Quality in Ready-Mixed Concrete – A Case Study on Specialised Marine Concreting in Singapore

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ABSTRACT: A case study on a recent ready-mixed marine concreting for an undersea cable tunnel constructed at the south-western tip of Singapore (at Tuas), as presented here, is a classic example of consistent high quality ready-mixed concrete that is available today for high quality / high performance construction.

The tunnel, 2km undersea and a further 800m under land, was built by the joint endeavour of the following : Obayashi Corporation (Contractor); Development Resources Private Limited (Consultant); Pioneer Singapore (Concrete Supplier); SsangYong Singapore (Cement/admixture supplier) and the owner PowerGrid Limited, Singapore.

As the quality of concrete was of prime importance in the project, this paper, after an introduction on the project/construction procedure, highlights the stringent raw materials/concrete specification requirements; the way they were met; the trials mixes; the actual production and the consistence of the production results over the entire duration of the project.

The paper concludes with reference to other specific high quality ready mixed concrete demands in the region pointing to the changing trends in the ready-mixed concrete industry - the move from lower grade retarded mixes to higher grade superplasticized mixes, in Singapore and the region.

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1.0 Introduction

Ready-mixed concrete for marine structures is not a novelty, particularly for a country like Singapore which has vast expanses of sea on all its sides. However, this particular project was the first of its kind in the region considering the complexity of construction and the quality/performance of concrete required. Detailed construction designs and procedures are beyond the scope of this paper. However, it highlights the quality and service performance of the concrete that was made available and used for this project. The primary reason for choosing this project with regards to concrete was due to the fact that specification requirements on concrete encompassed numerous aspects of high performance criteria ranging from temperature control, low w/c ratio and high slumps on fresh concrete to high early strengths, low permeability and high durability on hardened concrete.

2.0 Project details / Construction Technique

The project involved the construction of a reinforced concrete tube about 2.1 km long, placed on the ocean bed for carrying power supply cables from two large new installations on the Tuas peninsula on the western side of Singapore, across Tuas Bay to Electricalsub-stations at Ayer Rajah and Labrador in southern Singapore. Fig.1 shows the length and layout of the cable tunnel.

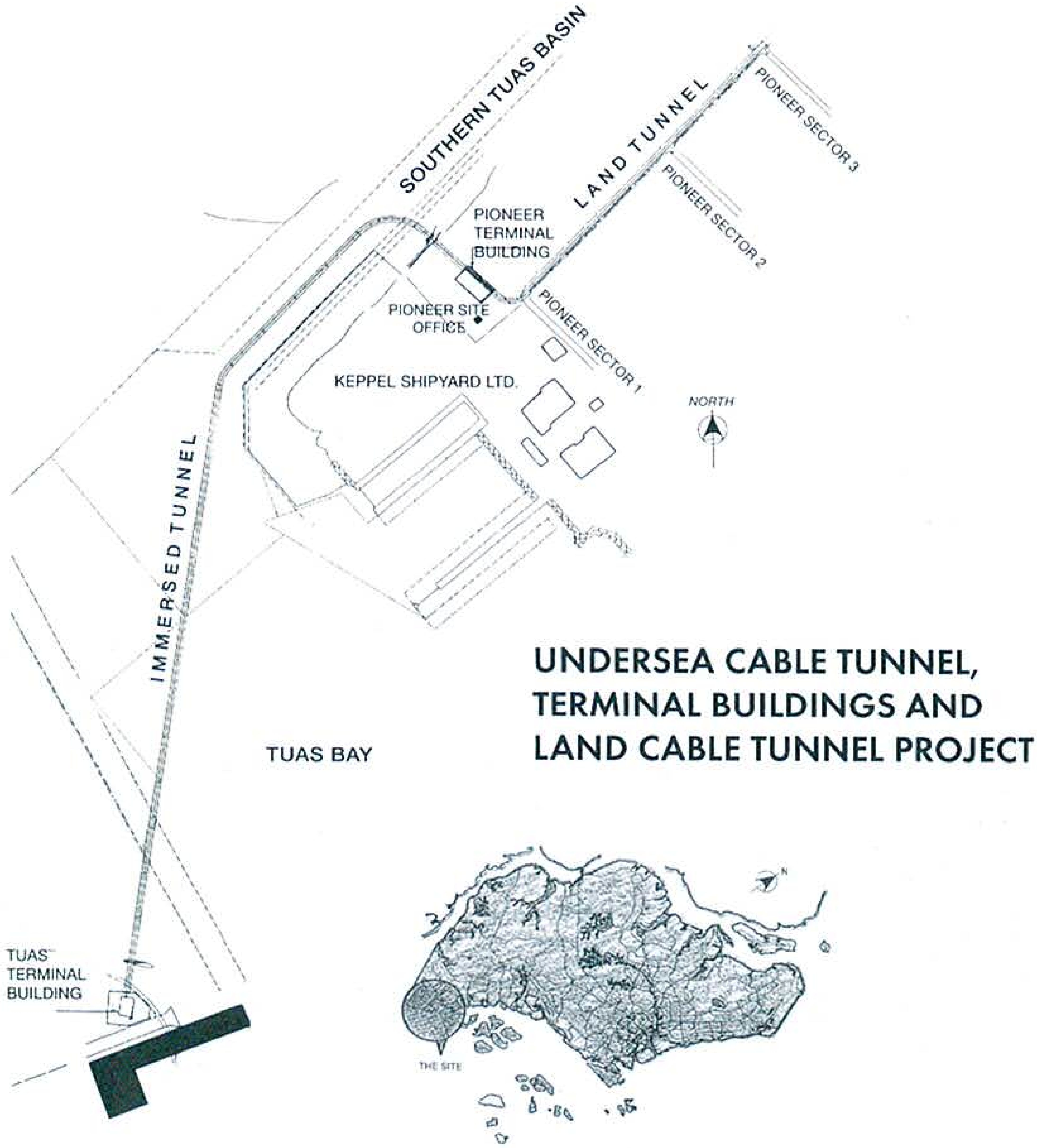


Fig.1 Layout of the Cable Tunnel

The total length of 2.9km tunnel is 2.1km under the sea - on the ocean floor and another 0.8km is under land enabling duct routes to connect with their final destinations.

The central immersed tube section of 2.1km consists of 18 straight prestressed concrete elements each 100metres long, 11.8metres wide and 4.4metres high and another 4 curved prestressed concrete elements of 50metres length each. Each element consists of 25nos. 4metres long segments cast in the casting yard and then joined together with prestressing strands on the launching jetty. After prestressing, the elements were lowered down approximately 10metres into the ocean with the help of synchronized jocks. This is the second project in the world to adopt this scheme, however, the size of the cross-section of the elements was twice that of the former project. Fig.2 shows the flowchart of construction procedure for the immersed tunnel. Fig.3 and Fig.4 show the schematic diagrams of the actual procedures right from casting of segments down to sinking of the elements, jointing them and subsequent sand-filling of the tunnel bed.

