Recommendations for Casting Inclined Columns

A case study on the architectural concrete columns for the Rio de Janeiro Museu da Imagem e do Som

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The State Secretary of Culture for the city of Rio de Janeiro, Brazil, along with the Roberto Marinho Foundation (FRM), recently promoted an important international competition for the design of the new headquarters of the city's Museu da Imagem e do Som (Museum of Image and Sound [MIS-RJ]). The ultimate goal was to make the MIS headquarters a globally renowned architectural icon for Rio de Janeiro. The U.S.-based architectural firm Diller Scofidio + Renfro won the contest and the design was developed in Brazil by the renowned firm Índio da Costa Arquitetura, Urbanismo, Design e Transporte (Índio da Costa A.U.D.T.).

In this bold design, the design architects proposed the museum as a vertical boulevard, with seven stories, a continuous external promenade, and a display of sequential ramps and floors. The new MIS-RJ headquarters, shown in Fig. 1, is being built by the construction company Rio Verde. Also, the construction works are being managed by Engineering S.A., a subsidiary of Hill International.

With architectural concrete finishes specified for its unique forms and oblique lines, this building's superstructure presented some special challenges—especially for the construction of inclined columns with high-performance concrete (the subject of this article). In some cases, the columns had 6 m (20 ft) heights per segment. Further, the columns' unusual geometries required the use of metal formwork. In addition to meeting aesthetic demands and compressive strength requirements (specified as a characteristic compressive strength f_{ck} of 50 MPa [7250 psi] at 28 days), the concrete placements were influenced by other factors, such as weather and logistics. The local climate is very hot, requiring concreting operations during temperatures of about 35°C (95°F), and the concrete supplier's plant is 30 km (19 miles) away from the work site. Trucks had to pass through heavy traffic during business hours, so transit times of at least 1 hour were required.

(a)

(b)

Fig. 1: The future MIS-RJ headquarters: (a) an architectural rendering; and (b) a work in progress, in December 2015 *(images courtesy of Diller Scofidio + Renfro)*

The concrete type used, as well as some of the construction practices applied for casting the inclined columns, will be addressed in the following sections. For the most part, the procedures complied with requirements of Brazilian national standards—ABNT NBR 6118:2007,[1] ABNT NBR 12655:2006,[2] ABNT NBR 14931:2004,[3] and ABNT NBR 15823:2010[4]; and recommendations in recognized technical literature—Neville and Brooks,[5] Kosmatka and Wilson,[6] and References 7 and 8.

Architectural Concrete Structural Elements

It is noteworthy that concrete, as a building material, is not the only factor affecting any project's aesthetic requirements. The technical specifications must also include strict requirements for formwork, release agents, shoring systems, spacers, reinforcement, and construction practices to minimize effects of bugholes and cracking in the finished concrete surface.

A good architectural concrete surface finish (texture and homogeneity) is also related to the mixture design and the specific placing and consolidation procedures used on the project. Furthermore, curing and form stripping time may also affect the finish significantly, with the latter related to stains and prominent color changes in the elements.[9-11]

Independent of the technical and practical construction knowledge required to produce architectural concrete, experience has demonstrated that site simulations and mockup studies are valuable and necessary tools in these types of projects. Full-scale mockups, for example, correlate well with real conditions and allow teams to assess the combination of factors related to building materials used for casting of elements (concrete, release agents, and forms), as well as to the adopted procedures (placing, consolidation, curing, shoring, and timing of form stripping).

It should be also noted that the probability of completely avoiding superficial bugholes on a structural concrete element is null, considering that air is intrinsic to the material itself in the fresh state and is also introduced by the placement and consolidation processes. The main objective is to design a material and a casting method that can minimize superficial bugholes.[12-14]

In this aspect, CIB Report No. 24[15] presents an interesting classification system for bugholes in concrete surfaces. Class 1 represents a low occurrence level—in other words, a significantly reduced frequency and quantity of superficial bugholes, acceptable for architectural concrete projects with strict aesthetic requirements. This article addresses the procedures that were required to meet Class 1 requirements for inclined columns of the MIS-RJ, cast using high-strength self-consolidating concrete (SCC).

