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36-YEAR MONITORING OF FULL-SCALE MASS CONCRETE TEST PIECES AT NUCLEAR POWER PLANT PART 3: STUDY OF STRENGTH ESTIMATION FOR HIGH-STRENGTH CONCRETE IN STRUCTURES

Genki Uchikoshi[1], Yasumichi Koshiro[2], and Tomoyuki Koyama[3]

[1] Assistant Manager, Kyushu Electric Power Co., Inc., Saga, Japan (Genki_Uchikoshi@kyuden.co.jp)
[2] Senior Engineer, Technology Research Institute, Dr. Eng., OBAYASHI CORPORATION, Tokyo, Japan
[3] Assoc. Prof., Dr. Eng., Faculty of Human-Environment Studies, Kyushu University, Fukuoka, Japan

ABSTRACT

Part 1 of this report summarized the physical properties of mass concrete cast in summer, and Part 2 the results of an exposure test and those from durability evaluation. This article offers a summarized report on the correlation between the results of non-destructive testing with a rebound hammer and core strength. To begin with, it was confirmed that the rebound number method with the use of the rebound hammer was effective for high-strength concrete in structures if the equation proposed by Shiba, et al. or that for PCCV is used. Next, the observation of a correlation between dynamic elastic modulus and core strength confirmed the possibility of compressive strength estimation based on the elastic modulus and propagation velocity obtained through non-destructive testing, even for old concrete. The physical properties of mass concrete were verified over a prolonged period through a monitoring test discussed herein. This type of testing is extremely useful since it can be done under the same conditions as critical structures such as a nuclear reactor building where direct destructive testing is restricted.

INTRODUCTION

Direct compression test methods for concrete in structures include JIS A 1107 “Method of sampling and testing for compressive strength of drilled cores of concrete.” However, in the case of structures in nuclear power facilities, core sampling is likely to be difficult due to dense reinforcement.

On the other hand, the rebound number method has been used widely as a non-destructive testing method to estimate concrete strength. Recently, studies that applied the rebound number method to concrete with a compression strength in excess of 60N/mm^2 have been published. However, it is necessary to accumulate more data that cover dozens of years which correspond to the service period of structures at nuclear power facilities, based on the scales and environmental conditions similar to those of such structures.

In this context, this study carried out non-destructive testing (rebound number method) on full-scale test pieces that had been subjected to long-term exposure to simulate actual critical units in waterfront sites, analyzed the correlation with core strength, and discussed the possibility of strength estimation for high-strength concrete in structures with the use of non-destructive testing.

As for the correlation between non-destructive testing results and core strength at the 22nd year of exposure, it was reported in the literature that strength estimation is possible even in a high compression strength range of 60 - 90N/mm^2, by using previously proposed equations suitable for high strength cases [2][3]. This article summarizes the correlation between core strength and non-destructive test results which were obtained using full-scale test pieces that were subjected to 36-year exposure.

TEST OVERVIEW

Exposure situation, exposure environment conditions and specifications of full-scale test pieces

The exposure situation, exposure environment conditions and specifications of full-scale test pieces are as described in Part 1.

Test items and method

As a non-destructive way to estimate the strength of high-strength concrete in structures, the rebound number method was examined. Now, Inatomi, et al. reported in a previous paper a high correlation between compressive strength, estimated dynamic elastic modulus and measured dynamic elastic modulus for 22-year-old concrete [2][3]. Also, there are other reports that indicate a correlation between compressive strength and elastic wave propagation velocity as well as ultrasonic propagation velocity. In this article, in order to examine the correlation between compressive strength and non-destructive testing results for 36-year-old concrete, the correlation between compressive strength and dynamic elastic modulus was confirmed.

The rebound number was measured using the rebound hammer, according to JIS A 1155 “Method of measurement for rebound number on surface of concrete,” and the number of points struck per measurement area was 9. The dynamic elastic modulus was obtained based on JIS A 1127 (2010) “Methods of test for dynamic modulus of elasticity, rigidity and Poisson's ratio of concrete by resonance vibration.” Compressive strength was obtained following JIS A 1107 (2012) “Method of sampling and testing for compressive strength of drilled cores of concrete.”

Core specimens were taken from each test piece at two locations in a horizontal direction. Also, several core specimens were taken in a depth direction, of which the core specimens from the surface layer part were used for this article. The locations from which core specimens were taken are shown in Figure 1.

TEST RESULTS

Relationship between rebound number method and core strength

Figure 2 shows the relationship between the rebound number obtained with the use of the rebound hammer and core strength observed in large test pieces reported by Shiba, et al. [4], with the addition of the results from this test. It was confirmed that the test results from this study generally fall within the range reported by Shiba, et al.

