation.

المستخلص

تهدف هذه الورقة لتوثيق أكبر وأطول عملية صب خرسانة في الجو الحار في السودان والتي جرت أثناء صب الأساس الحصيري لمشروع النادي الوطني في الخرطوم. الورقة توصف التخطيط وإدارة الخدمات اللوجستية التي تم تبنيها قبل وأثناء وبعد عملية الصب هذا بالإضافة إلى عملية ضبط وضمان الجودة. علاوة على ذلك قيمت الورقة جودة الخرسانة المنتجة في عمر 7 و 28 يوم باستخدام كودات ممارسة مختلفة. أظهرت النتائج إن مقاومة الخرسانة تلبي متطلبات المشروع. أيضاً الورقة عرضت التوزيع المكاني لمقاومة الخرسانة في الأساس الحصيري.

Keywords: Largest concrete pour, Longest concrete pour, Raft foundation, Mass concrete, Hot weather, Quality control, Quality Assurance.

1. Introduction

During the period 13-18 June 2015, the raft foundation of the National Club Project (NCP) in Khartoum, Sudan, was cast using 21,451.35m³ of concrete completed in 115 hours. This is considered the largest and the longest continuous concrete pour in the Sudan. Therefore, this paper aims to document the executive measures taken to pour successfully the largest concrete pour in Sudan utilizing reinforced concrete (RC) grade C30/35, at the NCP project as well as to assess the quality of the cast concrete.

According to Guinness World Records [1], at that time, the world record for the largest and also for the longest concrete pour was 19,624.0 m³ completed in 49 hours, achieved during the pouring of the foundation for the Lakhta Center Multifunctional Complex (Russia) in Saint Petersburg, Russia, during the period 27th of February to 1st of March 2015. The concrete pour took about 49 hours, with concrete being delivered to the site from 13 different production plants. The Russian's record was then broken in Dubai, UAE when a 19,793.0 m³ of concrete continuously poured during 9 - 11 Sep. 2016 for Geepas International Limited tower In Sharjah, UAE, during 13-16 April 2017. That record has also been broken in Muweilah Mall foundation pouring continuously 20,246 m³ of concrete. Up to that date, the continuous concrete pour in the NCP-Sudan records (i.e. 21,451.35 m³ and 115 hours) have not been broken although a great opportunity was missed to set it as a Guinness World record, Figure 1. In May 20th 2017 this record was broken in Dubai, UAE during the casting of the raft foundation of 21,580 m³ of concrete over 35 hours and 19 minutes. In March 2018, a new record for the longest continuous concrete pour was set by PS-CO in Iran for continuously pouring concrete over 5 days and 4 hours and 11 minutes (approximately 124 hours), [2]. Recently, in January 2019, a new record of the largest continuous concrete pour of 32,315.5 m³ in 24 hours was set by Navayuga Engineering Company Limited at the spill channel of the Polavaram Dam Project in India.

The NCP is located on the Nile Avenue in Khartoum, Sudan. The raft contains 21,451.35 m³ spread over an approximate surface area of 15,000 m² with thickness varying between 750 and 1700mm. The project is lying

only a few meters far from the Blue Nile River bank, it is a challenging task to avoid any possible water leakage through construction joints. Thus, it was decided to cast the raft foundation continuously, without any stoppage, as a one casting operation to prevent water leakage in addition to the other water proofing measures. This decision was the one of the major challenges of the project. Another challenge, is that the mass concrete pour took place during hot weather with temperature range of 35-45°C with a possibility of rain.

