Performance Based Design with Cost-Reducing Production Process for Shield Tunnel RC-Segment

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***ABSTRACT*:**

The production process of the lining segment for a long road tunnel constructed using shield TBM is examined to be simplified from the performance based design point of view. First, several types of simplified production processes are proposed considering the relation between the function, which each stage of the standard production process has, and the required performance of the RC-segment. Next, a series of experiments is carried out using specimens produced through the simplified production processes to confirm their performance. Then, the long-term durability of the specimens is analyzed using the DuCOM (a Finite-Element based thermo-hydro analytical system). The output is evaluated focusing on the transition of the hydration rate which is closely related to the density of the concrete. As a result, a simplified production process, where a significant cost reduction is expected, has been found. In the process, the performance of the RC-segment satisfies the required level.

KEYWORDS: RC-Segment, Hydration Rate, Durability

1. INTRODUCTION

All the long road tunnels to be constructed by the Metropolitan Expressway Co. Ltd. are planned to be bored with shield TBM. It is estimated that about 30 to 40 % of the total construction cost is the production cost of the segments with which the tunnel structure is formed.

Since the shield TBM is often used in the underground water pressure of 0.2 to 0.5MPa (approx.), high water-tightness and durability are required as a lining of the tunnel. In addition, since the unit production cost is high, the defective rate of the production is required to be reduced as much as possible by manufacturers. Therefore, lining segments are produced under a very high quality control.

However, it is possible that the lining segments under the high quality control achieve partially much higher performance than needed by users. So that, the role of each stage in the production process, which effects the performance level of the lining segment, and the cost of each stage are clarified in this research to find that the production process is more simplified, satisfying the required performance of the lining segment, at the same time.

2. SUMMARY OF RESEARCH

In this paper, RC segment is focused on because it has an advantage in the cost and generality. The function and the cost of the each stage in the production process are analyzed, and then stages which occupy relatively large share in the total cost are selected. Each stage of production process is simplified or substituted by a more efficient alternative considering their functions; and several simplified production processes are proposed by combining those simplified or substituted stages.

On the other hand, the required performance of the RC lining segment is clarified, and the experiments to test the performance of the lining segment as a structure and the concrete material are selected. Specimens are produced using simplified production processes and tested in order to confirm their performance and to judge the validity of the production processes.

Meanwhile, the long-term durability of the lining segment concrete is confirmed using the DuCOM (Maekawa et al. 1999, 2003, 2008), a Finite-Element based thermo-hydro analytical system. In the analysis, the hydration rate is focused on as an indicator of concrete density. The long-term durability is examined by analyzing the effect of production process on the transition of hydration rate.

3. SIMPLIFIED PRODUCTION PROCESS

3.1 Standard Production Process

In order to propose the simplified production process of RC segments, a standard production process is arranged, and then each stage and related facilities are examined to be omitted, simplified or substituted by an alternative.

When RC segments are produced, the quality control is generally very high in order to obtain sufficient water tightness and durability. The concrete with a slump of usually 2 to 3 cm is chosen and cast using a vibration table or on-mold vibrators together with bar vibrators to compact the concrete properly. Moreover, the water curing is used to minimize the shrinkage cracking.

Concerning the production cost for RC segments, the cost such as mold building cost, concrete casting cost, and post-demolding curing cost have a comparatively high proportion.

3.2 Required Performance and Quality

RC lining segments, which are widely used in road tunnel constructions with TBM in Japan, are usually produced in factories under a high quality control, as mentioned above. In this section, a required performance of an RC lining segment is defined; and it is stated that production processes and related facilities can be omitted or simplified for cost reduction, only if a required segment's performance is achieved. The relation between the required segment's performance and the production process of the segment is classified in Table3-1.

Measures for production process simplification and potential problems concerning the measures are arranged in Table3-2, considering the function of each process stage. As Table3-2 shows, the production stage such as material purchase, concrete casting, demolding and temporary storage is impossible to be omitted or simplified because of their characteristics in the production process. On the other hand, the other process stages are possible to be omitted or simplified if the related problems shown in Table3-2 are solved.

