DESIGN OF DURABLE PRESTRESSED REINFORCED CONCRETE BEAMS FOR AN EXTENDED UNLOADING PIER IN INDIA

Luc Maertens
Engineering Manager
BESIX
Brussels, Belgium

Manfred Zinserling
Engineering Review Consultant
BERGER/ABAM Engineers Inc.
Federal Way, WA, USA

Dominic Izzo
Manager of Projects
Dabhol LNG Terminal
Houston, TX, USA

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1 INTRODUCTION

The Dabhol Power Company (DPC) is constructing India's first Liquefied Natural Gas (LNG) terminal on a remote strip of India's western coast along the Arabian Sea about 160 kilometers south of Mumbai (Bombay). Designed to handle the world's largest LNG carriers, the terminal's marine facilities include a pile-supported trestle that extends 1,620 meters into the open sea to reach adequate depth and an LNG unloading dock. The project site is not only fully exposed to incoming waves from the open sea, but also subject to earthquake loads from a peak ground acceleration of 0.16 g. Driven by a short schedule, the difficulty of mobilizing major equipment to this region, and the hostile marine environment, DPC determined to use a reinforced concrete superstructure supported by steel piles. The 29.1-meter-long prestressed concrete beams had to be manufactured primarily from local materials, on site, yet meet stringent quality standards and a 40-year design life. During the early phases of the project, a significant design discussion ensued as to whether the beams would be more suitable designed with 75 mm of cover over mild reinforcing steel or with 50 mm of cover and a "no crack" criteria. The solution finally selected included use of ground granulated blast-furnace slag (ggbs) cement, pretensioning, and elevated temperature curing. This paper discusses the various alternatives considered during the design process, as well as the final selection. It concludes with recommendations for future code development, as well as for design and project planning in difficult environments.

Fig. 1 Location Map

The project was constructed in Maharashtra State, on the west coast of India. See Fig. 1. The site is located on the exposed Malabar Coast, on the Arabian Sea. This area, halfway between Mumbai and Goa, is relatively remote and undeveloped; the local population being mainly subsistence farmers and fishermen. The project site is located at the mouth of the Vashishti River, and is locally known as Smuggler's Cove. The primary work area, about 7 hectares, was located on the beach, surrounded by 110-meter-high bluffs on three sides.

The site was challenging for a number of reasons. First and foremost, the Southwest Monsoon in the Arabian Sea made offshore construction impractical from early June through late September.

Second, the site is largely inaccessible. Third, any project infrastructure, such as batch plants or precast facilities had to be built before construction could start. Fourth, workers had to be brought in, or local residents had to be trained to perform heavy civil construction works.

2 PROJECT DEVELOPMENT SCHEDULE

This terminal facility is part of the second phase of a three-phase integrated energy project. Phase I consisted of a “power block” with one steam turbine generator, two gas turbine generators with heat recovery steam generators, and one smaller turbine generator. This power block generated approximately 780 MW burning distillate fuel oil and naphtha. The Phase II facilities will triple the power output by adding two power blocks and converting the entire plant to burn clean natural gas from regasified LNG. The LNG terminal consists of receiving, storage, and regasification as well as the associated port infrastructure to allow year-round delivery by modern LNG carriers. Phase III of the project will construct a pipeline to transport (export) natural gas to other users in India. The LNG terminal is designed to supply all the needs of the power station and export to the pipeline.

The developer obtained U.S. $1.8 billion in project financing for Phase II. The size of the project and the financing made it critical that the LNG terminal go into operation on time to generate a revenue stream as soon as possible. The LNG terminal was divided into three distinct projects: the mechanical works for the process and unloading pipelines; the marine civil works for the unloading dock, approach way (trestle) and breakwater; and the dredging. The project management team had to plan the construction of the unloading dock and approach way so that the marine civil works contractor would turn a finished structure over to the mechanical contractor in time to install and commission the unloading pipeline and supporting facilities for the arrival of the first shipment of LNG in November 2000.

From a construction planning point of view, this meant that 278 beams had to be cast in the period from August 1999 to February 2000 to support placement during the non-monsoon season of October 1999 to May 2000. The construction and commissioning of the batch plants and the precast facility, and, therefore, the design of the precast beams became a critical schedule event. Engineers had to optimize the beam designs early enough to put the required infrastructure and logistics in place to support the construction schedule (see Table 1). The original conceptual design specified ordinary Portland cement (OPC) and 75 mm of cover over reinforcing steel to ensure the durability of the structure for 40 years in what was characterized as a hostile marine environment. Unfortunately, the detailed design of the beam cross-section did not allow designers to meet this criteria and the project team was forced to explore other options. The ensuing research and discussions led to a delayed start of precast operations with the first beam being cast on 24 November 1999 instead of August 1999 as planned. The last beam was not completed until September 2000. Nevertheless, good management and planning allowed the Contractor to complete the structure on time. This paper describes the optimization of that design, which led to the use of a ground-granulated blast-furnace slag (ggbs) cement and 50 mm of cover to meet the durability requirements.