Figure 2 also shows the data for test pieces from 22 years of monitoring. The figure confirmed that the data fell mostly within the range reported by Shiba, et al., as was the case with those from 36-years of monitoring, and that the rebound number was higher for the 36th-year test pieces. Further, with the test pieces at the 36th year, the neutralization of uncoated surfaces was found to be 0.8mm or less, and that for coated surfaces 0.5mm or less.

Figure 3 shows the relationship between the rebound number obtained with the rebound hammer and core strength in the 36th year. A regression of the test data using an exponential function yielded a contribution rate of about 0.40.

The figure also shows compressive strength estimated using four equations and compares it with the actual core strength. Those four equations are: the equation used by the Society of Materials Science, Japan (JSMS) which has been generally used (1), equation used by the Architectural Institute of Japan (AIJ)

(2), equation proposed by Shiba, et al. for high-strength ranges (3)[4], and equation for PCCV (4)[1] which was examined based on experimental results from concrete up to five years in age and is included in Appendix II of the "Guidelines for Maintenance and Management of Structures in Nuclear Facilities" by the Architectural Institute of Japan. F is estimated compressive strength (N/mm^2) and R the rebound number.

Equation used by JSMS*	$F=-18.0+1.27\times R$	(1)
Equation used by AIJ*	$F=0.72\times R+9.8$	(2)
Equation proposed by Shiba, et al.	$F=0.561\times R/(1-0.0135\times R)$	(3)
Equation for PCCV	$F=16.4\times \exp(2.91\times 10\text{-}2\times R)$	(4)

* JSMS: Society of Materials Science, Japan
* AIJ: Architectural Institute of Japan

The test pieces at the 36th year had higher core strength of 60 - 90N/mm^2; however, the equations used by JSMS and AIJ tend to estimate compressive strength as being lower than core strength, to be on the safe side. This is because both the JSMS and AIJ equations were originally developed as empirical equations for concrete with compressive strength of 60N/mm^2 or less.

Here, the relationship between compressive strength calculated by using the equation proposed by Shiba, et al. and core strength is shown in Figure 4, and the relationship between estimated compressive strength calculated using the PCCV equation and core strength in Figure 5. Also, the figures indicate ±20% ranges by referring to the aforementioned papers [2][3] and a report by Shiba, at el. [4]. With the equation proposed by Shiba, et al., which deals with a high-strength range, a relatively high correlation was observed between estimated compressive strength and core strength. With the PCCV equation, the core strength generally fell within a ±20% range of the estimated compressive strength as seen in Figure 5, signifying a high correlation between estimated compressive strength and core strength. The presence or absence of coatings appears to have had no impact on the results.

Thus, the rebound number method with the use of the rebound hammer seems to be an effective non-destructive test method to estimate the strength of high-strength concrete in structures, when the equation proposed by Shiba, et al. or the PCCV equation is used. The reasons for the high correlation when the PCCV equation is used are that the PCCV equation targets concrete test pieces with a wall thickness of about 1.5m, and that the compositions of the test pieces were also similar. Thus, it is believed that this equation can be used to estimate the strength of members such as those used in this study.

Relationship between dynamic elastic modulus and core strength

The relationship between the dynamic elastic modulus and core strength of the test piece surface layer parts is shown Figure 6. A regression of the test data using an exponential function gave a contribution rate of around 0.7, which confirmed a correlation between the dynamic elastic modulus and core strength. Thus, the authors were able to confirm the possibility of compressive strength estimation based on the elastic modulus and propagation velocity obtained through non-destructive testing, even for old concrete. The presence or absence of coatings appeared to have no impact on the results.

CONCLUSIONS

Based on the results of the 36-year exposure test conducted on the full-scale test pieces, the authors draw the following conclusions:

・The rebound number method with the use of the rebound hammer appears to be effective if the equation proposed by Shiba, et al. or that for PCCV is used.

- Especially when applying the equation for PCCV, core strength generally fell within the ±20% range of estimated compressive strength, indicating a high correlation between estimated compressive strength and core strength.
- The observation of a correlation between dynamic elastic modulus and core strength confirmed the possibility of compressive strength estimation based on the elastic modulus and propagation velocity obtained through non-destructive testing, even for old concrete.
- There was no observed tendency to suggest the coatings or the lack thereof impacted the relationship between the rebound number method or dynamic modulus and core strength.

As explained above, the applicability of non-destructive strength estimation for high-strength concrete in structures was verified, based on the results of the monitoring test of full-scale test pieces that were 36 years old and subjected to long-term exposure.