3.3 Simplification of Production Process

A plan to simplify the production process of RC lining segments is proposed in this section by combining various measures, based on the assumption that the potential problems can be solved.

The comparison between a standard production process and the simplified process is shown in Figure3-1. The standard process has fifteen stages to complete a lining segment. On the other hand, it is assumed to be possible to reduce the number of stages up to ten processes, still including the stages possible to be simplified, by adopting six simplification measures shown in the figure. As a result, facilities used in the process can also be significantly simplified.

Concerning the cost, shortening the steam curing period and omitting or substituting the vibration table and water curing by more efficient methods are very effective to reduce the total production cost. Since the facility cost and the running cost of the vibration table are high, it should be omitted or simplified, if possible. Moreover, an expensive mold is more expensive if the vibration table is used, since the mold must be stiff and durable enough not to be distorted while it is vibrated on the vibration table. Therefore, the mold cost can be reduced if the vibration table is not used and the required number is reduced by shortening the steam curing period and by increasing the rotational frequency of the mold. The cost of water curing method is high because of the cost for disposal of high-alkaline water after curing.

4. PERFORMANCE OF RC-SEGMENTS

As a result of the study to simplify the production process, it is suggested that the production cost of RC lining segment can be significantly reduced by adopting the simplified process, which can reduce the cost for facility and labor. However, it is possible that the quality of the concrete is seriously affected by the way of steam curing, casting, compaction, surface treatment and post-demolding curing including water curing method. Various experiments are carried out in order to understand those effects on the concrete quality and to confirm the performance of RC lining segments produced through the simplified process.

4.1 Experiments

Experiments shown in Table4-1 are conducted to confirm that the required performance of RC lining segment, which is produced though the simplified production process, concerning water-tightness, carbonation resistance, load bearing capacity, stiffness, etc. are satisfactory. Experiments, shown in the table, include tests necessary for analyses carried out using DuCOM to evaluate the long-term durability of RC lining segments considering the environmental condition of the tunnel structure under use, as described in following sections. Table4-2 shows the relation between specimens and the parameters in the production process.

Three types of concrete, seen in Table4-3, are used for specimens. The first one is the conventional type concrete with a slump of 3 cm which is usually used when compact using a vibration table. Second is the slump-improved concrete with a slump of 8 cm which AE water reducing agent is used. And the other one is the super-plasticized concrete with a slump flow of 65 cm. The latter two types of concrete are used for the purpose of eliminating the vibration table of which the capital cost and the operation cost are high. All of the concrete include polypropylene fiber which is effective to improve the fire resistance performance.

4.2 Experiments using Full-size Specimen

After full-size specimens that are just the same as actual lining segments were produced, the efficiency of the simplified production process was confirmed. Then, those specimens were aired out in the same condition with actual lining segments when temporarily stored in a yard, and the cracks were observed for about a year. Some of those specimens were used to test their bending strength, after the crack observation.

When the full-size specimens were produced, different parameters in each selected stage of production were selected and the efficiency of processes with combinations of those parameters were evaluated. The parameters for each step were, 40 or 55 degree Celsius for the highest temperature in steam curing, 12 or 15 MPa for concrete compressive strength when demolding, gauntlet finishing or using a mold lid with anti-bubble function for surface treatment and 3 or 7days of water curing or wrapping curing using plastic sheets instead of the water curing. Photos in Figure4-1 show three types of post-demolding curing.

It was observed during the exposure test that micro shrinkage cracks occurred around segment joints made of steel and gradually extended to whole surface at last. However, the maximum width of those cracks was 0.4 mm which is much narrower than the allowed maximum width of 1.0 mm to satisfy a high water-tightness. Especially, specimens produced using wrapping curing had significantly small number and area of cracks showing that the wrapping curing could efficiently reduce shrinkage cracks.

Moreover, as a result of the bending strength test conducted after the crack observation for a year, all the full-size specimens were confirmed to satisfy the required bending strength, which is the design bending strength.