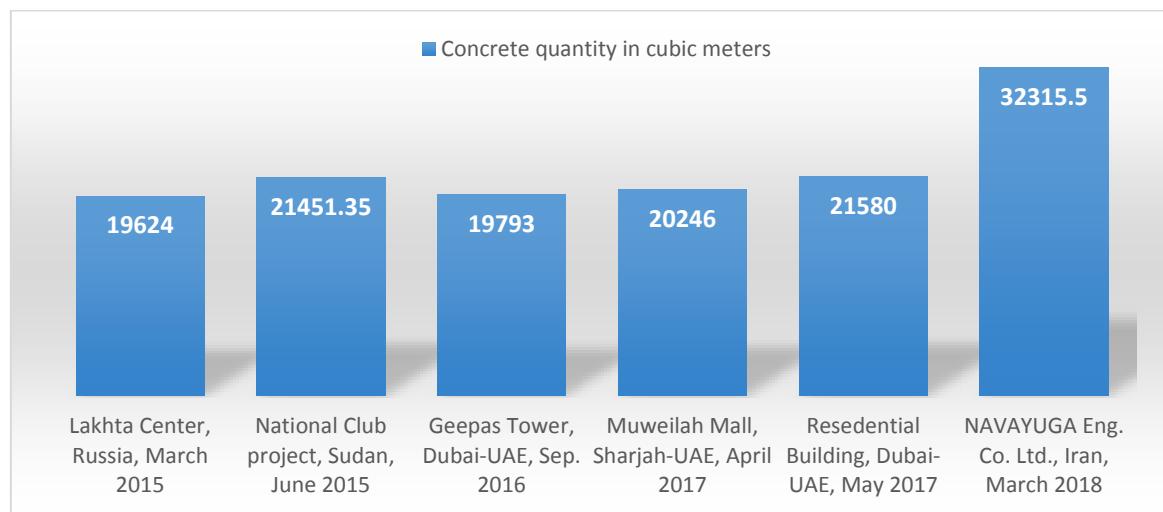


Figure 1: World records for the largest continuous concrete pours

2. Risks of mass concrete in hot weather of the NCP

According to the ACI Committee 207, Mass concrete is defined as '*any volume of concrete with dimensions large enough to require the measures be taken to cope with generation of the heat of hydration from the cement and attendant volume change to minimise cracking*' [3]. Therefore, special attention was paid to the possible risks of casting mass concrete in the hot weather. The risk of casting in hot weather, besides thermal cracking, is the rise of the internal concrete temperature above the 70°C suspected for causing Delayed Ettringite Formation (DEF), [4]. The DEF is well known to be caused by prevention of developing Ettringite and allowing internal sulphates to be free inside the concrete. Once the concrete is exposed to water after hardening, a most likely scenario to occur in the NCP, an internal sulphate attack will start jeopardising the durability of the structure raft foundation.

There is an evidence that the maximum adiabatic temperature increases with cement content as well as placing temperature [5]. They reported a direct linear proportionality between the maximum adiabatic temperature and placing temperature. Higher placing temperature produces higher maximum adiabatic temperature. Chuslip et al. [6] reported that a 350 kg/m³ mixture with W/C =0.350 got initial fresh concrete temperature of 27°C to 30°C. Also they reported that the temperature rise when casting a 300 mm cube of concrete in a block “hot box” was only 7° C per 100 kg of ordinary Portland cement (OPC), compared with the measured in situ values of 12–13°C per 100 kg of OPC. For the purpose of the design and to avoid any potential DEF attack arising from high hydration temperature of mass concrete, a concrete mix design for cube grade C30/35 (cylinder/cube strength) and 150 mm slump with fresh concrete temperature not exceeding 35° C was used.

3. Casting schedule and working plan of the RMCC

To achieve the task of continuous pour, a consortium of seven Ready Mixed Concrete Companies (RMCC) was formed to supply ready mix concrete as per the concrete mix design. For precaution and planning purposes, all the working plans were based on continuous casting of 23,000 m³ (as stated in the project BoQ) of concrete as one-non-stopping operation. The general schedule plan was to start casting on the 13th of June 2016 and finish on June 18th on 24 hours continuous casting assuming half-a-day in the first and the last days of the cast (i.e. 120 hours). To maintain the correction measures in the 1st day and possible compensation needed at the 6th day, the casting quantities per day are planned as shown in Figure 2.

Achieving this casting schedule was requiring to work continuously with a casting rate of about 192 m³ per hour as shown in Eq. (1).

$$\begin{aligned}
 \text{Casting rate} &= \frac{\text{Total concrete quantity}}{\text{number of days} \times \text{hours in a day}} & (1) \\
 &= \frac{23,000}{(0.5 + 4 + 0.5) \times 24} = 192 \text{ m}^3/\text{hr}
 \end{aligned}$$

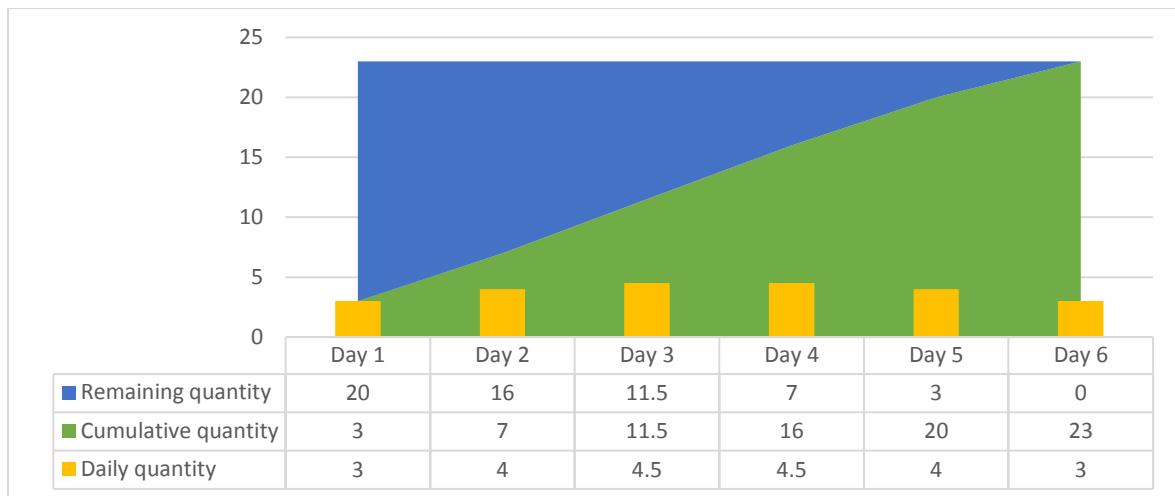


Figure 2: Proposed concrete casting quantity (in thousands of m³)

To calculate the number of concrete trucks required per hour, first the time needed for one truck trip has to be estimated. This should include any possible traffic delays as the location of the construction site relative to the RMCC batching plants requires passing through most of the busiest streets in Khartoum city. Moreover, some trucks especially those coming from plants in Khartoum North need to cross the congested Burri (Armed Forces) Bridge. According to the previous experience of the RMCC it was estimated that one round trip of a concrete truck to be 120 minutes (i.e. 2hrs). The round trip time was estimated assuming 10 minutes time for mixing and loading, average of 45 minutes to transit concrete to the site, 10 minutes for manoeuvring and pouring in the concrete pump, another 10 minutes for concrete pumping into the raft, and finally 45 minutes to return to the batching plant (Figure 3).