Project Data, Materials, and Procedures

Basic design data

The MIS-RJ columns have inclinations varying between 40 and 90 degrees to the horizontal (these are circled in Fig. 2). The structural design was developed by Escritório Técnico Julio Kassoy e Mario Franco Eng. Civis Ltda (JKMF). Stresses were calculated considering the actions of self-weight, other dead loads, wind, pretensioning, and post-tensioning. The maximum axial load in the columns will be about 800 tonnes (1760 kip). The longitudinal bars for the columns were arranged in layers, allowing the passing and positioning of post-tensioning tendons and bars from beams framing into the joints. Because of the high percentage of steel in the columns, mechanical splices (nonaligned) were specified to minimize the effects of congestion on concrete placement and consolidation.

Mixture proportions and constituents

The mixture design process started in October 2011, approximately 20 months before the first concreting of the building's inclined columns, which occurred in June 2013. Many mockups in different scales were tested during the design, and decisive factors affecting the concrete were evaluated. Simulations included having truck mixers affected by weather and logistics (route) as well as using various placement types, mixing energies, and pump types.

Full-scale mockup studies were also important for assessing the effects of column inclination and geometry,

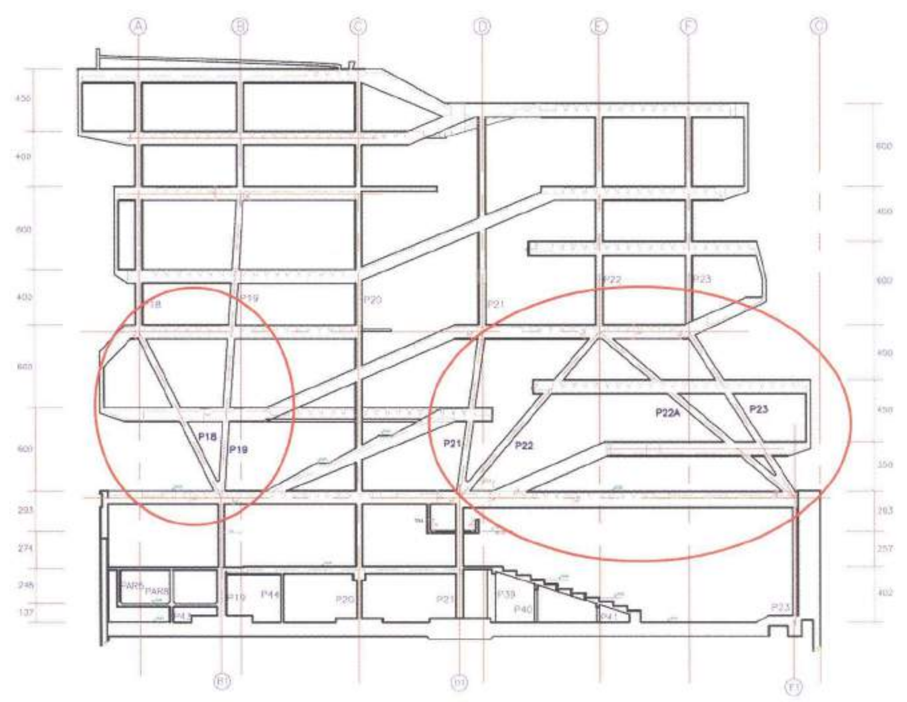

Fig. 2: Longitudinal section of the MIS-RJ structure showing inclined columns (circled in red)

reinforcing percentage and positioning, and lift height. The full-scale placements allowed the evaluation of fresh concrete conditions during placement, including its filling ability, as well as its compressive strength after hardening.

The concrete mixture proportions and sources of the materials are shown in Table 1. It must be observed that no mixing water was used other than the moisture in the sand (this amount was deducted from the total ice proportion). The total free mixing water was replaced by ice cubes under an initial specified temperature of −10°C (14°F). The technical specification for concrete acceptance was a temperature of about 20°C (68°F) to minimize thermal cracking. On very hot days, however, the concrete temperature was about 25°C (77°F) in practice.

Based on extensive historical data, the sand moisture content was assigned as 5% of the total sand mass. Polypropylene fibers (12 mm [0.5 in.] length) were specified to minimize shrinkage cracking. Inorganic iron oxide-based pigment (Bayferrox® 318) was specified to maintain aesthetic homogeneity (Brazilian standards allow Type CP III cement to comprise 35 to 70% slag amount, which can result in variations in the tone of the concrete).

Construction requirements

Construction was performed per Brazilian Norm ABNT NBR 14931. In addition to the basic principles covered in this standard, detailed techniques and improvements were specified to ensure the quality of the concrete finishes (texture and homogeneity) and the aesthetics of the structural elements. The most important requirements were related to concrete placement and consolidation.