4.3 Experiment using Small-Size Specimen

Water permeability tests, accelerated carbonation tests, and measurement of drying shrinkage were executed using small-size specimens. Concerning the drying shrinkage, no clear difference was observed between four types of post-demolding curing method, water curing for 3 days and 7 days, wrapping curing and in-atmosphere curing, as seen in Figure4-2. As for permeability test to confirm the water-tightness of concrete, the diffusion coefficient, that is an index for water-tightness and does not depend on the concrete type, was at around the order of 10^{-4} cm^2/s for all three types of concrete, and no effect of polypropylene fiber was seen.

On the other hand, as a result of accelerated carbonation test to see the effect of difference of the concrete type and the post-demolding curing methods, carbonated depths after 26 weeks, equivalent for 80 years in the real atmosphere, were nearly zero not depending on the curing method, for both of the conventional type concrete and the slump-improved concrete.

Meanwhile, the carbonated depth of the super-plasticized concrete was observed much larger, when in-atmosphere curing was used, as shown in Figure4-3. It is supposed to be because the rate of contained blast furnace slag was relatively high and the hydration reaction was delayed by being exposed in the atmosphere right after demolding.

4.4 Evaluation of Simplified Production Process

Simplified production processes are evaluated based on the result of tests executed concerning performance of the lining segment and their concrete. The required performance of the lining segment can be met even if some processes are simplified, for example, shortening steam curing time using higher temperature, eliminating surface treatment using the mold lid with anti-bubble function or employing wrapping curing instead of water curing, etc.

5. LONG-TERM DURABILITY

The DuCOM, a Finite-Element based thermo-hydro analytical system, is proposed to analyze the micro structure model of inorganic composite material consists of C-S-H gel particle group that forms a cement hardening body, and equilibrium and movement of materials on axes of time and space. The long-term durability of lining segments are analytically evaluated using the DuCOM.

5.1 Analysis Concerning Durability of Specimens

First of all, numerical analyses of specimens explained in §4 are carried out for the calibration of DuCOM. In the comparison between analysis and experiment, it is admitted that the results concerning the quality of cement paste are roughly corresponding in a microscope situation. It is a very profitable result to confirm the reliability of the analysis method. Figure5-1 shows a comparison of the ignition water losses at 600 degree Celsius used in the hydration rate tests as an example of analytical results.

Concerning comprehensive phenomena, such as shrinkage strain or carbonation, that appear as accumulations of microscopic phenomena, some analytical results are quantitatively corresponding to experiment results while some are not, as seen in Figure5-2, for instance. It becomes clear that the analytical accuracy is especially low concerning the super-plasticized concrete in which 65% of the cement is replaced by the ground granulated blast furnace slag. It will be a future task to be studied.

5.2 Predictive Analysis in Real Environment

Based on the analytical accuracy described in §5.1, effects of curing condition and environmental condition on the quality of concrete are analyzed using the DuCOM in a single dimension from the surface of the concrete to its center, and the sensitivities are examined. Analyzed concrete types are the conventional type concrete with W/C equal to 34.0% and the slump improved concrete with W/C equal to 35.9%. The evaluated period is assumed to be 100 years. The influence of the polypropylene fiber is decided to be disregarded as a result of sensitivity analyses.

In the analytical results, the effect level of each parameter on the two types of concrete used in the analyses show the same tendency. Moreover, the hydration rate, the saturation rate and the relative humidity tend to be different at the surface of the concrete and the center, only except the case for which the wrapping curing is kept. It is seen in Figure5-3 that effects of curing condition and environmental condition on the most surface of the concrete, which controls the durability of the whole concrete, are significant.

It deserves special mention that even though the hydration rate at the most surface of concrete is the highest until 7 days after casting when the water curing is used for 7 days, the hydration rate with the wrapping curing becomes better right after that, as a result of the analysis.

It is assumed that the hydration rate advances at the surface of concrete and the concrete becomes dense making it difficult to lose inside water by evaporation because of the wrapping. It is suggested that the combination of concrete with a low water-cement ratio and the wrapping curing method has a high possibility to improve the durability of concrete. In case of the water curing for 7 days, on the other hand, it is assumed that the density of concrete at its surface is not enough when put out of water and the inside water is lost by evaporation in the atmosphere delaying the hydration.