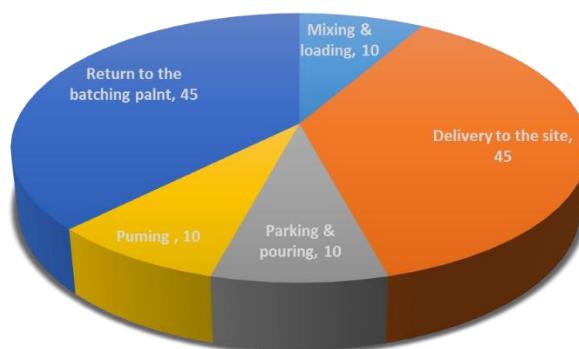


Figure 3: Estimated time required for one round trip for each concrete truck (120 minutes)

For a truck with capacity of 9 m³, the truck casting rate will be given by, Eq.(2):

$$\begin{aligned} \text{Truck casting rate} &= \frac{\text{Truck capacity}}{\text{Truck round trip time}} = \frac{9}{2} \\ &= 4.5 \text{ m}^3/\text{hr} \end{aligned} \quad (2)$$

As a result, the minimum number of trucks required to pump 192 m³ per hour are calculated by Eq. (3):

$$\begin{aligned} \text{Number of trucks} &= \frac{\text{Casting rate}}{\text{Truck casting rate}} = \frac{192}{4.5} \\ &\approx 43 \text{ trucks} \end{aligned} \quad (3)$$

In other words, the casting of the raft foundation in the NCP required at least 43 trucks per hour to work continuously to achieve the suggested plan. Accordingly, the RMCC were instructed to provide in total 55 truck mixers including extra 12 standby trucks. It was expected to have a truck every 1.4 minutes that required high level of traffic control inside and outside the construction site. Accordingly, location of concrete pumps, routes for entry and exit of concrete transit trucks were implemented as proposed in Figure 4. The traffic control was enforced using a one-way traffic system (see red arrows in Figure 4) for concrete transit and pumping trucks and providing one entrance and four exits for the site traffic.

The casting sequence was planned to start from the West (Zone 1) down to the East (Zone 3) as depicted graphically by the dotted arrows in Figure 4.

The proposed plan was executed with minor deviations. The concrete was poured over 115 hours continuously started from 13 June 2015 at 10:30 AM and finished on 18 June 4:00 AM. The quantities of poured concrete was 4621 m³ in the first 24 hour, then, 5051, 6667, 2567, 2600 m³, approximately. Note that the final total quantities agreed by all parties for payments is 21,451.35 m³.