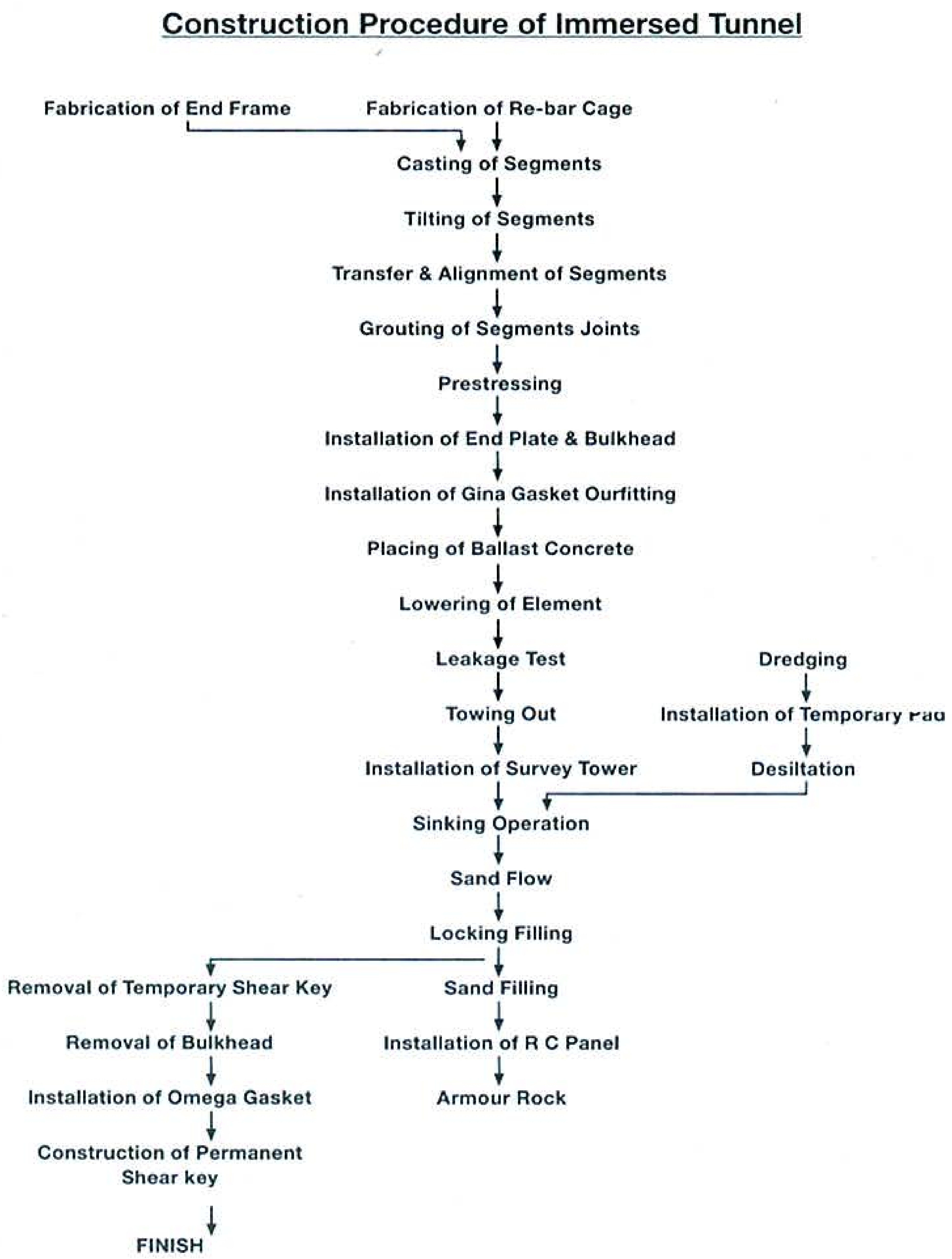


Fig.2 Flowchart of Construction Procedure

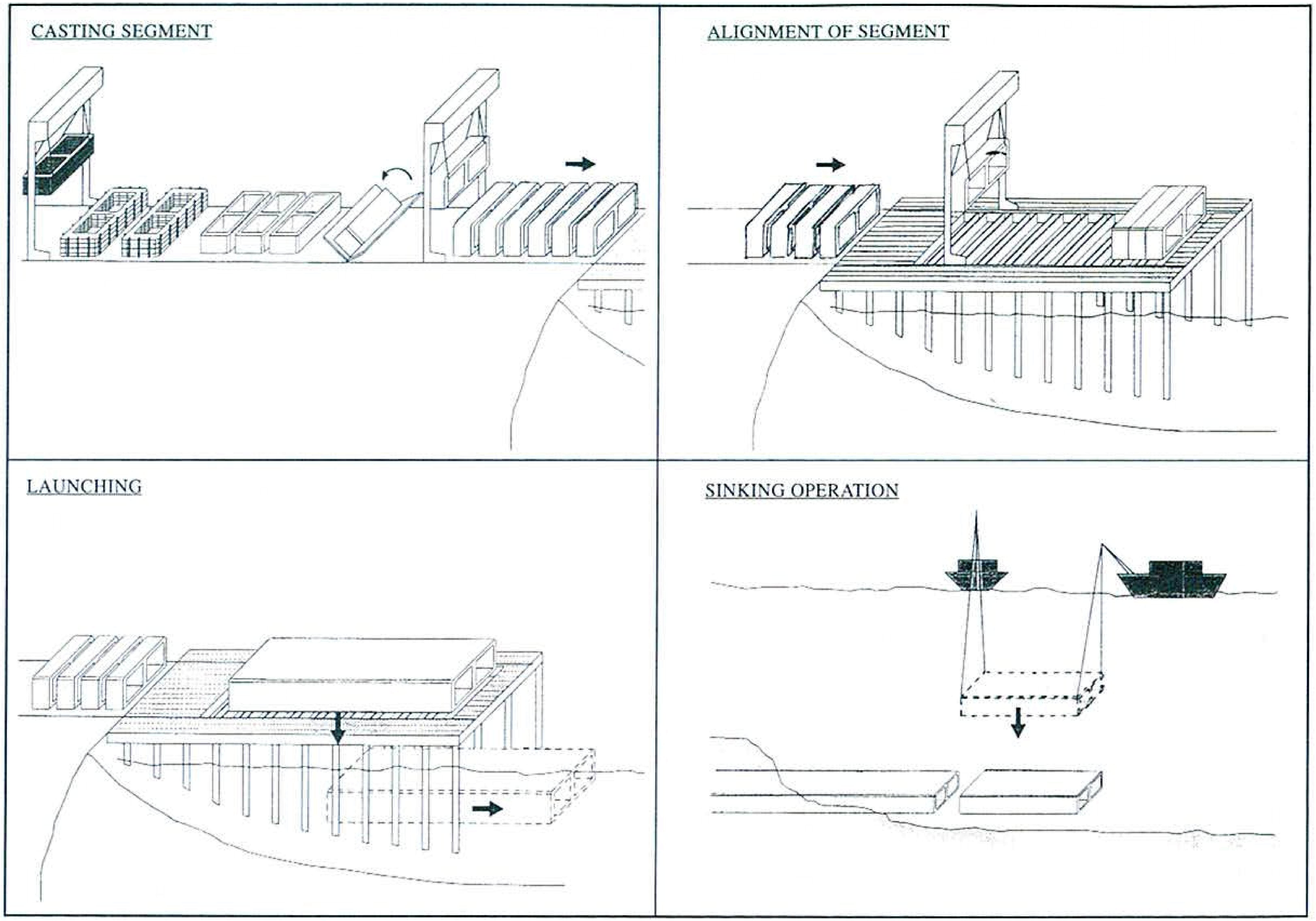


Fig.3 Casting / Aligning / Launching and Sinking Operations

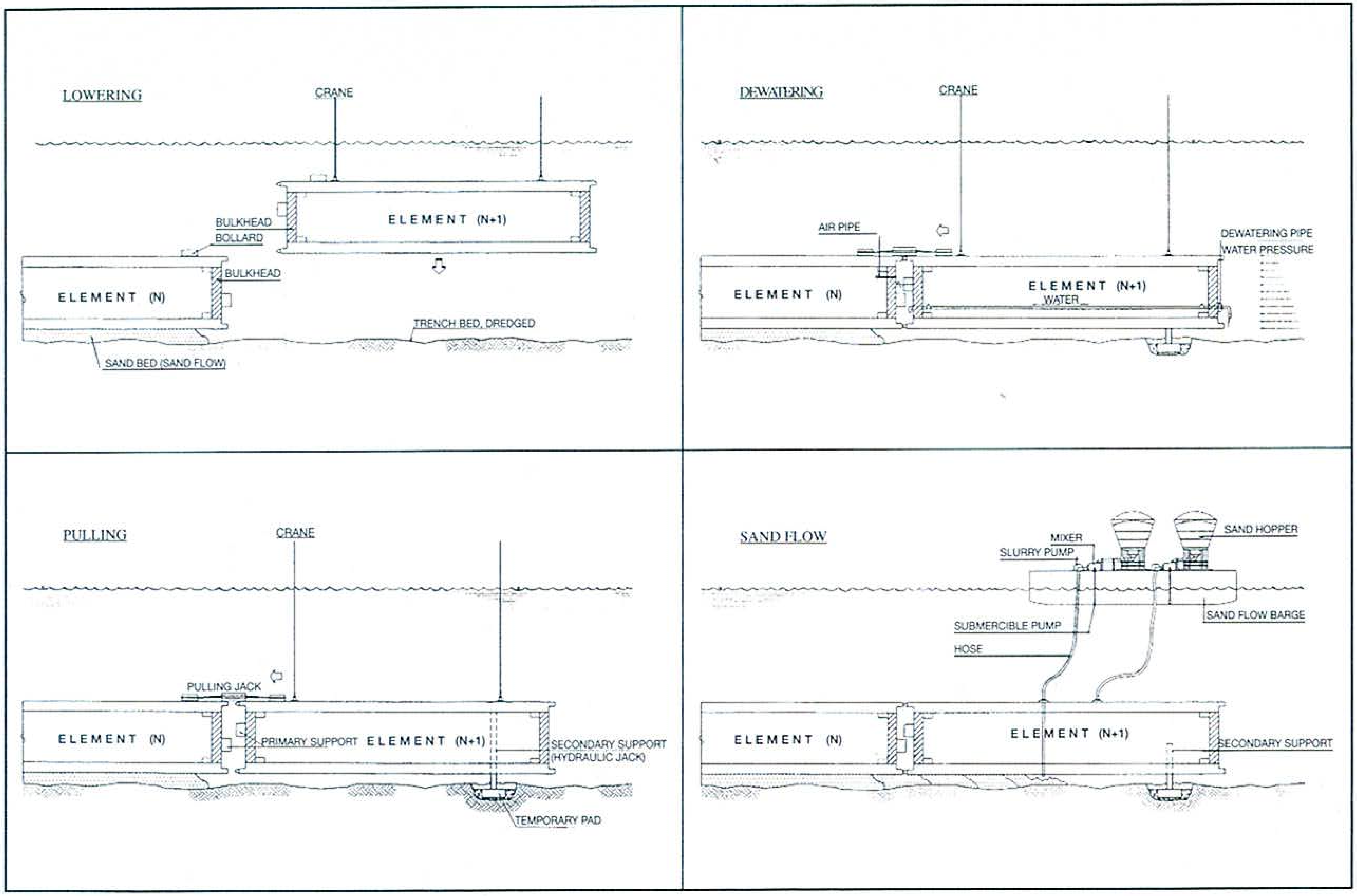


Fig.4 Lowering / Dewatering / Pulling and Sand Flow Operations

As a high standard of water proofing of the immersed tunnel was required (leakage rate not exceeding 5 millilitres/m2 of lining area per hour and not exceeding 10ml /m2 /hr for any 10metres length), water tight concrete was sought for the project. Hence, high performing integral water-proofing compound was used in the concrete. Also, the prestressing of the tunnel segments required high early strength concrete. Having briefly outlined the project and the complex construction procedures, let us now look in to the concrete supplied for the project - the specifications, the raw materials, the laboratory trials, the design mixes and the actual concrete production.

3.0 Concrete

3.1 Introduction

The concrete requirement for this project can very easily be classified as a classic example of marine concreting in this part of the world. It took a lot of teamwork amongst the Consultants (DRPL), Contractors (Obayashi Corporation) and concrete/material suppliers (Pioneer Concrete and Ssangyong Cement), over a period in excess of 20 months to successfully complete the project. The total concrete demand was about 80,000m3 out of which about 65,000m3 was supplied by Pioneer's state-of-the-art fully automated dry batch plant system. It being a marine structure job, the concrete and raw materials specification requirements were pretty stringent as evident under the following heading.