Table 1 Phase II Project Schedule

August 1999 Schedule Activity Description	Start	Finish
Mobilize – Precast Formwork	19-Apr-99	26-Aug-99
Concrete Mix Development and Trial Mixes	26-Apr-99	26-Aug-99
Fabricate Pile Caps – Approach Way (Trestle)	28-Aug-99	26-Nov-99
Fabricate Prestressed Beams (278) Approach Way (Trestle)	28-Aug-99	23-Feb-00
Mobilization of Jack-Up Platform for Pile Driving	01-Dec-98	07-Sep-99

3 DESIGN CONCEPT

3.1 Structural System

The vessel unloading dock, (4) breasting dolphins, and (4) mooring dolphins employ a cast-in-place concrete deck system over steel piling. The dock is designed to berth LNG carriers of up to 140,000 m^3 capacity. The minimum design life for all structures was 40 years.

Structural framing concept for the approach way (trestle) consisted of (13) four-span continuous units and (1) two-span continuous unit, all with nominal 30-meter spans. Nominal trestle width is 10 meters. The trestle is widened locally to accommodate a tug berth and passing lanes. The trestle supports a roadway and LNG piping racks. Deck design loading included HA loading (BS 5400), a 12-ton mobile crane, and 500-kN concentrated loads. A ground peak acceleration of 0.16g was used for the dynamic earthquake design. Deck surface for the trestle and unloading platform is at

+14.00 meters, so as to provide a large air gap between waves and the underside of the deck structure. The crosshead soffit elevation is at +11.17 meters and tidal range is from -0.10 meters to +3.15 meters.

The prestressed concrete beams will never be submerged in seawater. The design provides a minimum freeboard (air gap) of 1 meter between the maximum heights of a 100-year return period wave crest and the bottom surface of the crossheads. The maximum wave height, based on extensive physical and computational modeling using the best available ocean wave data, is 7 meters with a storm surge tide of +3.15 meters, resulting in a maximum wave crest elevation of +10.15 meters. However, the beams can be exposed to seawater from wave splash against the steel piling at the extreme wave crest elevation. The beams will be exposed to saturated salt air, but the beams should not become saturated with seawater even in the worst conditions.

The basic structural system consists of 762-mm diameter by 19-mm wall epoxy coated steel pipe piling, with lengths up to 33-meters, driven in to weathered basalt. Where needed to resist uplift forces, 610-mm-diameter by 1.5-meter-long sockets were bored beneath the pile tip; after cleanout, a reinforcing steel cage was inserted and the lower 3.5 meters of pile and socket were filled with concrete. The piling installation itself was a major undertaking and had to be accomplished in two construction seasons. The Contractor deployed a purpose-built jack-up platform from Singapore to drive the piling. The steel piles were imported from Europe and barged up the Vashishti River for storage until needed.

Nonstructural, 450-mm-thick precast concrete pile caps are used to align the pile tops and provide a seat for the precast concrete crosshead boxes. The crosshead boxes were set on top of the pile caps and leveled. Reinforcing steel cages were then inserted into the upper regions of the piles and the entire assembly was filled with concrete. Precast beams were then set on the first stage crossheads and connections made to the crossheads. The second stage crosshead concrete placement was then made. Precast deck planks, 180 mm thick, were placed on top of the beam flanges, deck reinforcement was placed and the 150 mm thick topping concrete placed. Miscellaneous curbing, barriers and pipe supports were then formed up and cast. Fig. 2 shows a typical trestle cross section.

3.2 Value Engineering

The conforming design (contract documents) of the approach way consisted of 20-meter spans with prestressed beams 1500 mm in height. In the alternative design, it was decided to increase the spans to the maximum possible without having to increase the height of the beams. The final span was, thus, fixed at 30 meters. The use of longer spans helped improve the construction schedule within a reduced budget because longer spans reduced the number of piles to drive; beams to install; and crossheads to prefabricate, install, and fill with concrete on site.