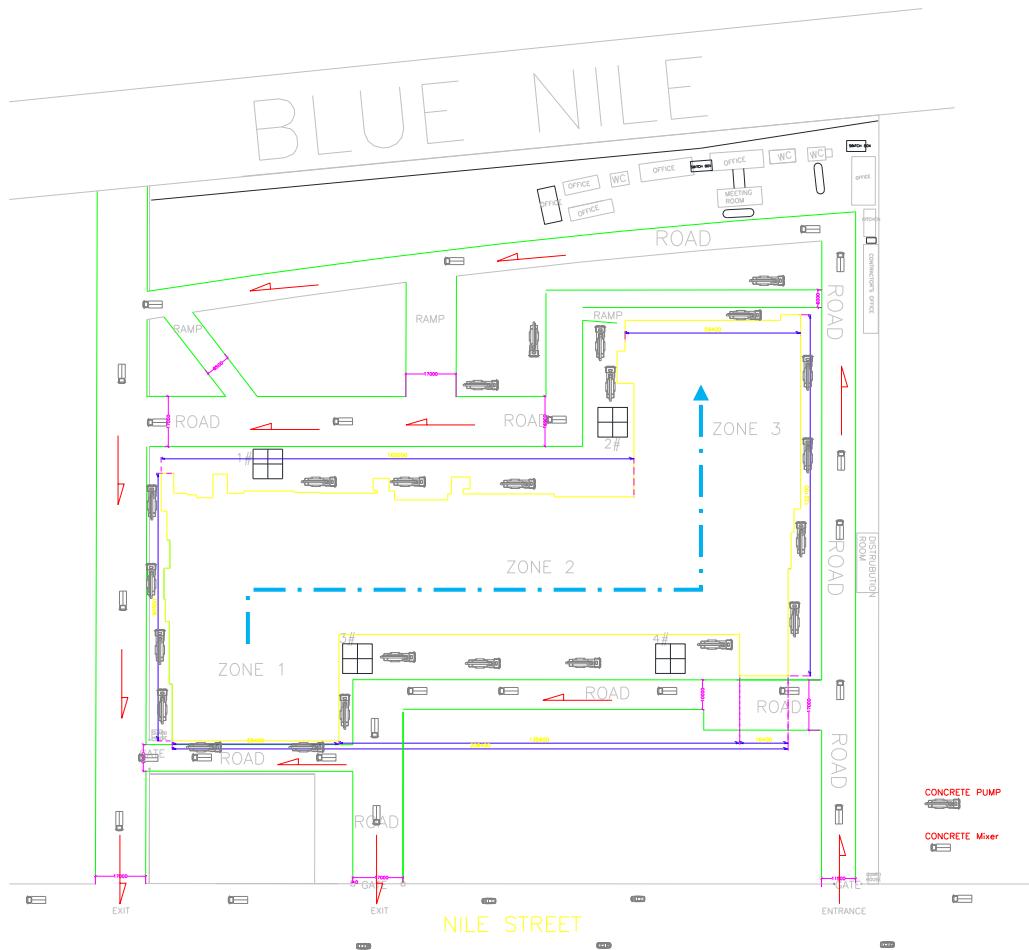


Figure 4: Proposed pumps location and traffic routes for trucks and casting sequence.

4. General precautions for concrete casting in the NCP

As mentioned in Section 3, the project specification does not permit construction joints in the RC raft foundation of the NCP. However, some extra provisions were prepared to prevent construction joints, in particular, when cold joint are formed, such as water jetter, air compressor, water stopper, and epoxy bonding agents. Also, plastic sheets were supplied to cover the concrete slab surface as a precaution for sudden raining.

Special attention was given to the surface levelling and slopes toward trenches because of the large area of the raft (i.e. 15,000 m²). For example an increment of one millimetre (1 mm) in concrete thickness of the raft foundation will result in an increase of the concrete quantity by 15 m³. It is

worth noting that the raft foundation has several variable depths, ranging between 750 and 1700mm, albeit having same finishing level.

Also, as a matter of precaution, it was agreed that all the RMCC companies should not work simultaneously to account for any possibility of breakdown considering the available resources of each company.

5. Quality Assurance (QA) and Quality Control (QC) Plans

Both Quality Assurance (QA) and Quality Control (QC) form an integral part of any job/organisation quality management plan. Although QA and QC are closely related concepts, they are fundamentally different in their focus: QA is the process of managing for quality while QC is used to verify the quality of the output [7].

The QA is focused on planning, documenting and agreeing on a set of guidelines that are necessary to assure quality. QA planning is undertaken at the beginning of a project, and draws on both concrete and industry standards. The typical outcomes of the QA planning activities are quality plans, inspection and test plans, and the training of people in the selected methods and processes. In addition to the known QA steps of the casting process in concrete, guidelines summarized in Appendix A were undertaken as a strategy to provide continuous pouring and preventing forming of any construction joints.

The QC is a strategy of detection and includes all activities that are designed to determine the level of quality of the delivered concrete. QC is a reactive means by which concrete is monitored, and QC includes all operational techniques and activities used to fulfil requirements for quality. These techniques and activities are agreed with client/stakeholders before project work is commenced. Appendix B summaries all steps for the QC measures adopted during the casting of the NCP raft foundation.

5.1 Casting

In total, huge resources have been mobilized to achieve the target set for casting. It involved more than 66 Crew/shift for the Contractor involved in placing and supervision. In addition to 15 staff/shift for the QA & QC

processes, Figure 5. Routine pre-concreting activities such as checking of steel reinforcement spacing, cleaning of debris, cooling of reinforcement had been performed and checked continuously. Also post-concreting activities such as inspections for defects and curing had been carried out routinely. Once the concrete was considered hardened (this is normally about one to two hours after casting), curing was immediately started by constructing sand ponds and pump curing water onto the surface of the hardened concrete. All measures of preventing water to reach wet/fresh concrete were put into place before starting the curing process. The post-concreting inspections showed there were few spots with crazing surface cracking.



Figure 5: a photograph during the concrete our

6. Assessment of Concrete Strength Results

In this section, the results of cubes compressive strength are analysed. The analysis is carried out for 285 cubes representing 95 test results for 7 days and other 285 cubes (i.e. 95 test results) for 28 days. First, each compressive strength test result was assessed separately before calculating the average strength. Secondly, because the concrete is dispatched from seven different ready mix concrete plants, conformity analysis were carried out using different codes of practice. Thirdly, the level of control of the produced concrete is evaluated using ACI 214R [8]. Then, the

concrete compressive strength is assessed using different codes. Finally, contour for the logged cube concrete compressive strength over the raft space is developed.

6.1 Assessment of the compressive test results

According to BS EN 206 criterion [9], which require that the difference between the individual cube tests from the same sample should not exceed 15% of their mean, some of the results are excluded.

It was found that the results of both 7 and 28 days show perfect normal distribution as expressed in Figure 6. The average of the results at age 7 days is 32.5 N/mm^2 which is greater than two thirds of the characteristic specified compressive strength with standard deviation of 4.41 N/mm^2 . The results at age of 28 days the average is 45.03 N/mm^2 which is greater than characteristic compressive strength with standard deviation is equal to 6.05 N/mm^2 .