On the other hand, the difference of hydration ratio at the surface of concrete, which is relatively large a few months after produced, tends to become smaller in several to ten years, in a long run. It is assumed that because the concrete has a low water-cement ratio, the concrete absorbs water from the atmosphere through its surface (Miyazawa et al. 1999), analytically. The humidity is always 60 percent, in the analysis. This analytical result shows the possibility of that the low quality of concrete due to a non-ideal curing method or environmental condition can be recovered in a long period, even though there is no example of direct confirmation of this phenomenon concerning the concrete with a low water-cement ratio, in that the self dehydration is significant, and more analytical study is needed.

In addition, the coefficient of permeability that well corresponds to the material transfer capacity is calculated as an attempt to judge concrete durability quantitatively, because the water permeability has a one-to-one correspondence with the hydration ratio if the material and the mix proportion are the same, and it is regarded as a coefficient which covers the effect of curing and environmental condition, in addition to the water-cement ratio (see Figure5-4). As an example, Table5-1 shows the period within which the water permeability coefficient of the 2-mm-meter-thick surface concrete produced under a particular post-demolding curing condition becomes equivalent to that for the concrete with water curing for 7 days right after picked up from the water. In this example, concerning the concrete cured in a wrapping for 90 days, the water permeability coefficient reaches to the same level with that for the water curing for 7 days, which is considered as the standard method, within 20 days after demolding. On the other hand, it seems to be highly possible that the quality of concrete becomes fairly low when cured in the atmosphere.

6. CONCLUSION

A standard production process of the RC lining segment was arranged. Then, several types of simplified production process were planned focusing on the concrete compaction method when cast, type of concrete suitable for the compaction methods, the highest temperature during the steam curing, concrete compressive strength when demolded, executing surface treatment or not and the post-demolding curing method, moreover considering the relation between the function of each step of the production process and the required performance of the lining segment.

Specimens were produced through the proposed simplified production process, and tested to confirm their performance. The test result showed that all the specimens produced through any type of proposed simplified production process had the performance equivalent to that of lining segments produced through the standard production process in a factory.

Meanwhile, the long-term durability of the segment concrete was analyzed using the DuCOM and the result was examined focusing on the hydration rate which well corresponds to the density of concrete. It was indicated that the post-demolding curing method significantly affect the transition of hydration rate, and the wrapping curing can keep better hydration rate even compared to the conventional water curing method, while the hydration was delayed when cured in the atmosphere.

As a result, a simplified production process including the steam curing with a higher temperature to shorten the curing period, a lower compressive strength when demolded, eliminating the surface treatment and the wrapping curing method as a post-demolding curing can be feasible to satisfy the required performance of the lining segment and also decrease the production cost.

Based on the conclusion made above, the total production cost of lining segments for a road tunnel is calculated as a trial, assuming that the diameter of the tunnel is 12 m, two tunnels for each direction are paralleled, the simplified production process is used and the facilities corresponding to the production process are newly purchased and built (land cost is not included). As a result of this calculation, the total production cost can be expected to decrease by 10% if the total length of the tunnel is 5km, and 20% for 8km, compared to the standard price.

REFERENCES

Maekawa, K, Chaube, R., and Kishi, T., Modelling of Concrete Performance Hydration, *Microstructure Formation and Transport*, E & FN SPON, 1999

Maekawa, K., Ishida, T., and Kishi, T., Multi-scale Modeling of Concrete Performance -Integrated Material and Structural Mechanics, *Journal of Advanced Concrete Technology*, Vol. 1, No. 2, pp.91-126, 2003

Maekawa, K., Ishida, T., and Kishi, T., *Multi - Scale Modeling of Structural Concrete*, Taylor and Francis, 2008

JIS A1153, *Accelerated Carbonation Test for Concrete*

Standard Specifications for Concrete Structures-2007, Design, JSCE, pp165-167, 2007

Miyazawa, S., Kuroi, T., and Kitada, E., Effect of Drying on Shrinkage of High Strength Concrete, *Proceedings of JCI*, Vol. 21, No. 2, pp.679-684,1999