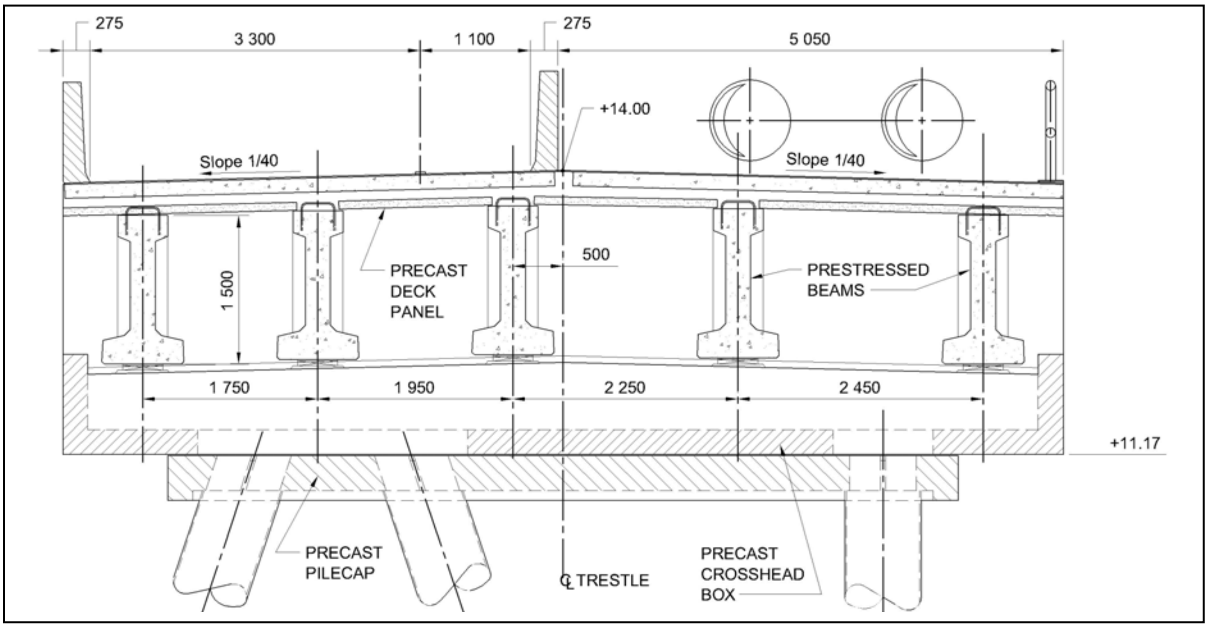

Fig. 2 Cross Section of Typical 10-Meter-Wide Trestle

3.3 Durability and Concrete Cover

The contract specifications called for 75-mm cover for all concrete structures and no distinction was made between plain reinforced and prestressed elements. The prestressed beams consisted of 250-mm-thick webs. From a structural point of view, excessive cover to the mild steel stirrups would reduce the sections resistance to torsional loads. As a result, the Contractor recommended using 50-mm cover for the precast, prestressed beams only with the following factors as further justification.

- The beams are located well above the maximum seawater level, in the less critical conditions of the zone exposed to sea spray. The beams would not be subjected to the more severe environmental conditions of the splash zone, even under the wave conditions of the 100-year design storm.
- The beams will be fabricated in a casting yard under controlled conditions and with special curing measures in place.
- Both the Contractor and DPC would employ additional, experienced quality control personnel to ensure that standards were met.

The approach way design life was 40 years and it was essential to demonstrate that the reduction in cover from 75 to 50 mm would in no way result in a structure with reduced durability. Following extensive discussions with DPC, the Contractor commissioned the services of the University of Leuven (Belgium) to perform computational analyses to establish the anticipated rate of penetration of chlorides into concrete for various design mixes. It was assumed that the initial chloride concentration in the concrete after casting was C_O = 0.1% Cl^- /cement (by mass). The chloride concentration at the concrete surface, from environmental conditions, was assumed to be 3.0% Cl^- /H_2O (by mass). A minimum cementitious content 500-kg per cubic meter and a maximum w/cm ratio of 0.50 were assumed for the concrete. The various mixes were then compared to the allowable chloride threshold limit; C_T = 0.2% Cl^- /cement (by mass) for prestressed tendons, and C_T = 0.4% Cl^- /cement (by mass) for the mild reinforcing steel as specified in European Standard ENV 206 (1992)[1]. Two types of cements were investigated; ordinary Portland cement (OPC) and granulated blast furnace slag (ggbs) cement which were both acceptable according to the contract specifications. The chloride ingress (during the design life) depends on the Diffusion Coefficient μ(D) of the concrete. For OPC-cement concrete, μ(D) = 29.6×10^{-9} cm²/sec and for ggbs-cement concrete, μ(D) = 1.2×10^{-9} cm²/sec were used. The main difference between the two cement types is the permeability of the resulting concrete matrix.

The probability that corrosion will occur at the level of the reinforcing steel or the level of the prestressing steel (tendon) as a function of the concrete cover was investigated. The reinforcing steel has a cover of 50 mm, and the prestressing steel a cover of 64 mm. Table 2 gives the resultant probabilities of failure for both 50/64-mm cover and for 75/89-mm cover, as originally specified.