3.2 Raw materials and Concrete Specifications

Raw Materials:

· Cement - OPC was not to be used for the marine works. Instead, high slag blast furnace cement - HSPBFC (PBFC conforming to BS 4246) with a fixed blend proportion of 30% (OPC) and 70% (GGBS) was to be used to reduce heat of hydration of thick sections and to provide better marine durability characteristics especially with regards to chloride and sulphate attacks. Minimum cement content specified was 380kg/m3 and maximum w/c specified was 0.45. Tables 1 and 2 show the typical properties of PBFC and its chemical composition, respectively.

Table 1. Typical Properties Of High Slag Cement HSPBFC

IOI (%)	SO3 (%)	S (%)	Fineness (m^2/kg)	Consis tency (%)	Initial Setting (min)	Final Setting (min)	3 d Mortar strength (MPa)	7 d Mortar strength (MPa)	28 Mortar strength (MPa)
1.2	2.5	0.5 1	445	31.5	185	245	23.0	40.0	63.0

Table 2. Typical Chemical Compositions Of High Slag Cement HSPBFC

Compound	Percentage (%)
Lime CaO	48.6
Silica SiO2	29.2
Alumina Al2O3	10.6
Iron Oxide Fe2O3	1.4
Magnesia MgO	5.1
Sulphur Trioxide SO3	2.5
Total Alkali	0.52
Loss of Ignition	1.2

· Coarse Aggregates - Well graded, high quality angular crushed granite with maximum size of 20mm ($^3/4$ in.). Fig. 5 shows a typical grading curve of the coarse aggregates.