Table3-1 Standard Production Process of RC Lining Segment and Related Required Performance

Standard Production Process	Load Bearing Capacity		Durability		Water Tightness		Space Holding Capacity (Rigidity)
	Main Body	Joint	Concrete	Steel Parts	Main Body	Joint	
Material Purchase	●	●	●				
Concrete Mix (Mixing)	●		●		●		●
Re-bar Processing	●						
Re-bar Assembly	●						
Mold Assembly	●	●				●	●
Re-bar Setting	●	●		●			
Concrete Casting	●		●	●	●		
Concrete Compacting	●		●	●	●		
Surface Treatment	●		●		●		
Steam Curing	●		●				
Demolding	●	●			●	●	●
Water Curing			●		●		
Products Check	●	●				●	●
Temporary Storage			●	●			
Shipping	●		●		●		

Table3-2 Measures and Problems for Simplifying Production Process of RC Lining Segment

Standard Production Process		Measures	Problems
Material Purchase	×		
Concrete Mix (Mixing)	●	Purchase of ready-mixed concrete	Securing concrete plants for gigantic amount Securing quality equivalent to in-factory made
Re-bar Processing	●	Purchase of processed re-bars	Securing processing accuracy
	●	Fiber reinforced concrete to reduce re-bars	Establishing performance evaluation (design) method Securing quality equivalent to in-factory work
Re-bar Assembly	●	Fiber reinforced concrete	Establishing performance evaluation (design) method
Mold Assembly	×		
	▲	Super-plasticized concrete	Being practiced
	▲	Larger tolerance	Effect on performance and workability
Re-bar Setting	×		
	▲	Fiber reinforced concrete	Way of joint-setting etc. to secure performance and quality
Concrete Casting	×		
Concrete Compacting	×		
	▲	Super-plasticized concrete	Being practiced
Surface Treatment	▲	Larger tolerance	Effect level on performance and quality
Steam Curing	●	Shortening cycle period	Effect on total production process
Demolding	×		
Water Curing	●	In-atmosphere curing, wrapping curing	Effect level of drying shrinkage on performance
Products Check	×		
	▲	Lower frequency, simplified procedure	Finding substitutable alternatives
Temporary Storage	×		
Shipping	×		

Legend ●:Can be omitted, ▲:Can be simplified, ×:Impossible to be omitted or simplified