Table 2 Corrosion Probabilities (P_f) for ggbs and OPC Cement Concretes

Cover	**Reinforcing Steel**		**Prestressing Steel**	
	ggbs	OPC	ggbs	OPC
50 mm/64 mm	10^{-18}	$>10^{-2}$	10^{-7}	$>10^{-1}$
75 mm/89 mm	$<10^{-22}$	10^{-3}	10^{-9}	$>10^{-1}$

According to Eurocode 1 (EC1, 10/1994)[2], the probability for failure shall be $<10^{-4}$ when ultimate limit state (ULS) is considered, and $<10^{-2}$ when serviceability limit state (SLS) is considered. Mostly, corrosion is considered as SLS. Figures 3 and 4 on the following page illustrate the probabilities of failure as a function of cover and concrete permeability. DPC and the Contractor concluded that the corrosion risk was too high with OPC cement but in the case of ggbs cement, a cover of 50 mm over the mild reinforcing steel is sufficient.

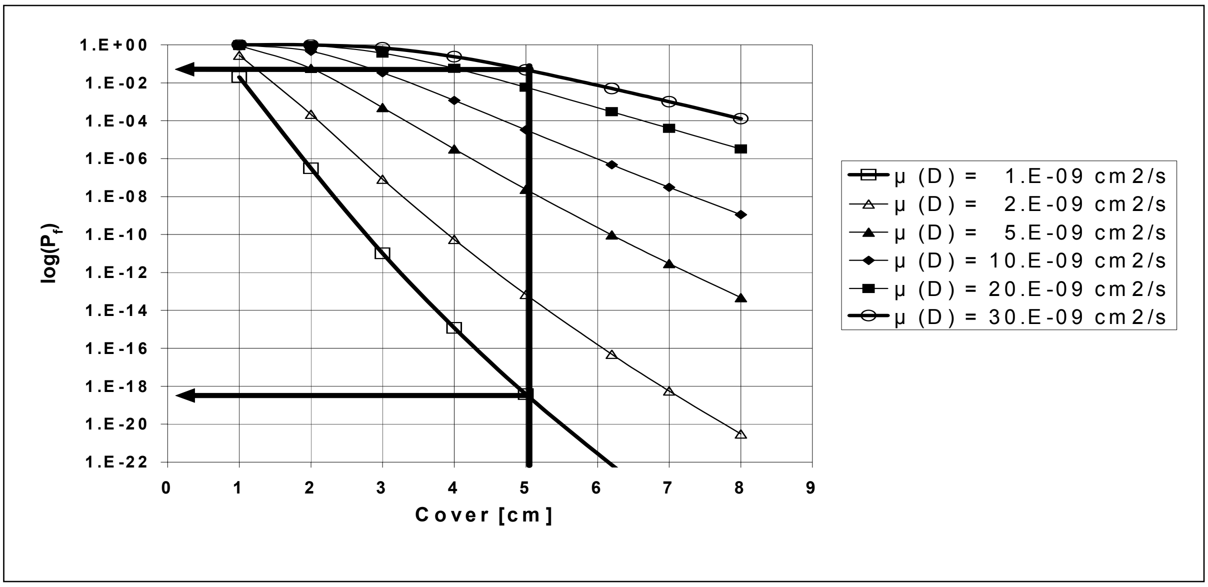

Fig. 3 P_f versus Cover for C_T = 0.4% Cl^- / Cement (Reinforcing Steel)

3.4 Proposed Solution

After the above investigation revealed the much higher risk of corrosion damage to prestressing tendons compared to mild steel reinforcement, DPC and the Contractor decided to use ggbs cement with the proposed 50-mm cover. They took this decision although ggbs is not commonly used to fabricate precast, prestressed beams mainly because ggbs cement reduces the heat of hydration, which results in a lower rate of increase in concrete strength versus time. The rate of precast fabrication typically relies on early concrete strength so that the prestressing force can be transferred into the concrete beams. The Contractor used heated formwork to speed up the development of early concrete strength and offset the lower rate of strength gain in ggbs cement concrete.