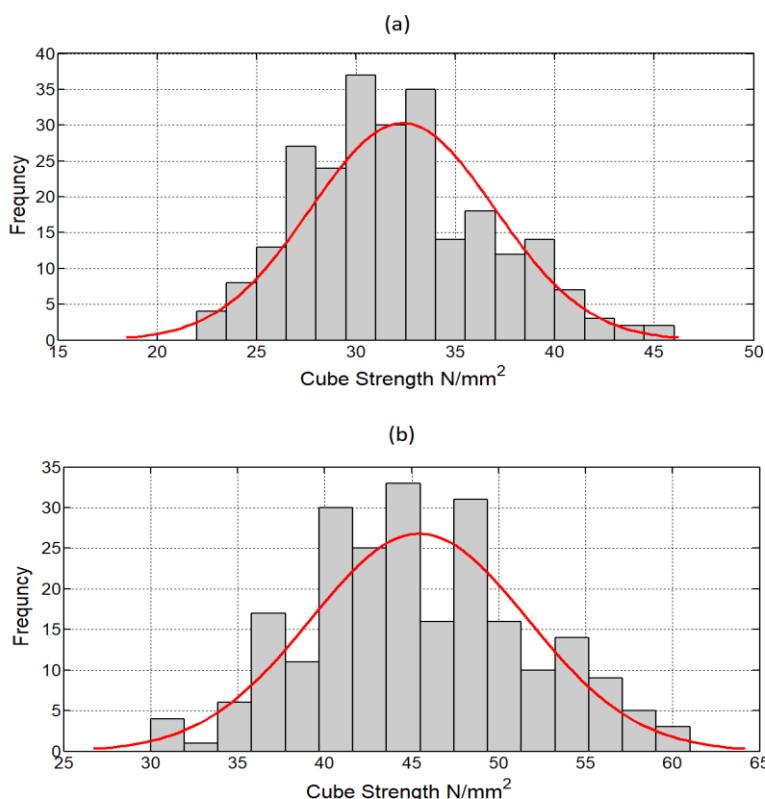


Figure 6: Distribution curve of concrete compressive strength at ages of: (a) 7 days, and (b) 28 days

6.2 Assessment of conformity of concrete

The new concrete standards give directives regarding the checking if the hardened concrete conforms to the compressive strength requirements of the designed compressive strength class [5]. In this paper, the conformity criterion of concrete is assessed using the American Concrete Institute - ACI 214R-11[8], the British European Standards BS EN 206-1 [9], and the Indian standard - IS 456:2000 [10]. Basically, the general conformity criterion of ACI 214R is based on accepting failure of 1% of the samples, Equation (2), in comparison to 7% for the BS EN 206-1, Eq. (3) and 20% for the IS 456:2000, Eq. (4).

*ACI 214R-02
criterion*

$$\alpha \geq \frac{1}{1 - \frac{2.33 COV}{\sqrt{n}}} \quad (2)$$

*BS EN 206-1
criterion*

$$\alpha \geq \frac{1}{1 - \frac{1.48 COV}{\sqrt{n}}} \quad (3)$$

*IS 456-2000
criterion*

$$\alpha \geq \frac{1}{1 - \frac{0.825 COV}{\sqrt{n}}} \quad (4)$$

Where, α is the bias factor (the ratio of average strength to required strength), COV is the coefficient of variation and n is number of tests.

Figure 7 and Figure 8 shows acceptable and unacceptable results according to ACI 214R, BS EN 206 and IS 456 conformity criterions. The data above the curves considered to be accepted and below the curve considered to be unaccepted.

At age 7 days according to ACI 214R, there are 94% acceptable results compared to 98% and 99% for BS EN 206 and IS 456, respectively. At age 28 days according to ACI 214R, 93% of the test results are considered acceptable in comparison to 96% for both BS EN 206 and IS 456. The conformity results of concrete in the NCP could be regarded as satisfied considering that the casting of concrete was carried out during five days and the concrete was dispatched from seven different ready mix concrete plants.

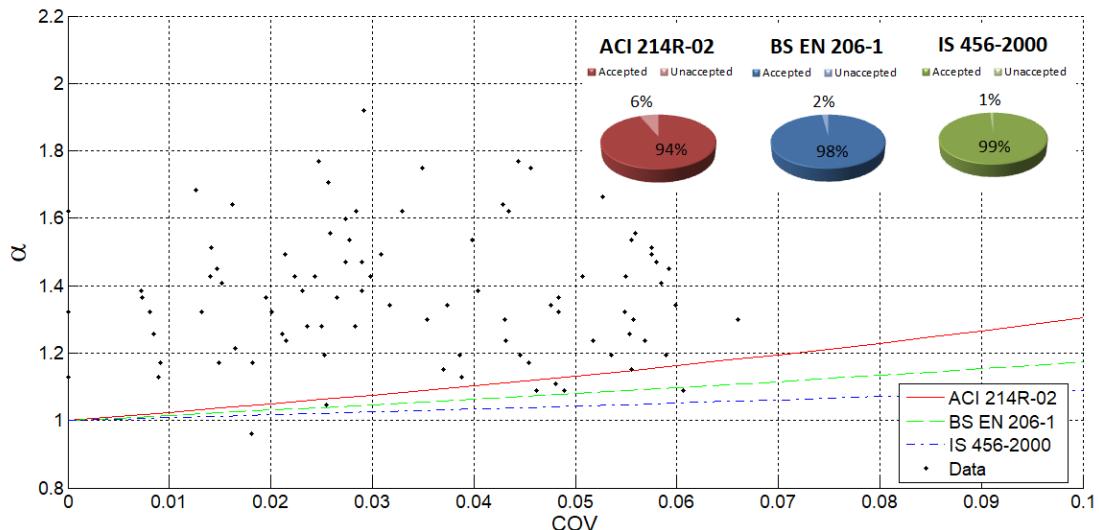


Figure 7: Accepted and unaccepted data at age 7 days according to ACI 214R, BS EN 206 and IS 456