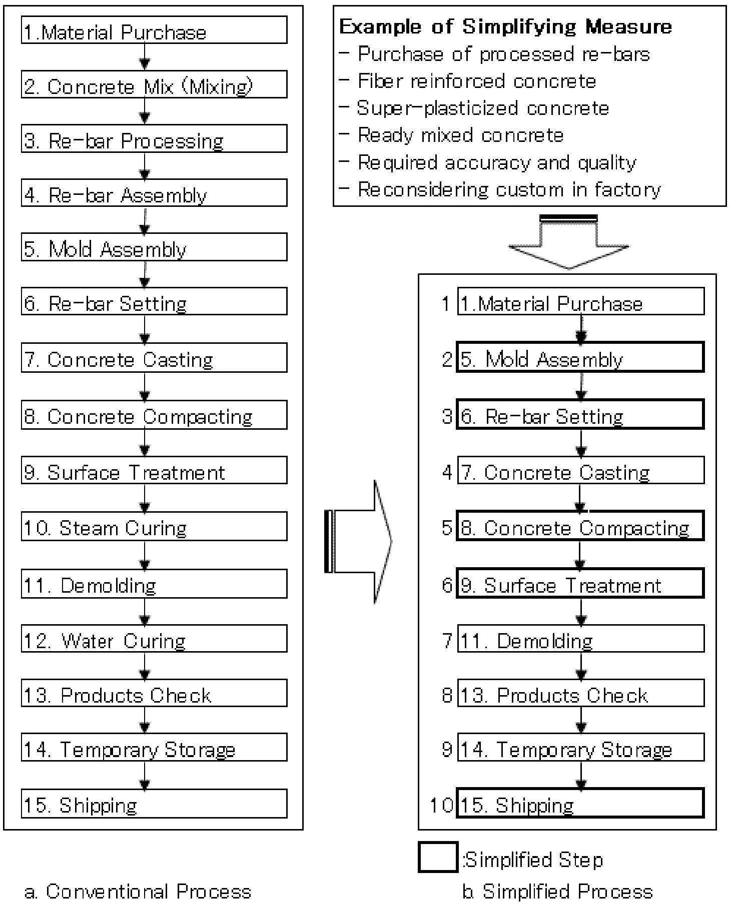


Figure3-1 Example of Simplified Production Process of RC Lining Segment

Table4-1　Experiment Menu to Confirm Performance of RC Lining Segment

Performance	Measures (test)	Specimen Size	Note
Load Carrying Capacity	Bending Strength	Full-Size	
Durability	Drying Shrinkage	Small-Size	
	Accelerated Carbonation Test	Small-Size	JIS A 1153
	Water Permeability (Input Method)	Small-Size	DIN1048
	Crack Observation (Exposure Test)	Full-Size	
Productivity	Concrete Void Elimination	Full-Size	
Concrete Quality	Water Content Measurement	Small-Size	For analysis
	Hydration Rate Measurement	Small-Size	For analysis
	Air Permeability Test	Small-Size	For analysis

Table4-2 Relation between Specimens and Parameters of Production Pricess

Concrete Type		Convent-ional		Slump Improved					Super-plasticized					
Slump		3 cm		8 cm (3cm base slump)					Slump flow 65 cm					
Specimen Number		N1	N2	SB2	SB6	SD12	SD16	SD18	KB2	KD6	KD12	KD16	KD18	KE24
P.P. fiber	No	●												
	Yes		●	●	●	●	●	●	●	●	●	●	●	●
Steam Curing	Max temp. 40°C, σ=15MPa	●	●	●					●					
	Max temp. 55°C, σ=12MPa						●					●		
	Max temp. 40°C, σ=12MPa				●	●		●		●	●		●	●
Post-demold-ing Curing	Water 7 days+in-atmosphere	●	●	●					●					
	Water 3 days+in-atmosphere				●					●				
	Wrapping					●					●			
	In-atmosphere						●	●				●	●	●
Surface Treatment	Anti-bubbling lid			●	●	●	●	●	●	●	●	●	●	
	No measure (conventional lid)													●
	Surface treatment	●	●											
Experiment Case (No. of Specimen)	Accelerated carbonation test	1		1				1	1				1	
	Drying shrinkage test	1	1	1	1	1	1	1	1	1	1	1	1	
	Water permeability test	1	1	1					1					
	Crack observation	1	1		1	1	1	1		1	1	1	1	1
	Bending strength capacity	1						1					1	

Table4-3　Concrete Mix

Conventional	Improved Slump	Super Plasticized
Design Strength: 48 N/mm^2 Slump: 3±1.5 cm W/C: 34.0% Air: 1.5±1.5% Fine Aggregate: 43.0 %	Design Strength: 48 N/mm^2 Slump:　8±2.5 cm W/C: 35.9% Air: 2.0±1.5% Fine Aggregate: 46.5 %	Design Strength: 48 N/mm^2 Slump Flow: 65±5 cm W/Binder: 34.0% Aggregate Volume: 0.280m^3/m^3 Slug Substituting: 65 %