4 CONCRETE

4.1 Trial Mix Designs

Qualifying concrete mix designs were prepared offsite using various laboratory sands and standard curing procedures. The objectives were high 28-day compressive strength and early release strength. Laboratory mixes were developed using grade 53 OPC cement, and 50/50 and 70/30

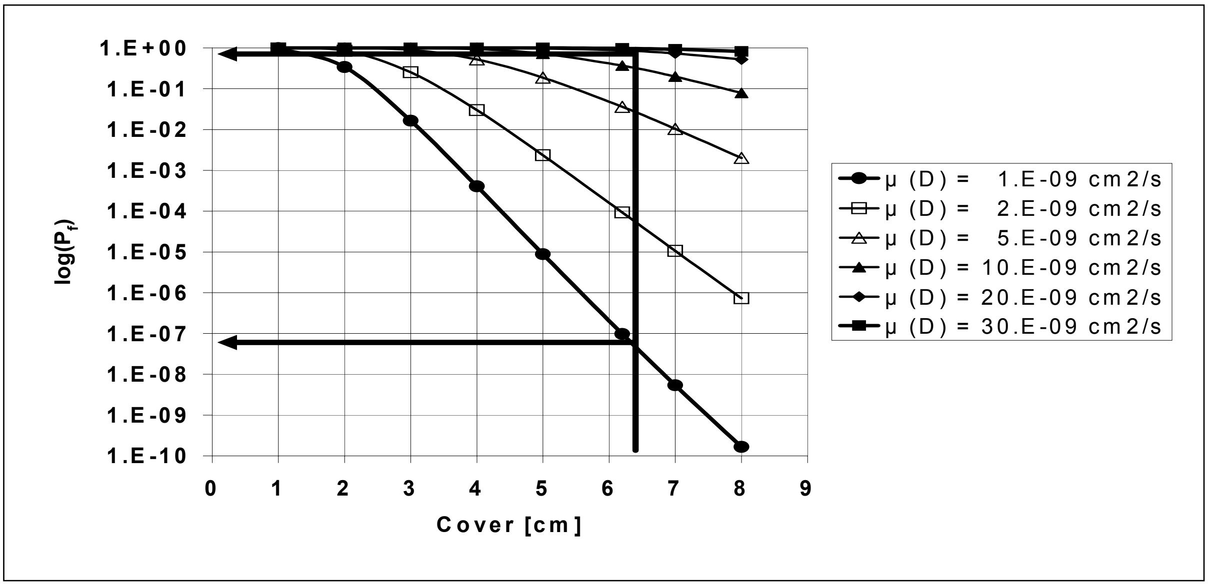

Fig. 4 P_f versus Cover for C_T = 0.2% Cl^- / Cement (Prestressing Tendons)

blended ggbs cements (first number represents Portland cement in percent, second number represents ggbs in percent, weight basis). Concrete for prestressed beams was to be grade C50 with a release strength of 32 MPa. The slag cements could not meet the C50 criteria in 28 days nor the release strength within 3 days, as the construction schedule required. This was not a surprise given that rate of strength gain for ggbs cements is slower than for OPC cements in equal amounts. Initial trial mixes in the field also produced poor results.

Site personnel developed further trial mix designs using Indian slag cement with cementitious contents varying from 470 to 530 kilograms per cubic meter. The selected design mix for the prestressed beams is shown in Table 3.

Table 3 C45/20 Concrete Mix Design

Ingredients	**Weight (per cubic meter of concrete)**
ACC slag cement (50/50 blend)	530 kg
Aggregate – 20 mm	633 kg
Aggregate – 10 mm	510 kg
River sand	615 kg
Glenium 51	1.0%*
Pozzolith CRP-4	1.3%*
w/cm	0.30
Air entrainment	none
Target slump (at batch plant)	200 mm
Target slump (at time of placement)	150~200 mm

* by weight of slag cement

To meet the schedule requirements, the Contractor developed a strategy to modify the acceptance criteria to compressive strength at 56 days (or later) because the casting and erection schedule could be adjusted to allow this additional curing time. As a further precaution, DPC nominated an independent reviewer to check the trestle design and determine the minimum concrete compressive strengths that would satisfy the design loading criteria. This independent review recommended a reduction in the required compressive strength to grade C45. Prestressed beam production started before DPC and the Contractor could resolve all mix design and acceptance criteria issues. Therefore, they decided to core each of the first 48 beams cast, to ensure that the production met all strength requirements (see later discussion).

The Contractor also investigated cement consistency and admixture performance. All the slag cements were produced locally in India. Two separate sources were investigated, one for the 50/50 blend and one for the 70/30 blend. Early trial mixes experienced rapid and unpredictable loss of slump. Apparently, the locally produced cements contained low levels of SO_3 (<2.0%) and thus had a tendency to false set, or stiffen prematurely. The Contractor controlled this false by the addition of a set retarder and by keeping the fresh concrete temperatures below 30^0 C. He also used a polycarboxyl-based superplasticizer to provide high slump and flowability. High slump and flowability were necessary to place and consolidate the concrete because of reinforcement congestion, especially in the end regions of the beams. The 50/50 blend provided the best balance between early strength and design strength. This cement producer also achieved better consistency between different mill shipments. Independent laboratories, in Europe, also verified cement chemistry during the beam production.