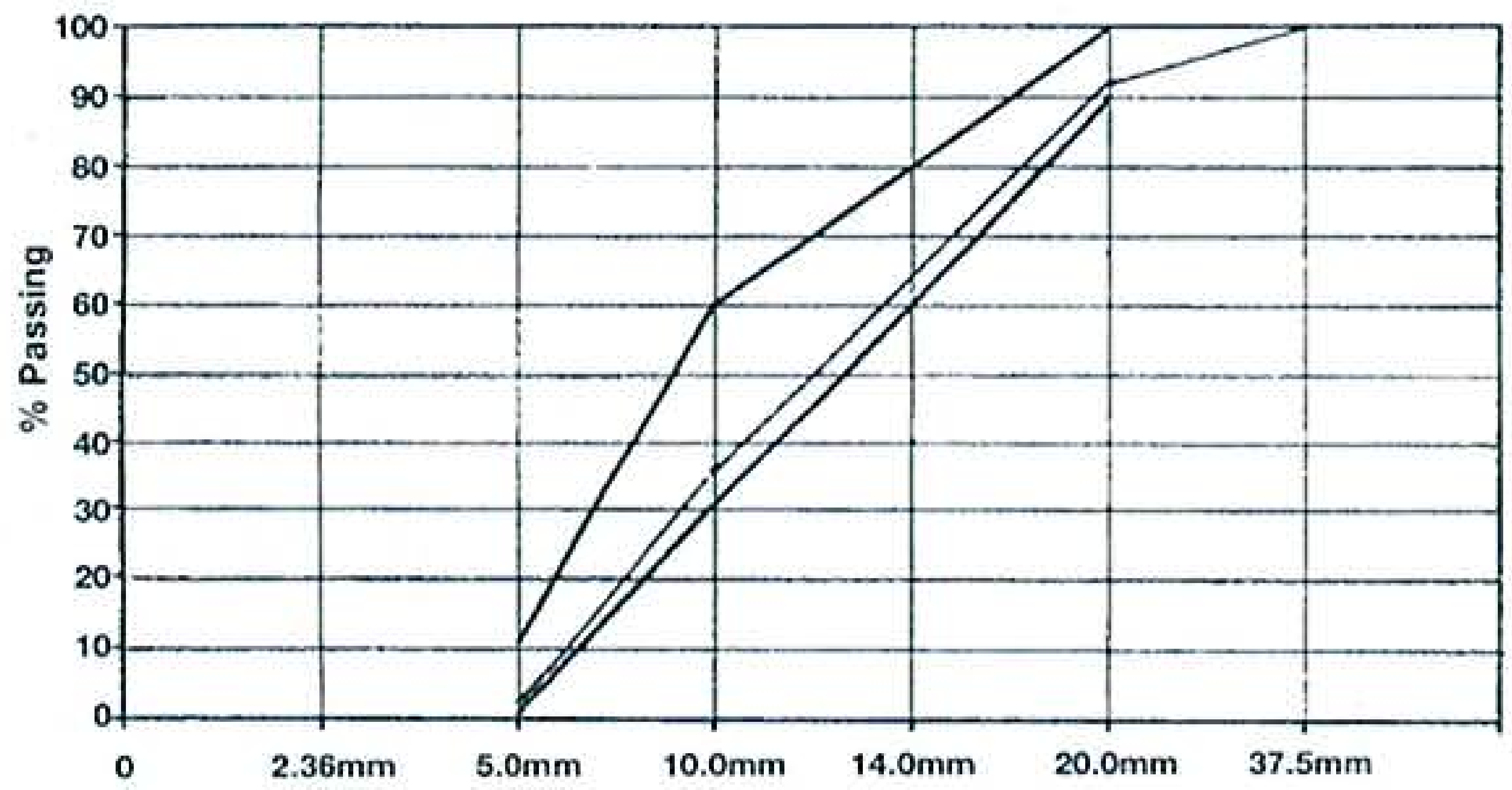
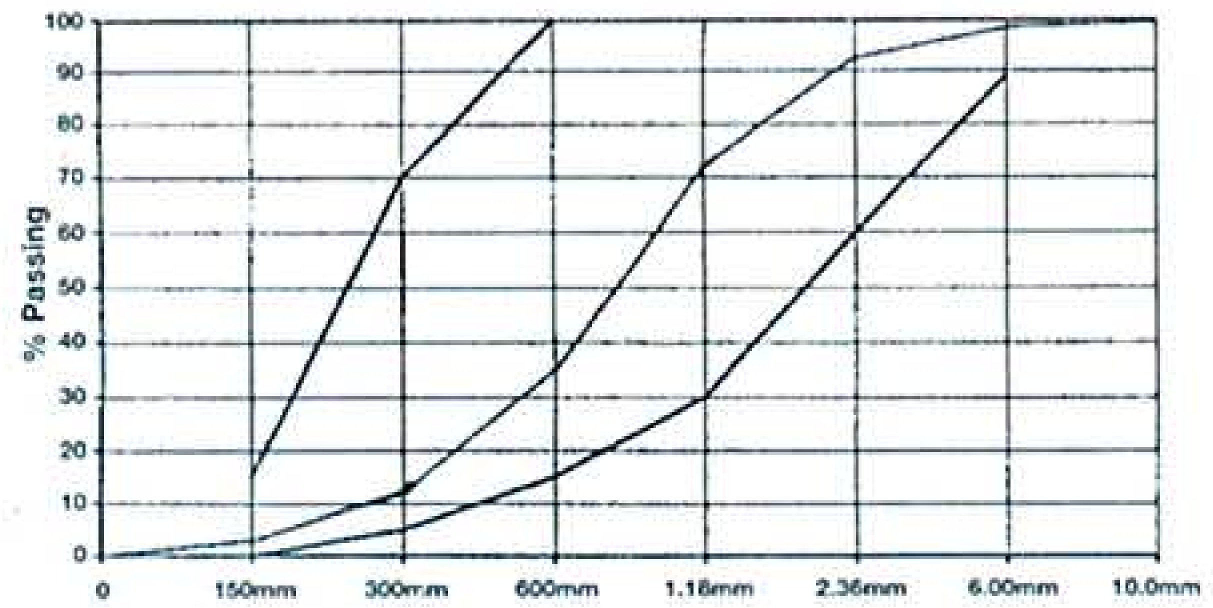


Fig. 5. Typical Grading of 20mm maxm size Coarse Aggregates Used in the Concrete Mixes

· Fine Aggregates - Well graded, high quality, low silt natural sand with low organic impurities. No granite dust or manufactures sand was permitted for this project. Fig. 6 shows a typical grading curve of the fine aggregates. For both coarse and fine aggregates, grading tests were to be conducted on a weekly basis and the quality monitored.



Fineness Modulus : 2.91 ; Organic Impurities : Color Plate no. TWO
Silt Content: 8% (by vol.); 0.76% (by weight)

Fig. 6. Typical Grading of Fine Aggregates Used in the Concrete Mixes

· Free water - Chilled water or crushed ice was to be used as most of the concrete had a placing temperature requirement.

· Admixtures - Superplasticizers and Water Proofers were to be used to satisfy slump and water absorption requirements. As the tunnels were either under the sea or under the ground with high water table, waterproofing of the structures was required. An integral waterproofing admixture SmartPruf from SsangYong Cement (Singapore) Ltd was used. SmartPruf consists two parts of liquids, SmartPruf part A and SmartPruf B. SmartPruf A is a viscose liquid consisting proprietary metallic soaps and other polymeric additives. The metallic soaps react with the hydration products of cement to form insoluble particles which reduced the porosity of concrete and at the same time forming a hydrophobic layers at the capillary walls of the capillary pores of the concrete and therefore reduced the capillary suction of the concrete. SmartPruf part B is a specially formulated type G superplasticizer which works perfectly well in combination with SmartPruf part A to enable a highly workable and cohesive concrete with extended slump retention and yet relatively high early strength in 18 hours to allow a fast turn around time of the form works.

Fresh and Hardened Concrete requirements:

· Tremie-pile slumps (175 + /- 25mm), was required, on the concrete.
· High early cube strengths of 10 MPA at 24 hours was required for prestressing works - quite a challenge for concrete containing high slag cements!.
· 28days cube characteristic strengths of 40 MPA was desired, but because of the high early strength requirements, the average 28days cube strengths were much higher than 40 MPA (as seen later in the tabulated /graphical results).
· 7 days water absorption determined as per British Standards BS 1881:part122, of less than 1% - a very stringent requirement.
Placing temperature of concrete not exceeding 28deg.C (for the precast segments) and not exceeding 32deg.C (for the land tunnel segments) - so chilled water and crushed ice had to substitute the free water in the concrete mix!
Fresh concrete to be compacted in its final place within 2 hours of the introduction of cement to the aggregate.
Minimum sampling rate of concrete was 1sample per 10m3 (for prestressed concrete); 1sample per 20m3 (for structural concrete) and 1sample per 50m3 (for infill/blinding concrete).

3.3 Mix Proportions / Laboratory Investigations

Mix designs were suggested using a variety of alternative chemical admixtures from various sources (some even were specially flown in from Japan). Numerous trial mixes were performed and finally Ssangyong Cement's Smartpruf admixture system was approved to be used in the concrete mix. Low permeability concrete was required for the tunnel construction. A low water to cement ration of 0.38 was proposed which in combination with the integral waterproofer allowed the production of a water-tight concrete with very low porosity and low permeability. A w/c ratio of 0.38 was well below the specified maximum w/c of 0.45. A cement content of 420 kg was used which was well in excess of the minimum 380kg specified for the immersed tunnel. The same design mix was adopted for the underland tunnel as well. The target mean strength of concrete at 28 days was 48 MPa. Fresh concrete slump was 175 mm+/-25mm. The mixed proportions are summarized in Table 3.