Aggregate Maximum Size: 20mm

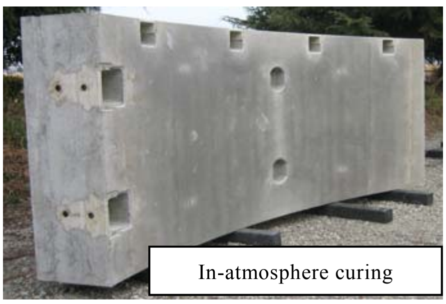


Figure4-1 Post-demolding Curing Methods

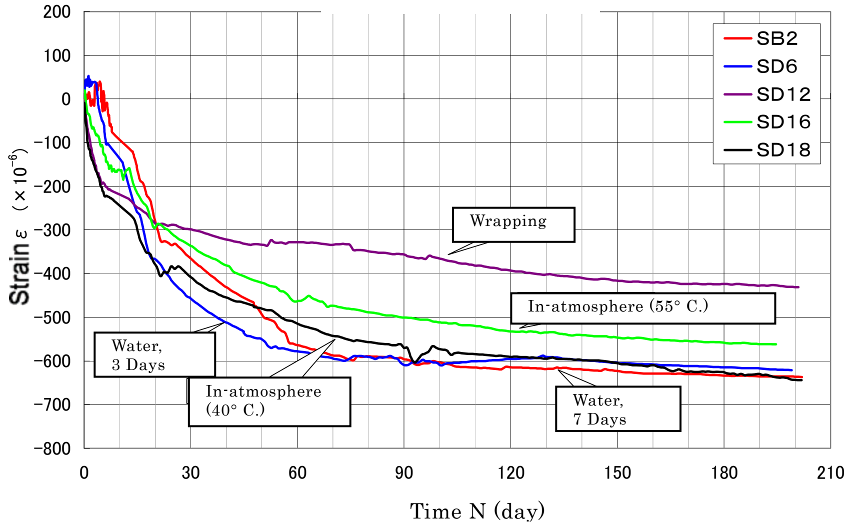


Figure4-2 Relation btw Post-Molding Curing & Drying Shrinkage (Slump Improved Conc.)

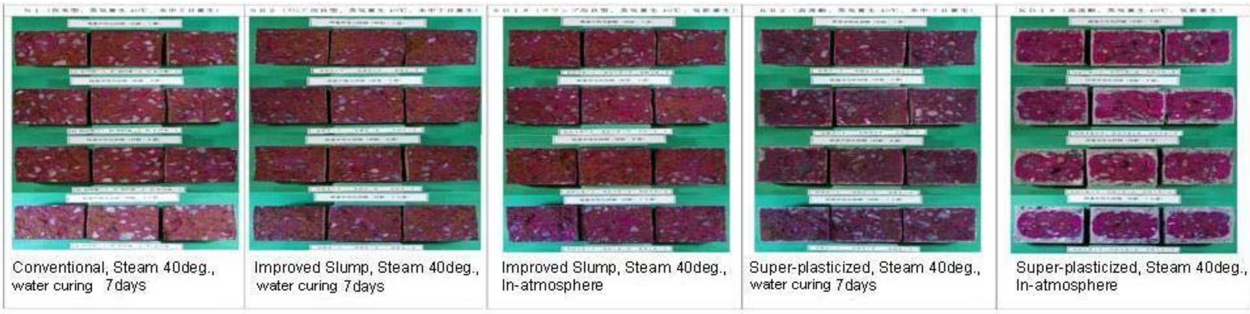
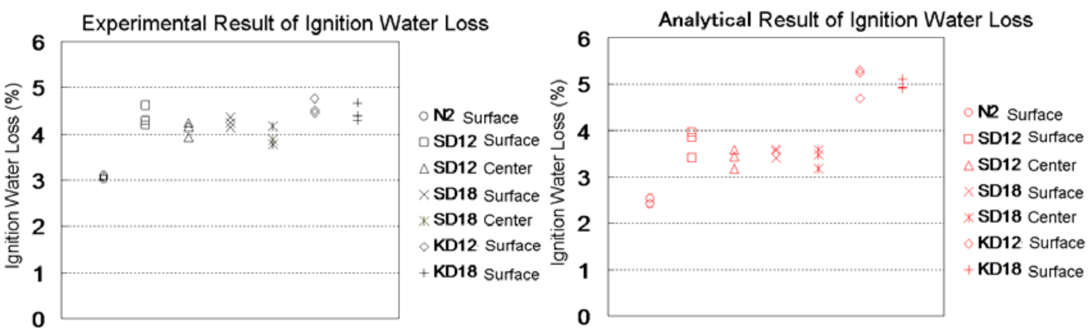