4.2 Aggregates

Independent operators quarried the coarse aggregates from basalt and crushed them locally. They also mined sands from the Vashishti River. Initial trial mixes were not consistent and corrective efforts were focused on sands, and admixtures. The mined sands varied greatly from one shipment to the next. Early shipments contained large amounts of organics and silts, and varying amounts of laterite. Laterite is derived from weathered basalt and is usually found in tropical regions. Laterite is very porous and has a tendency to absorb large amounts of water. This became evident when measuring sand moisture contents using a “speedy measurement” versus the oven drying method. Eventually, consistent quality of the sands was achieved by more careful selection of dredging sites and additional washing of the sands to eliminate organics and silts, but the laterites could not be eliminated. Other concrete production at the site also attributed concrete quality control problems to the laterite content and arid the conditions. Hence, moisture control of the sand was extremely important. Both the Contractor and DPC's quality assurance staff measured moisture contents frequently during daily concrete production. Sand moisture content during production varied from 4.5 percent to 7 percent, typically.

4.3 Beam Fabrication

The Contractor work area on the beach was very limited. A compact precasting yard, batch plant, and materials stockpiles were laid out. All raw materials were trucked into the site. However, storage space for finished products was very limited. Key to the success of the entire process was an efficient precasting operation and good concrete mix designs to minimize wastage and rejected products. This casting yard produced precast, prestressed, and non-prestressed concrete elements. Grade C45 (reduced from C50) concrete was used for the prestressed beams and grade C40 concrete was used for all other precast and cast-in-place concrete. The precast, prestressed beams were on the critical path for erection. Hence, most of the concrete mix design efforts were focused on these elements. 282 beams were produced for the trestle, DPC rejected only 4 beams for various defects including rock pockets and excessive "bug holes."

Two 120-meter-long insulated steel form tables (bottom pans) and two sets of insulated side forms were used to fabricate the beams. Electric resistance heating wires were located under the form tables and provided the heat for elevated temperature curing. Four beams were produced in each form table cycle. Average cycle time was approximately 3~5 days. Critical issues for the precasting operation were ease of concrete placement, beams were 1500-mm deep; and production cycle time. Concrete strength gain for prestress release (detensioning) became one of the biggest issues and required further modification to the laboratory design mixes by the addition of more cementitious materials. This is one of the first projects to use large amounts of ggbs slag cement in precast, prestressed production. The non-prestressed, precast elements were cast in steel and wooden formwork and did not require heat curing. The Contractor inserted thermal couples at multiple locations on each beam to record curing temperatures. Field cast cubes, used to determine release strength, were placed in an insulated chamber adjacent the web of one beam. The other cubes were stored under standard conditions at the on-site laboratory. Fig. 5 illustrates a typical temperature record. After a preset time of approximately 2 hours, preheat was applied for the first 12 hours. Typically, detensioning operations commenced in 36~40 hours after concrete placement. Required release strength was 32 MPa.