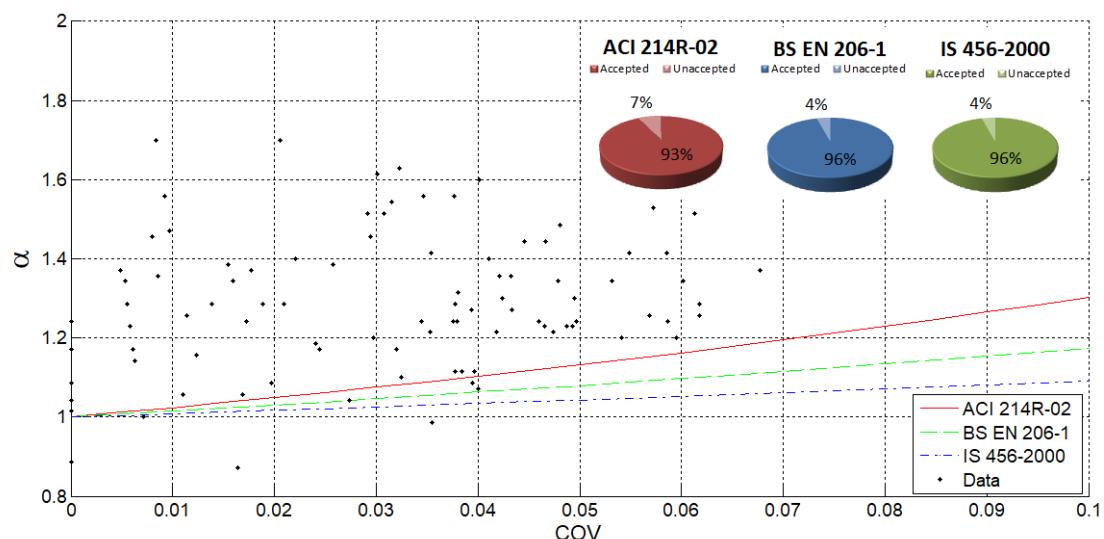


Figure 8: Accepted and unaccepted data at age 28 days according to ACI 214R, BS EN 206 and IS 456

6.3 Assessment of level of quality control

ACI 214R [8] classifies the concrete control into five levels: Excellent, Very good, Good, Fair, and Poor based on dispersion of compressive strength test results (Table 1). For 7 days results, it was found that all the test results (i.e. 100%) are in the quality control level of excellent. At 28 days, 96% of the results have excellent quality control, 4% have very good control level as shown in Table 1.

Table 1: Comparison of compressive strength results to the ACI 214 different control standards

Standard deviation for different control standards (MPa)					
	Excellent	V. good	Good	Fair	Poor
ACI 214R quality levels	Below 2.8	2.8 to 3.4	3.4 to 4.1	4.1 to 4.8	Above 4.8
7 days test results (95)	95 (100%)	-	-	-	-
28 days test results (95)	91 (96%)	4	-	-	-

6.4 Evaluation of concrete strength using Control Chart

Using control chart is well-established methods used widely to evaluate the quality of concrete [8]. The control chart has a central line for the average, an upper control limit and a lower control limit. Simple strength chart is provided to present the results by taking the central line as the characteristic compressive strength f_{cu} which is 35 N/mm² in this study. The lower control limit can be specified as the acceptance criterion, According to ACI 214R any individual result must be greater than $(f_{cu} - 3.5)$ N/mm² while in BS EN 206-1 and IS 456:2000 greater than $(f_{cu} = 4)$ N/mm². It is assumed that concrete gains 2/3 of the characteristic strength (i.e. 23 N/mm²) in 7 days. As shown in Figure 9, all results are found to be above the specified strength line. The scattering of both 7 and 28 days compressive test results ($\sigma = 4.41$ N/mm² and 6.05 N/mm²) because the concrete supplied from seven companies over nearly five days.

6.5 Contour map

For better visualization of the compressive strength test results contour map is developed. The map gives quick idea about the strength in the raft foundation in spatial domain (Figure 10). In other words, it shows the concrete strength at different locations. It is clear that the concrete strength is gained more than the characteristic strength (i.e. 35 N/mm²) over the raft. To the better knowledge of the authors, this kind of illustration has

never been used before in such way. However, it is reported in a previous study variation of the rebound hammer number and ultrasound pulse velocity across on columns and presented in spatial domain [11]. This spatial variation open a question about the structural performance of such structural members. Only few studies give attention to this matter. For example, a previous study was conducted to understand the effect material variability on the seismic behavior [12]. Also, stochastic nonlinear fracture mechanics finite element analysis of concrete beams under four-point load test revealed the effect of this type of variation on the crack formation [13]. Further studies could be carried to investigate this issue.