Mockups

After the development of the concrete mixtures, focus shifted to designing mockups for the evaluation of several technical and aesthetic factors. Initially, during mixture design, small cubes were cast to evaluate the type of release agent and the formwork panels on concrete coloration. Different pigment contents were tested (at dosages of 0, 1, and 1.5% by weight of the cement) to maintain the natural tonality of the concrete. Then, a vertical wall was cast at the jobsite in January 2012. The filling ability of the SCC was evaluated to determine the minimum number of pump discharge points required for adequate placement (that is, limiting the occurrence of bugholes). Further, inclined walls were cast for evaluation of the same parameters. The boldest event was the construction of three large-scale mockups in the courtyard of the concrete supplier. These mockups were designed to allow clear assessment of different formwork systems and SCC finishes in walls cast at various inclinations (in addition to the other factors already mentioned). Those walls were also used to verify some procedures for application of concrete coating systems. The different types of concrete specimens and mockups can be seen in Fig. 3.

The wall mockup was very important for evaluation of several factors; however, it did not simulate an inclined column. To test procedures for the columns, a full-scale mockup of two inclined columns that intersected at the base was also cast at the concrete supplier's plant. One of the columns was inclined at 40 degrees to the horizontal and represented the worst case for the project (Fig. 4(a)). Before the mockup placement, additional rules were made with respect to the SCC and placement procedures to cast these architectural concrete elements with minimal bugholes and cracking.

First, a special biodegradable release agent based on aliphatic hydrocarbons (DESFORM 70 supplied by Grace/Rheoset) was used to prevent superficial bugholes. To help avoid segregation, the maximum drop height was set at 2 m (6.5 ft). Also, a drop chute (tube) was used to help ensure that mortar reached the base of the element without losses due to impact with reinforcement or forms. To help ensure consistent

Table 1:
Mixture proportions for inclined columns of MIS-RJ (dry materials for 1 m³ of concrete by weight)*

Materials	Mass, kg/m³
Cement CP III-40 RS (sulfate resistant—ABNT NBR 5735:1991[16])	472
Silica fume (ABNT NBR 12653:2014[17])	30
Water (from sand moisture only, mean value fixed at 5%—ABNT NBR 15900:2009[18])	42
Water in the form of ice cubes[2]	144
Medium sand, natural (ABNT NBR 7211:2009[19])	700
Artificial sand, crushed sand Type II[19]	123
Crushed stone 0[19] (maximum aggregate size = 9.5 mm)	426
Crushed stone 1[19] (maximum aggregate size = 19 mm)	426
Polypropylene fibers (12 mm)	0.6
Pigment (Bayferrox® 318), simulated for 1%	4.7
Water-reducing admixture (Muraplast FK 110, MC Bauchemie—ABNT NBR 11768:2011[20])	1.4
High-range water-reducing admixture[20] (Glenium® SCC 160 with incorporated antifoaming agent or Glenium® SCC 161, BASF)	4.7

*Designed for a characteristic compressive strength f_{ck} of 50 MPa (7250 psi) at 28 days and slump flow of 660 to 750 mm (26 to 29.5 in.), the mixture's water-cementitious materials ratio (*w/cm*) was 0.37
Notes: 1 kg/m³ = 1.7 lb/yd³; 1 mm = 0.04 in.

flow, a "bottomless" metal pail was adapted as a funnel and reservoir at the top of the delivery tube (Fig. 4(b)). The concrete was placed using a bottom-up approach, helping to prevent the introduction of air into the concrete and thus minimizing bugholes.

To further minimize bugholes, concrete placement progressed at a slow speed, in small portions, and using 10 L (2.6 gal.) buckets (Fig. 4(c)). The delivery tube was inserted in the column form so that its discharge end was about 400 mm (16 in.) from the bottom of the form. A 35 mm (1.4 in.) diameter vibrator was inserted in this tube until its head contacted the base of the form.

When concrete covered the entire length of the vibrator head, the concrete was vibrated briefly to ensure its full contact with reinforcing bars and with previously placed concrete. Although the SCC mixture had sufficient cohesion to withstand slight vibration without segregation, the vibrator was used in cycles of only 5 to 10 seconds.