Table 3. Mix Proportion of Concrete

Materials	Mix Design
HSPBFC (kg/m^3)	420
20 mm Aggregate (kg/m^3)	1015
Fine Sand (kg/m^3)	795
Free water (kg/m^3)	160
Admixture (SmartPruf A) (L/m^3)	10
Admixture (SmartPruf B) (L/m^3)	4.2
Water to Cement Ratio	0.38
Initial Slump (mm)	175+/-25

A laboratory investigation was also undertaken to determine:

a) the workability, pumpability and setting time of the design mixtures
b) early strength development suitable for stripping formworks and strength at various ages
c) water absorption and penetration of the designed concrete
d) resistance to chloride penetration of the designed concrete

Fresh Properties

High slag cement generally produces more workable concrete as compared to OPC for the same mixed proportions due to lower water absorption of the GGBS particles. The addition of the integral waterproofing admixture SmartPruf does not affect the workability significantly. In fact the concrete produced according to the mix proportion gives a highly workable concrete of a slump more than 175 mm without bleeding or segregation thanks to the special rheology controlling agent in the SmartPruf admixture. No increase of air entraintment was observed. The air content of the fresh concrete was around 2-3%. The setting time was normal as shown in Table 4.

Table 4. Stiffening Time of HSPBFC Concrete

	Resistance to Penetration (MPa)	Results	Test Method
Initial Setting Time (hrs: min)	0.5	3:00	BS5075: Part 1
Final Setting Time (hrs: min)	3.5	6:45	

Strength Development

As the turn around time of the formwork for the tunnel segment was critical to ensure the meeting of the construction schedule, a compressive strength of 10 MPa at 24 hours after the casting was desirable. It was a challenge to the concrete producer as well as the cement and admixture manufacturer. As the slag cement generally set longer and has lower early strength, high blaine GGBS was produced for blending the HSPBFC cement. The high fineness (more than 4500 cm2/g) of GGBS and the right combination of the admixture allowed a fast strength gain of the concrete and yet retain good workability and long retention of workability to meet the site requirement. Table 5 summarizes the trial results of concrete made from OPC and HSPBFC concrete for same mix proportions except the type of admixtures. For OPC concrete, a typical commercially available type G admixture (Daracem 100) was used while SmartPruf A and B were used for HSPBFC concrete. It was interesting to note that for achieving the same workability, 1.2 L type G admixture was required for OPC concrete which resulted over retardation of the concrete and no strength at 18 hours was detectable, however, a relatively high strength of 24 MPa was achieved at 24 hours. For HSPBFC concrete with SmartPruf, a flowable and cohesive concrete was obtained and the strength of 15 MPa was achieved at 18 hours however, for safety reason the actual site requirement was set at 10 MPa at 24 hours. The 28 days strength of the waterproofing concrete was 57.5 MPa which was far above the target mean strength of 48 MPa. As HSPBFC concrete will develop strength further beyond 28 days, the strength of the concrete was expected to overtake OPC concrete after 56 days.

Table 5. Trial Results of Concrete Made from OPC and HSPBFC

Sample Reference	**OPC**	**HSPBFC/SmartPruf**
Concrete Grade	C40P	C40P
Cement Type	OPC	HSPBFC
Cement content kg/m^3	420	420
20 mm Aggregate kg/m^3	1015	1015
Fine sand kg/m^3	795	795
Free water kg/m^3	160	150
Water/cement ratio	0.39	0.38 (including 10L SmartPruf)
Type G admixture L/m^3	5.04	
SmartPruf A L/m^3		10
SmartPruf B L/m^3		4.62
Fresh Properties		
Initial slump (mm)	190	210 (cohesive, no bleeding)
Compressive Strength (MPa)		
18 hours	0	14.5
24 hours	24.0	22.0
3 days	52.0	36.5
7 days	63.0	50.5
14 days	67.5	55.0
28 days	68.0	58.0
Water Absorption (%) (BS1881:Part122)		
7 days	2.05	0.84
28 days	1.75	0.65
Water Penetration (mm) (DIN1048)		
7 days	20	1
28 days	10	0
Chloride Penetration (Coulombs) (ASTM C1202)		
7 days	3983	871
28 days	3718	513

Water Absorption and Water Penetration

Low water absorption and low permeability of the concrete are critical to ensure the designed service life of the tunnel. The use of the integral waterproofer SmartPruf guaranteed the produced concrete meet the required water absorption of less than 1% when tested in accordance with BS1881:part 122 at 7 and 28 days. The laboratory evaluation showed that the water absorption was as low as 0.65% at 28 days. The low water absorption is beneficial as it also means low sorptivity of concrete which ensure the long term dryness of the tunnel interior under the sea. If the sorptivity is high, rising dampness would be expected even there is no water leakage. The water penetration was tested in accordance with DIN1048. The pressure applied was 5 bar and maintained for 72 hours. The penetration depth of HSPBFC concrete treated with SmartPruf was negligible while remarkable water penetration of 20 mm and 10 mm was observed for OPC concrete without SmartPruf at 7 and 28 days respectively. The low water penetration exceeded the minimum requirement of water-tight concrete as specified by ENV206.

Resistance to Chloride Penetration
As the tunnel is under the sea or under the ground with high chloride and sulphate content, chloride and sulphate resistent concrete is required. HSPBFC is well documented for its superior durability performance in marine environment. The question was however, how it would perform after modifying with the integral waterproofing admixture. It was however expected that the integral waterproofer shall enhance the durability performance rather than deteriorating it due to the reduced porosity. Rapid chloride permeability test in accordance with ASTM C1202 was carried out in the laboratory using core samples from the cured concrete at the respective ages. The results were in line with the expectations as the total charges measured for waterproofed HSPBFC concrete was only 871 and 513 Coulombs at 7 and 28 days respectively which were considered very low in chloride permeability as indicated in the classification of ASTM C1202. The OPC concrete without waterproofing additive showed relatively high chloride permeability of 3983 and 3718 Coulombs at 7 and 28 days respectively. The classification of different classes of chloride permeability by ASTM C1202 is summarized in Table 6.

Table 6. Classification of Chloride Permeability Based On Total Charge Passed

Total Charge Passed (Coulombs)	Chloride Permeability
>4000	High
2000 - 4000	Moderate
1000 - 2000	Low
100 - 1000	Very Low
< 100	Negligible

3.4 <u>Actual Production - Results and Analysis</u>:

The concrete with such stringent requirements was produced by a state-of-the-art fully-automated dry-batch plant system of Pioneer Concrete, dedicated solely for this project. The installed capacity of the plant was 80m3 of concrete per hour with 16 on-site truck mixers. The average daily volume of concrete supplied was about 400m3 with a maximum daily volume of 1000m3. Chiller for chilling the batch water capable of chilling 50,000 litre (the size of our standard water tank) of water from 27 to 4 degree C in 3 hours, was used. In addition, crushed ice was used to substitute the batch water in the mix to get the required placing temperatures. An additional 10ton ice storage refrigerator had to be deployed at the batch plant to ensure uninterrupted supply of ice for concrete batching. The mix had low w/c ratio in the 0.35 range to meet the high early strength and the low early water absorption requirements. Such low w/c ratio superplasticised mixes could provide high slump loss with time. Hence, keeping in mind a maximum travel time of 30 minutes, the mix had to be designed such that even after slump loss the concrete was still pumpable when it arrived at site.

Another factor considered was that 100% natural sand was used which normally have very high moisture contents. The sand moisture was accurately assessed by a state-of-the-art microwave moisture probe and was connected online with the batch computer which automatically deducted the total batch water after taking into account the sand moisture. However, care had to be exercised to use low moisture natural sand due to the fact that high moisture natural sand would deduct a large quantity of batch water and hence very little batch water would be left to be substituted with either ice or chilled water to bring down the fresh concrete temperature to the specified level of 28/32deg.C.

For monitoring quality of concrete produced, an independent accredited laboratory was engaged to test for the strength and water absorption of the concrete produced at site.

Concrete samplings were performed as per the Specifications - 1sample per 10m3 (for prestressed concrete); 1sample per 20m3 (for structural concrete) and 1sample per 50m3 (for infill/blinding concrete). The temperature of fresh concrete was measured from the truck just before pouring to ensure that the fresh concrete temperature was within the specified level of 28/32deg.C. Table 7 shows a summary of the strength and water absorption data over the entire period of 20 months. It can be seen that the standard deviation was kept below 5 in actual production over the entire period and all the strength and water absorption criteria were achieved generally.