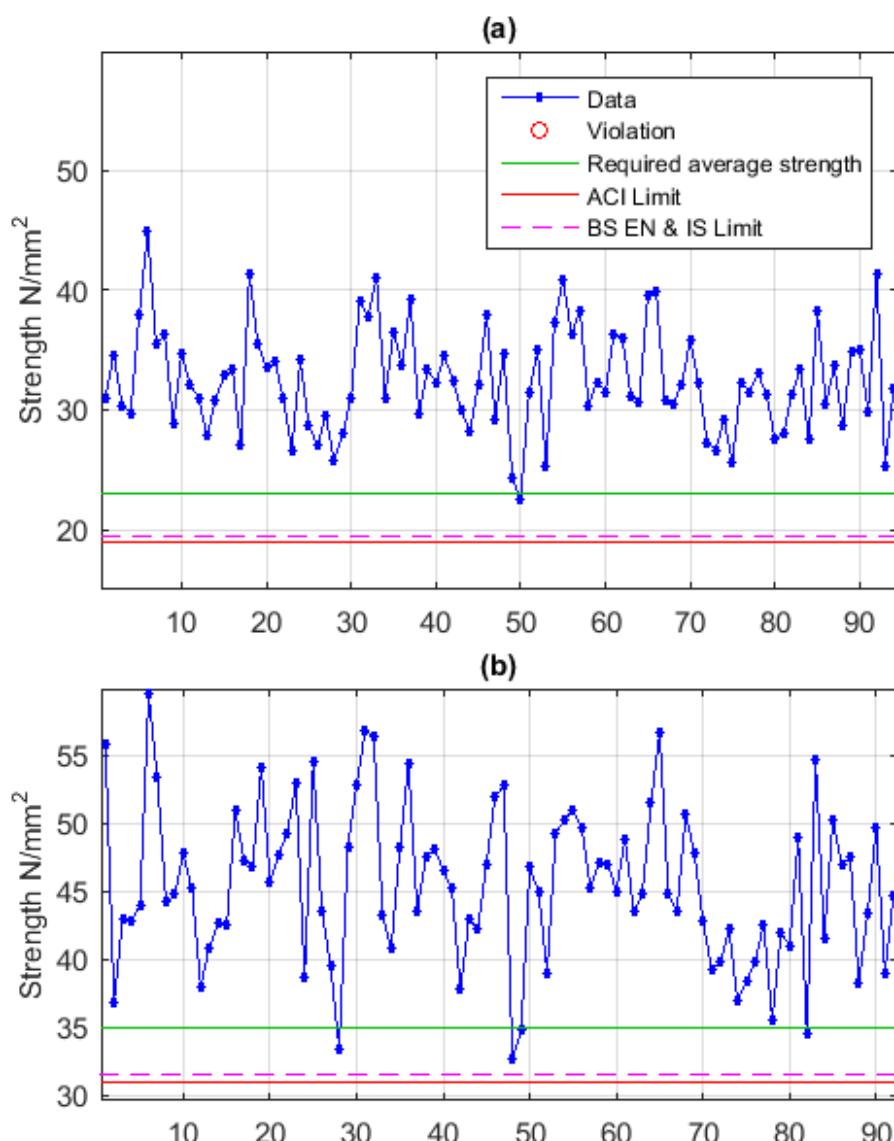


Figure 9: Control chart of the compressive strength results at age of:
(a) 7 days and (b) 28 days