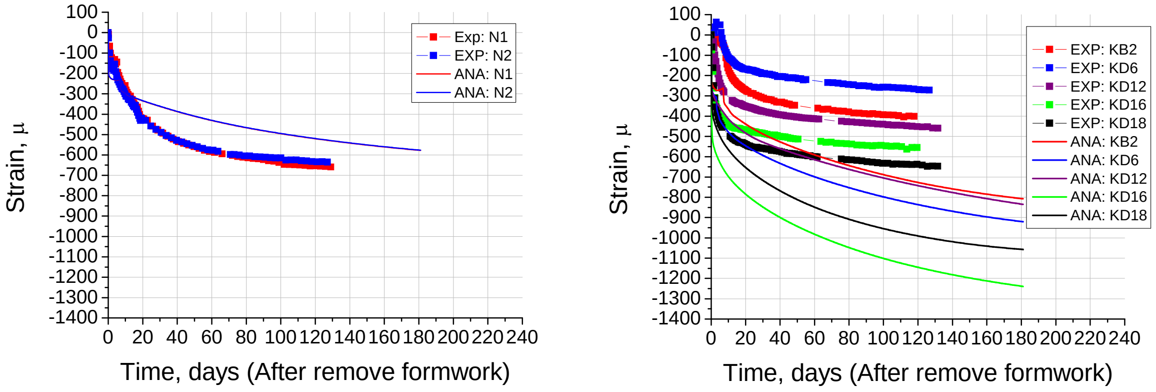
Figure4-3 Result of Accelerated Carbonation Test



(a)Experimental Result

(b)Analytical Rsult

Figure5-1 Experimental & Analytical Result of Ignition Water Loss



(a)Conventional Concrete (b)Super-plasticized Concrete (Slag 65%)

Figure5-2 Drying Shrinkage from Experiment & Analysis

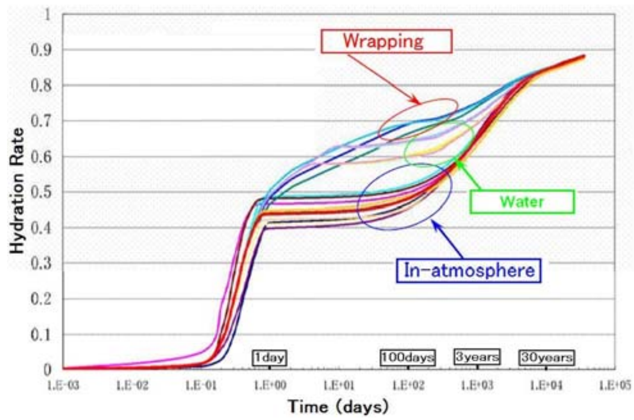


Figure5-3 Relation between Post-demolding Curing & Hydration Rate

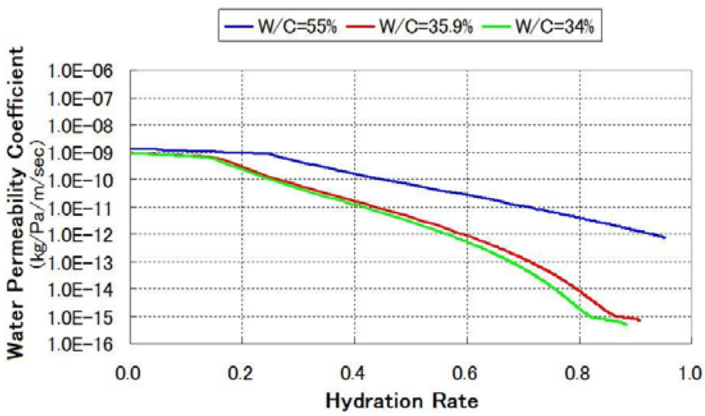


Figure5-4 Relation between Hydration Rate & Water Permeability Coefficient

Table5-1 Period Hydration Rate of Concrete Surface (2mm) Reaches that for Water Curing

Concrete Type	Wrapping 90days	Water 3days	Water 7days	In-atmosphere
Conventional	21.5 days	19.2 days	7.0 days	172.2 days
Slump Improved	20.4 days	18.7 days	7.0 days	184.4 days