Table 7. Summary of results of Concrete Supplied over the entire project duration.

Test Items	No. of data sets	Mean	SD		Design Requirements
Compressive Strength (MPa)					
24 hours	922	12.18	2.96		10 MPa
3 days	922	29.52	3.60		
7 days	922	37.00	4.10		
28 days	922	52.53	4.97	f'c=44.37MPa	f'c = 40 MPa
Water Absorption(%)					
7 days	922	0.81	0.072		<1%

Fig.7 shows a plot of the cube strengths over the entire project duration and Fig.8 represents a plot of compressive strength growth with time. The 7days water absorption results over the entire project duration, are plotted in Fig.9. These results indicate that high performance criteria on fresh and hardened concrete can be achieved by ready mixed concrete in a consistent manner if quality control on raw materials and processes are prudently managed.

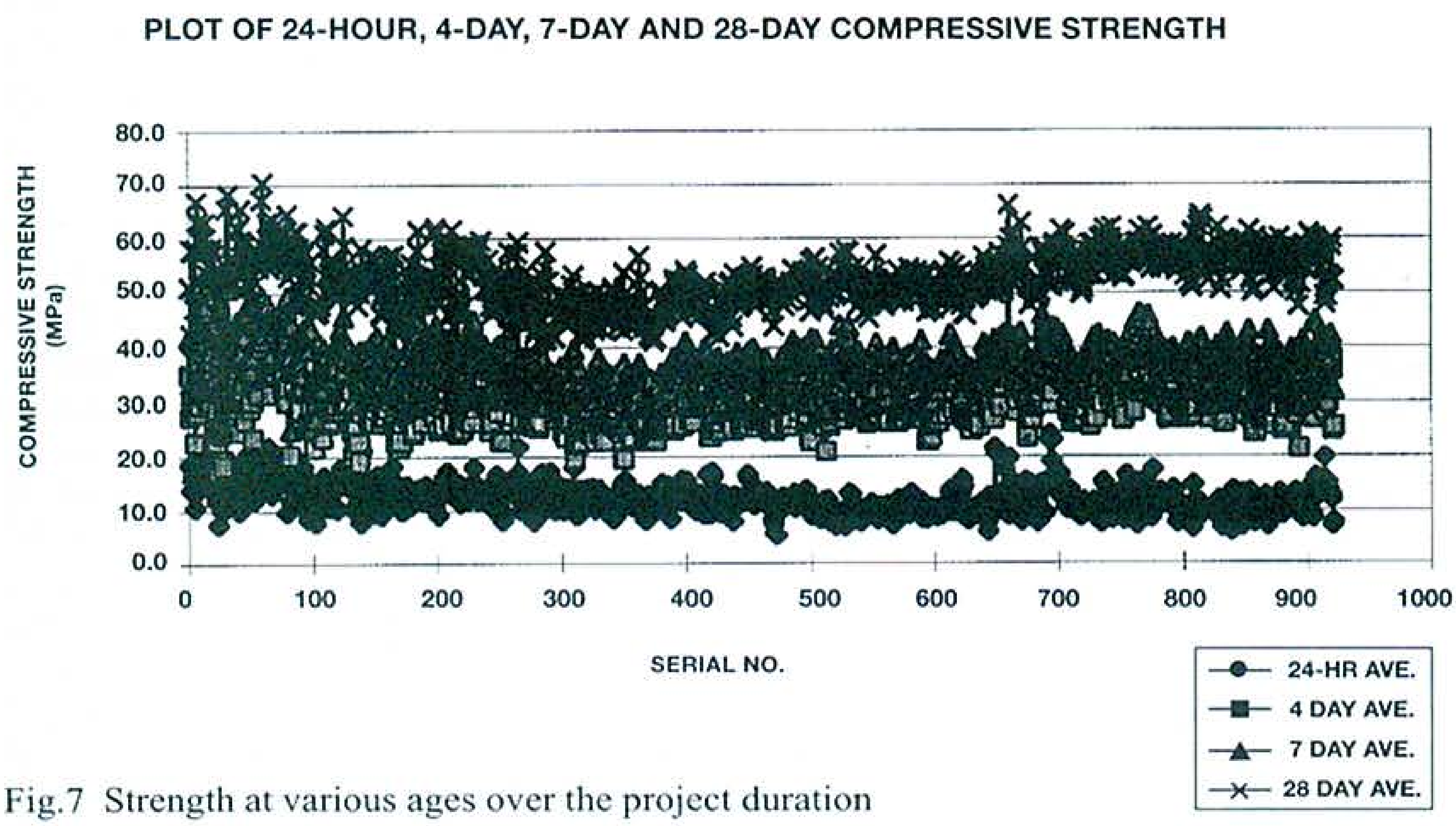


Fig.7 Strength at various ages over the project duration

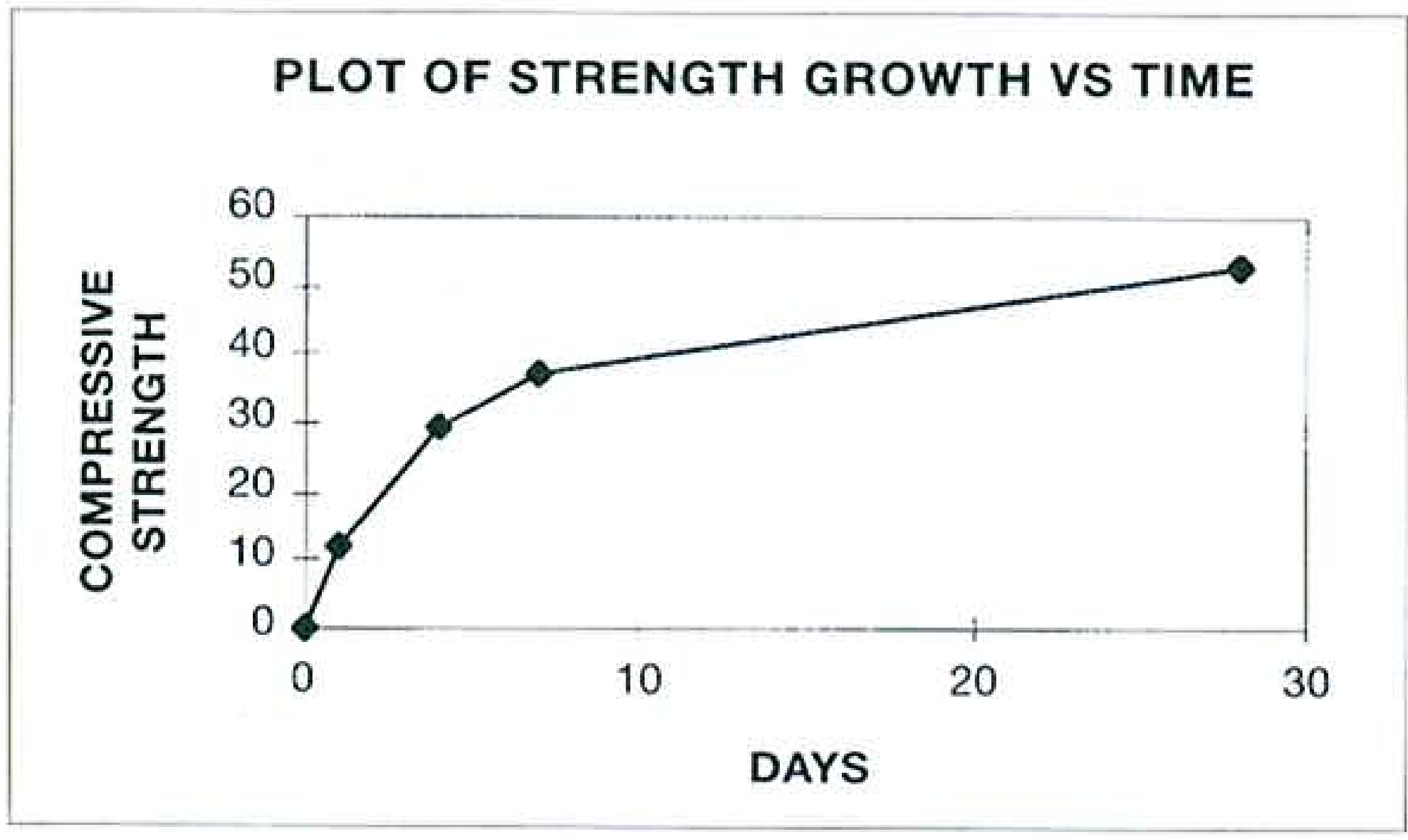


Fig.8 Plot of average cube compressive strength over time (in days).