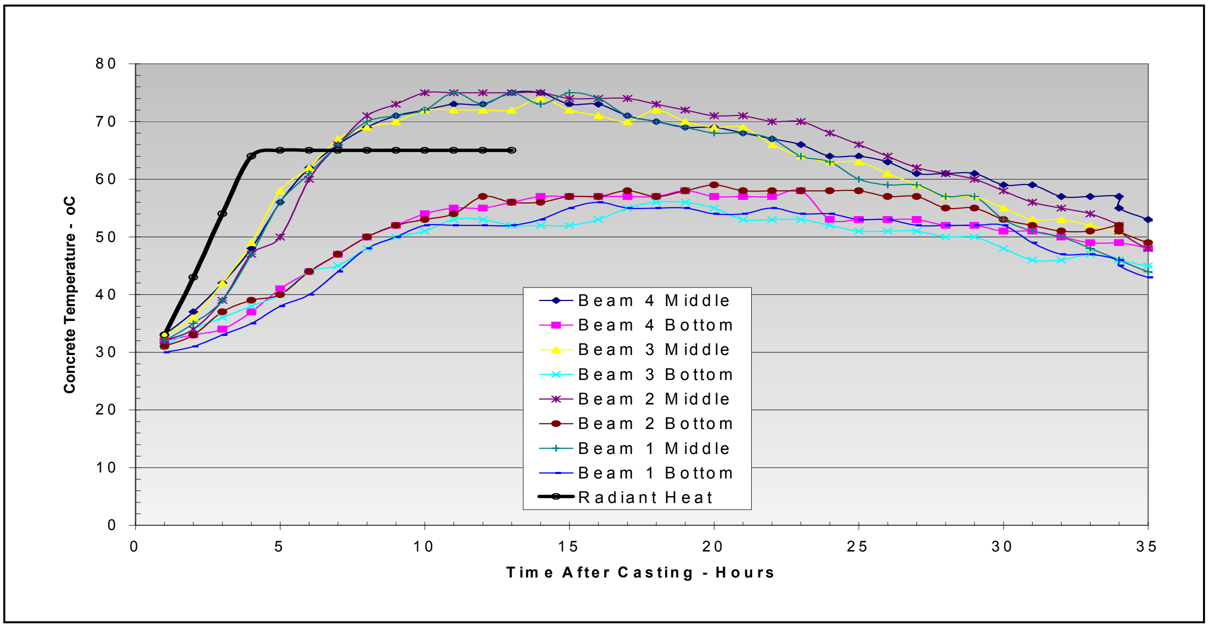

Fig. 5 Typical Temperature Record

The weather conditions varied at the site. For eight months of the year the temperatures were mild and dry. The monsoon period, lasting from June to September, was warm and rainy. This climate required hot weather concrete practices. The most effective moisture controls for the aggregate stockpiles were sprinkling and shading from the sun. Chilled mixing water (~ 5° C) was used for all concrete production. Batched concrete temperatures rarely exceeded 30° C even after up to one hour holding time in the transit mixer. Transit time from the batch plant to the forms was very short.

Concrete was placed and vibrated in a moving front starting from one end and progressing to the other for each beam. Fresh concrete was revibrated after approximately 30 minutes using internal vibrators inserted from the top; additional concrete was added as required. External form vibrators were not used.

4.4 Concrete Quality Control

Concrete test cubes were cast for determining release strength and testing at 7, 28, and 56 days. The release cubes were stored in special insulated side pockets in the beams so as simulate the actual curing regime of the beam. The remaining cubes were stored adjacent the forms and demolded after 12 to 18 hours and then stored in a water bath at the on-site laboratory. Fig. 6 presents individual test results and trend lines for the first 84 beams cast.

Because of the ongoing mix design development and the lack of adequate storage space in the field laboratory, concrete test cubes cast during the production cycles were insufficient. Some poor quality control practices and laboratory equipment maintenance issues further exacerbated this problem. Cube molds were damaged and not square. Testing machine platens were distorted. Cubes were stored in the beam side pockets without moisture retention means, which resulted in a large number of unsatisfactory break patterns (per BS 1881) and low strengths. These early problems contributed to the decision to core 44 of the first 48 production beams to verify beam concrete strength. The core samples were taken more than 60 days after beam casting and sent to an independent laboratory in Dubai, UAE for testing. The results of the core tests are plotted against the 56-day compressive strength results in Fig. 7 (next page). The testing confirmed that these early production beams had adequate strength and erection was then able to proceed with confidence.