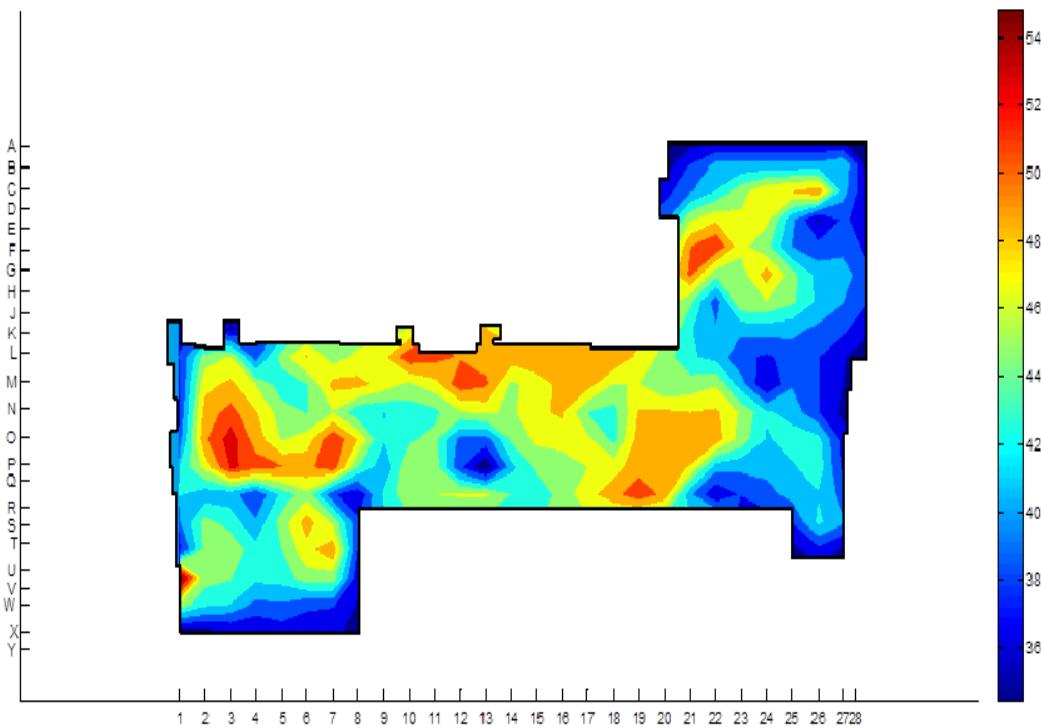


Figure 10: Concrete compressive strength contour map (N/mm²)

7. Conclusion

The paper presented a documentation for casting of the raft foundation at the National Club Project in Khartoum, Sudan in June 2016. The casting process was carried in five days as one of the largest and longest continuous concrete pour the world at its time. Planning, preparation, quality assurance and quality control process are described. Moreover, compressive strength result of 285 cubes for 7 days and another 285 cubes for 28 days are assessed days using three different standards, namely the European BS EN 206-1, *the American ACI 214R-02* and the Indian *IS456:2000*. At age 7 days according to ACI 214R, there are 94% acceptable results compared to 98% and 99% for BS EN 206-1 and IS 456, respectively. At age 28 days according to ACI 214R, 93% of the test results are considered acceptable in comparison to 96% for both BS EN 206 and IS 456. The conformity results of concrete in the NCP could be regarded as satisfied.

Moreover, the spatial distribution of the concrete strength is opened a question about the effect of concrete strength variation in the structural performance, further research is needed in this field.

Acknowledgement

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Appendix A: Quality Assurance (QA) Plan

- All the RMMC scales at plants were calibrated in accordance with Annex G of BS EN 206-1 using the services of Sudanese Standards and Metrology Organisation (SSMO) to assure appropriate proportioning of mix ingredients.
- All the RMMC members were instructed to stockpile crushed coarse aggregate, cement from a specific cement factory and sand prior to casting to avoid shortage leading to complete stoppage of the casting process.
- Based on the exposure conditions and to avoid the possibility of the DEF and excessive thermal cracking as highlighted in Section 2, a prescribed mix proportion was designed by each member of the RMCC using his stockpiled materials as follows C28/35 (cylinder/cube), Maximum water/cement (W/C) ratio=0.49, a maximum Cement content of 375 kg/m³ and minimum cement content of 320 kg/m³. For fresh concrete, the maximum fresh concrete temperature should not exceed 35°C and a consistence of class S4 as per project specification requirements.
- All the RMMC plants were instructed to prepare their prescribed mix and provide record of their trial mixes as per Annex A of BS EN 206.

- The RMCC plants are instructed to shed the aggregate and use ice in concrete mixing to achieve the required fresh concrete temperature.
- The contractors have been instructed to provision skilled labourers for placing, compacting and curing of the concrete for continuous five days pour.
- The time gap between different concrete layers during casting shall not exceed 60 minutes to prevent formation of cold joints.
- Managing and supervising the QA process should be implemented by a third Party Concrete Technologists Group from the University of Khartoum, Civil Engineering Department (18 Staff) and extra 7 staff provided by the quality control of the RMCC staff.
- The representatives of the Third Party Group should be stationed at each mixing plant of the RMCC to assure the approved mix proportion is used. Also, representatives are stationed at each pump station to assure the tests are carried out as per schedule and using correct procedures by the RMCC staff. Furthermore, representatives of the Third party are also placed with each casting team to assure appropriate placing, compaction and levelling. Also to make sure that curing commencing upon hardening of the concrete is executed as per instruction.

Appendix B: Quality Control (QC) Plan

- Sampling Fresh Concrete in accordance with BS EN 12350 part 1 obtaining a spot sample for recording consistence measured by Slump as per BS EN 23350 Part 2 which should not exceed 150 mm (i.e. class S4: 150-230 as per BS EN 206). However, Self-compacting concrete had been specified for some zones having congested areas.
- Temperature of fresh concrete should not exceed 35° Celsius to safeguard against DEF development discussed in Section 1.
- Recording of ambient temperature, fresh concrete temperature, slumps, location of casting and time of casting are mandatory for every received concrete truck.

- Making and curing test cubes from a composite fresh concrete sample and prepared as per BS EN 12390 part 2 and logging record and cubes identification cards. A set of 6 cubes should be made and each 3 cubes will be tested for 7 and 28 days.
- Traceability of all concrete placed on site will be recorded on the concrete Pour Record and marked up on record drawings. These documents will be cross referenced for inspection request and Concrete test Cubes.
- The rate of sampling for slump (every 25m³), Temperature (every truck) & compressive strength testing (every 200m³) according to the project specification
- If a fresh concrete delivery is found to be out of specification with respect to consistence, temperature or duration after mixing it will be rejected and sent back to the Batching Plant. The next load of concrete delivered will not be slump tested for every truck till found to be within specification. If the slump is lower than specification then it is permissible to add Type F admixture on site to increase its value but no tempering with extra water is permitted.