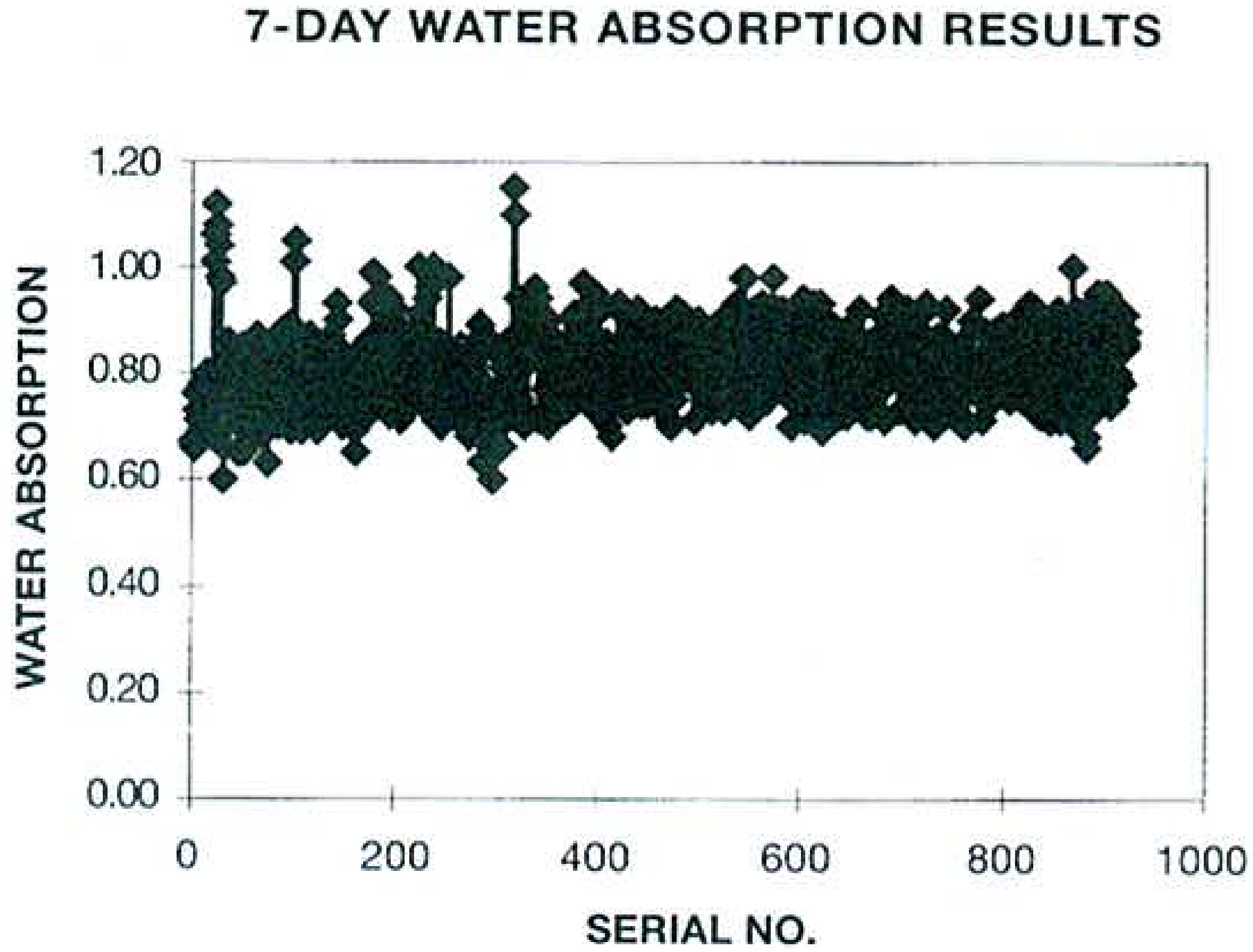


Fig.9 7days water absorption results over the project duration

4.0 Conclusions / Future Trends :

Marine concrete using high slag replacement cements but with very high early strengths (10 MPA at 24 hours), less than 1% water absorption at 7days and fresh concrete temperature not exceeding 28/32deg.C, is a very specialized concrete and is quite a challenge for the ready-mixed concrete industry. However, this challenge was well met pointing to the fact that raw materials and ready-mixed concrete in the region has technologically evolved over the years, extensively.

Although, up until now, regular grade 30 concrete (f'c=30MPA) still forms the bulk of ready-mix concrete supply in Singapore and the region, the trend towards high strength, high performance, superplasticised concrete is apparent. Recently, the Housing and Development Board (HDB) in Singapore, which consumed about 1.1million m3 of concrete in 1997, upgraded its concrete requirements from primarily grade 30 to grade 40 concrete. Also, discussions are underway to specify the use of grade40 concrete using superplasticisers rather than using only retarders. Among recent projects in the region that used high grade, high performance concretes, the following are noteworthy:

- Kuala Lumpur City Centre (KLCC), Malaysia - 80MPa, 60MPa and 40MPa
- Springleaf Towers, Singapore - 60 MPa and 40 MPa
- HDB Centre, Singapore - 40MPa, 60 MPa and 75 MPa concretes have been proposed
- Dry Dock for Singapore Technologies Shipbuilding - 50 MPa

Other than these few high grade concrete requirements there are numerous other jobs that require all other kinds of high performance with regards to high early strengths, low permeability or water proofing, temperature controlled or even abrasion resistant concretes. Most of the high performance criteria are generally met by prudent and technologically superior fully computerised batching processes, stringent quality requirements on raw materials, use of chemical and/or mineral admixtures. However, a lot needs to be done to educate and train batching plant personnel, mixer truck drivers and the Contractor's men at site to handle highly cohesive superplasticised concrete mixes which may have a deceptive dry look and may be a little harder to pump. Also, because of low w/c ratio of these superplasticised concrete, slump losses can be drastic and redosing of superplasticiser at site may be necessary. Nonetheless, the current trend shows that we are moving in the right direction with regards to quality in ready mixed concrete towards the next millenium.