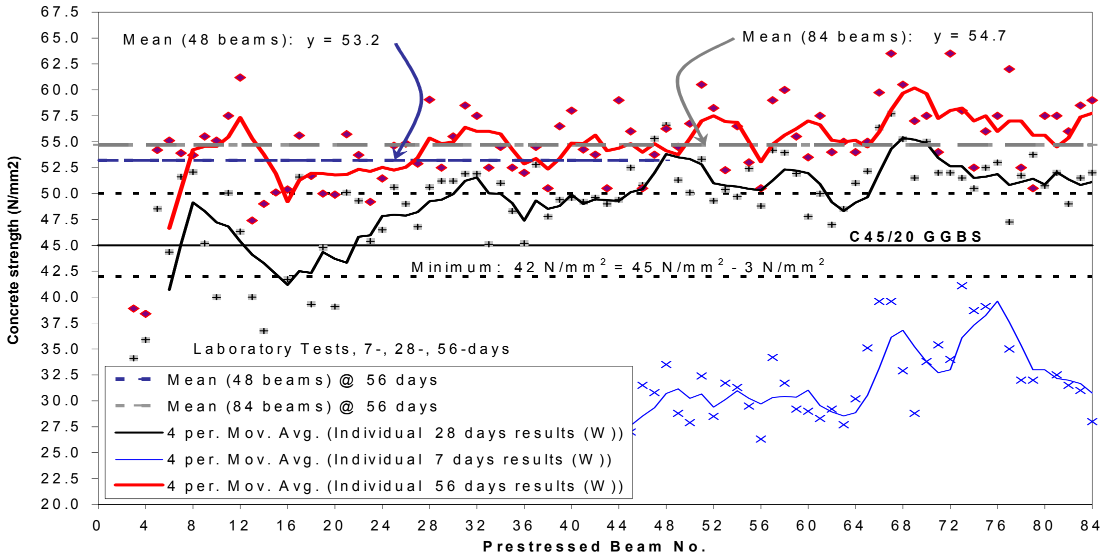

Fig. 6 Laboratory Test Results – Prestressed Beam Production

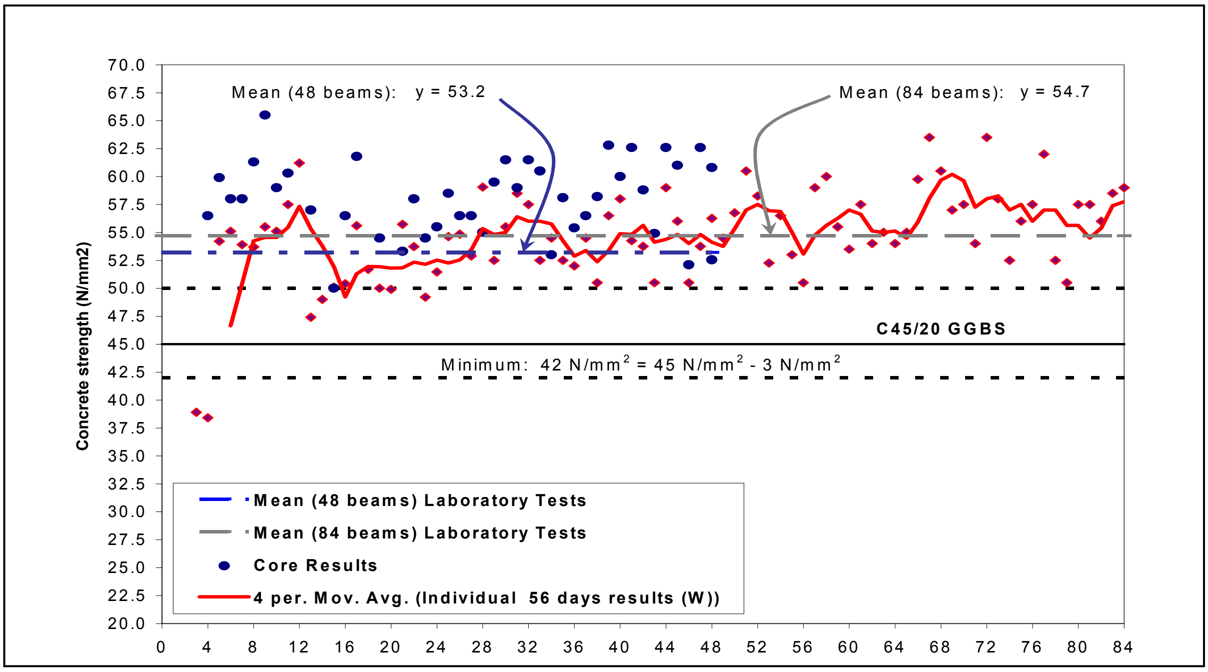

Fig. 7 Core Test Results versus Laboratory Test Results

5 CONCLUSIONS

The use of ggbs cement in a highly controlled manufacturing process on site led to improved durability and strength for the prestressed beams. Excellent quality control and supervision ensured that the beams met the high design standards required for a minimum 40-year design life. With a state-of-the-art batch plant and precast yard, the beams were produced in time to support the construction schedule. Figures 8 and 9 on the following page show photographs of the casting yard. In retrospect, the decision to change to ggbs (slag) cement could have been made earlier to facilitate the development of the production infrastructure.

Design codes for marine structures should encourage the use of ggbs (slag) cement and incorporate a requirement to evaluate all concrete mix designs for chloride penetration. Research and testing in this project has demonstrated that increased concrete cover is not the best solution to increase durability and design life. Plant cast, prestressed concrete elements should be considered for all marine structures.

The site posed some very difficult conditions for this type of sophisticated construction because of its limited accessibility and limited local resources. Although the Contractor accomplished this task successfully, future projects should consider whether more basic construction techniques in these conditions might lower construction risk or whether additional mobilization and planning time should be included to prepare the precast operations. The use of OPC cement with very low w/cm ratios, in shorter beam spans, may save time and money. Alternatively, some contractors may determine that it is more cost-effective to cast ggbs precast, prestressed beams at an existing permanent facility and transport them to the site.

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1. ENV 206: Concrete – Performance, Production, Placing, and Compliance Criteria – European Committee for Standardization 1990.

2. Eurocode 1: Basis of Design and Actions on Structures – Part 1: Basis of Design (ENV 01991-1) – European Committee for Standardization 1994

Fig. 8 Precasting Facility

Fig. 9 Precast Yard and Trestle Erection