This procedure was repeated in successive turns until concrete reached the middle of the column element. Then, the tube was removed and the remaining height was placed (still using buckets) in lifts of 300 to 400 mm (12 to 16 in.), using the length of the vibrator head as a reference. Each lift was vibrated slightly. It is important to note that concrete placement was stopped whenever the vibrator was being used. Placement resumed only after vibration was completed.

Simultaneously, workers tapped softly on the outside of the steel forms using rubber mallets. This effort helped to minimize pockets of air in the concrete in contact with the forms. Finally, the fresh concrete was allowed to overflow the top level of the form, eliminating bleed water and fines, and allowing the concrete to adequately reach the upper form level.

The completed inclined column mockup is shown in Fig. 5.

As shown in Fig. 5, the finishes are very good. Bugholes are minimal, indicating that the completed surfaces would satisfy Class 1 requirements per CIB Report No. 24. Also, none of the mockups exhibited any type of cracking. The procedures were therefore deemed suitable for actual placements.

Fig. 3: Various simulations and mockups used to establish materials and methods incorporated in the building construction: (a) cubic specimens in the laboratory of the concrete supplier, October 2011; (b) vertical wall cast at the jobsite, February 2012; (c) inclined wall (45 degrees) cast at the jobsite, February 2012; and (d) full-scale mockup cast in the courtyard of the concrete supplier's plant, July 2012

Fig. 4: Casting the inclined column mockup helped in the evaluation of various factors: (a) metal forms and inclined reinforcement projected from a previously cast base joint; (b) a drop tube was used to deliver concrete from the concrete bucket to the base of the column form; and (c) a bottomless pail acted as a funnel and reservoir for concrete, allowing a vibrator to be inserted into the drop tube without overflow

Integrity and Aesthetics

Figure 6 shows some of the inclined columns in the building. The finishes are of similar quality to the finishes obtained in the mockups. Developing and evaluating an appropriate concrete mixture design, creating many mockups, and adjusting the procedures provided in ABNT NBR 14931 were decisive actions that allowed the execution of inclined architectural concrete columns of the MIS-RJ project. The final results are sound structural elements with high aesthetic form.

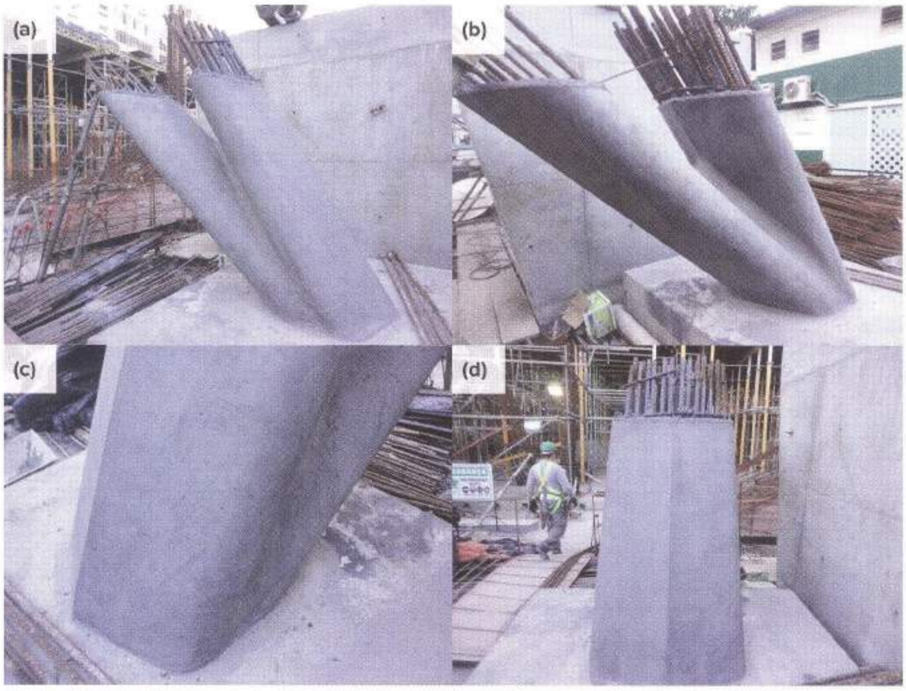

Fig. 5: Mockup finishes: (a) sides; (b) sides and lower region at joint; (c) detail at base and joint; and (d) overview of upper inclined region


Fig. 6: Actual inclined columns in the building exhibit the high-quality finishes required of the exposed structural and architectural elements

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