5.0 References:

1. BS 1881: Part 122, 1983, "Method for determination of Water Absorption".

2. BS 4246:Part2, 1974, "Specification for low heat portland blast furnace slag cement".

3. ENV206:1990, "Concrete Performance, production, placing & compliance criteria".

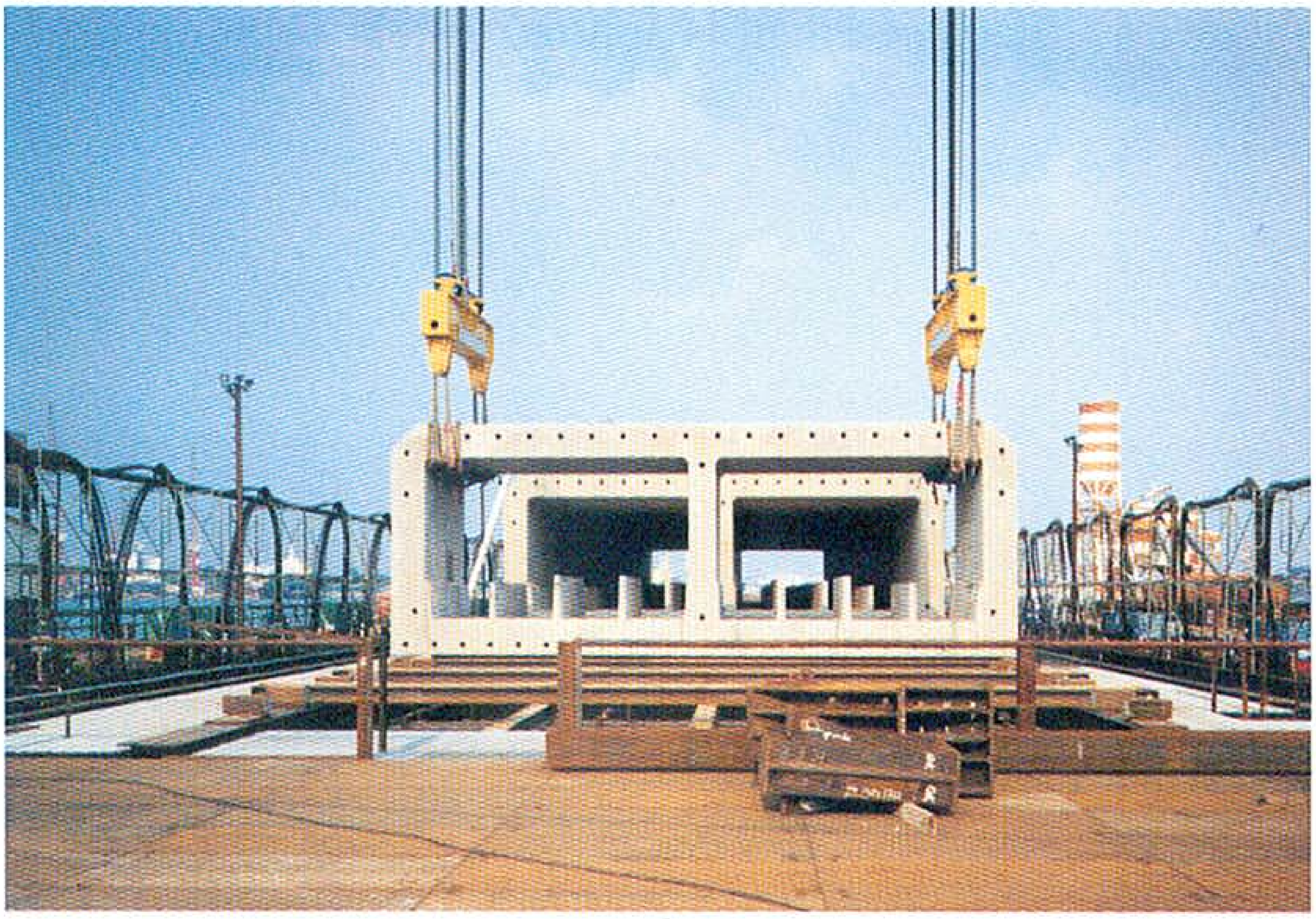
4. DIN1048:part5, 1991, "Testing Concrete, para.7.6. Water permeability".

5. ASTM C1202, 1991, "Test method for electrical indication of concrete's ability to resist chloride ion penetration".

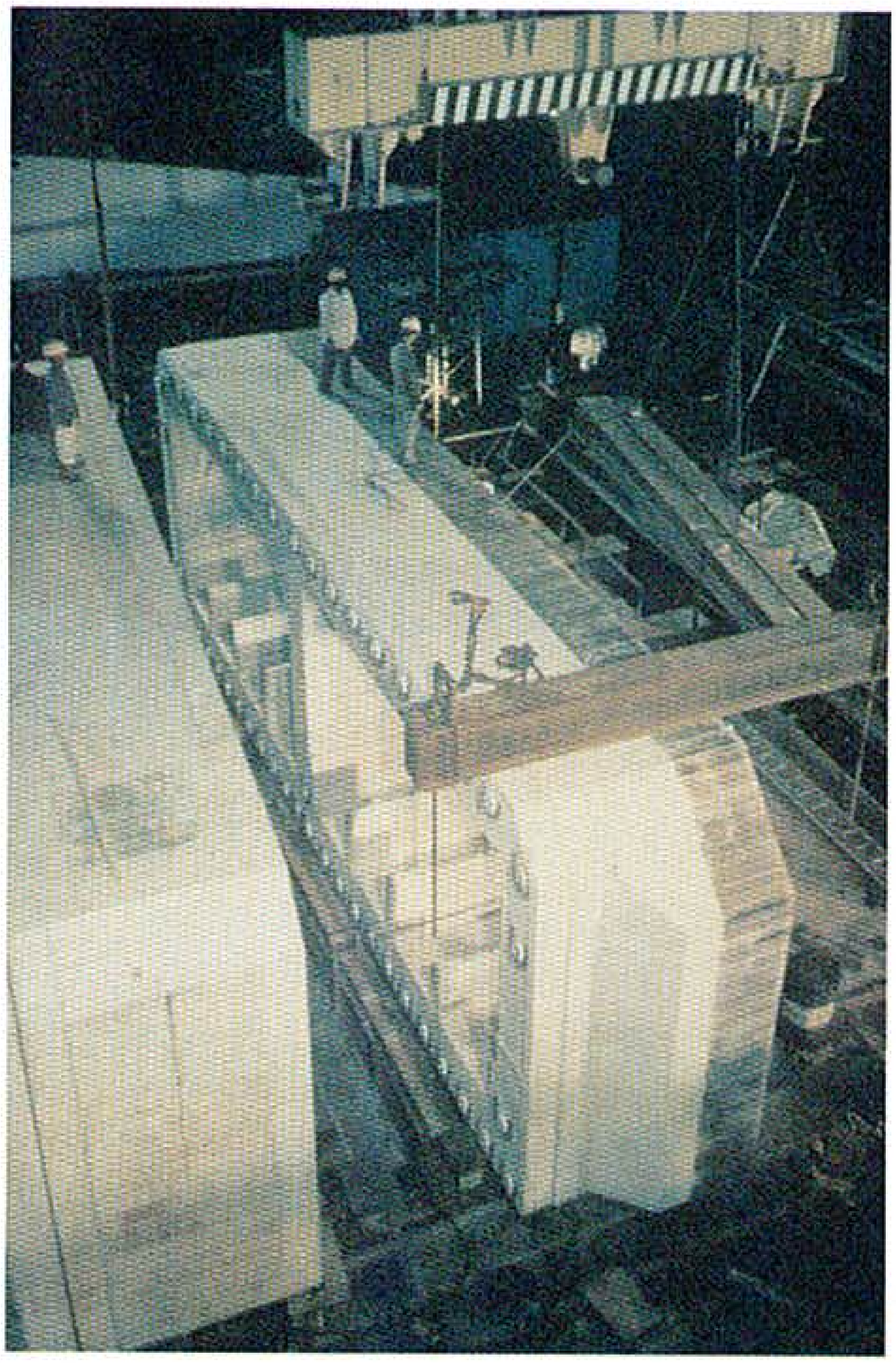
Picture 1: Casting of tunnel segment with SsangYong Cement's HSPBFC (Premium 4246) and S3 Technologies' integral waterproofer (SmartPruf)

Picture 2: Rapid demoulding of tunnel segment after 24 hours

Picture 3: Precast yard for undersea tunnel segments



Picture 4: Precast segments are aligned at launching jetty



Picture 5: Each segment is approximately 11.8m wide, 4.4m high and 4m length

Picture 6: A close-up view of the aligned segments at the launching jetty

Picture 7: Each 100m element consists of 25 segments of 4m length

Picture 8: Towing of tunnel element

Picture 9: Towing of tunnel element out to its designated location

Picture 10: Sinking operation of tunnel element

Picture 11: Complete dryness in the submerged tunnel at 15m below sea

Picture 12: View of one side of the completed twin-box undersea cable tunnel