This article entailed a long-term exposure test for reinforced concrete structures in nuclear power plants in waterfront sites, and reported the results from the 36-year study. The monitoring test case reported herein has proven to be capable of tracking the durability of concrete and finishes at critical structures such as nuclear power plants under the same environment as actual units, when the direct study of the units is restricted, thus contributing greatly to soundness confirmation and maintenance planning. The authors hope to utilize the data obtained from this case not only for special and critical structures, but also as a reference for non-destructive estimation of high-strength concrete durability, body protection effect of coatings, and compressive strength in the planning of future construction work.

[1] *AIJ Guidelines for Maintenance and Management of Structures in Nuclear Facilities*, (2015)
[2] Inatomi, T., Watanabe, J., Funamoto, K., Mitarai, Y., Miyajima, H., Oike, T. "Strength Estimate of Hight Strength Structure Concrete by Concrete Test Hammer," *AIJ Chugoku Summaries of technical papers of annual meeting*, pp.777-778, (2008.9)
[3] Inatomi, T., Watanabe, J., Funamoto, K., Mitarai, Y., Miyajima, H., Oike, T. "Strength Estimate of Hight Strength Structure Concrete by Nondestructive Test," *AIJ Kyushu chapter architectural research meeting*, No.47, pp.157-160, (2008.3)
[4] Shiba, A., Ishikawa, S., Watanabe, S., Kawakami, H. "The Proposal and Evaluation of Concrete Strenght Estimation by Rebound Hammer," *Concreate Journal*, Vol.43, No.2, pp.35-40, (2005)

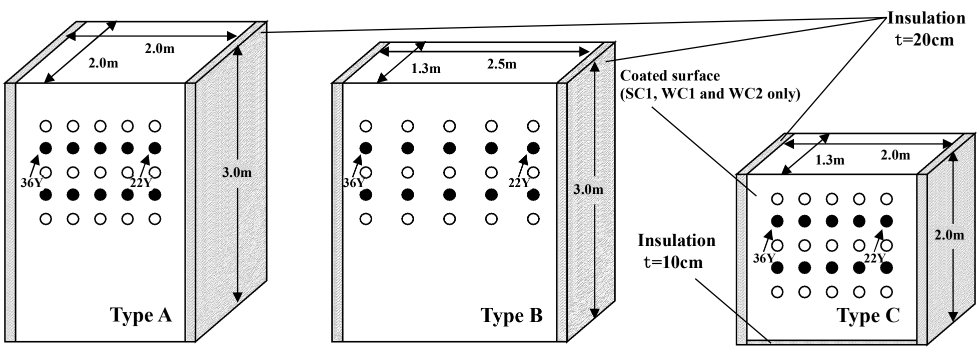

Figure 1. Test piece core sampling locations

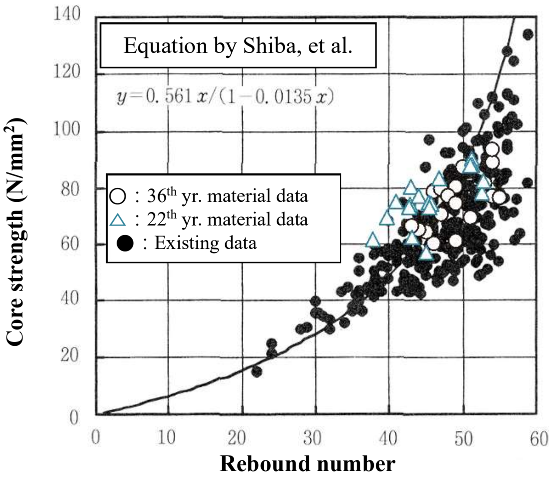

Figure 2. Relationship between rebound number obtained with rebound hammer and core strength

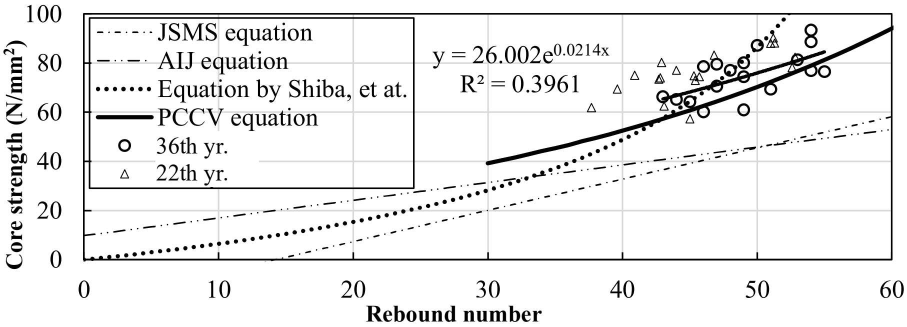

Figure 3. Relationship between rebound number obtained with rebound hammer and core strength

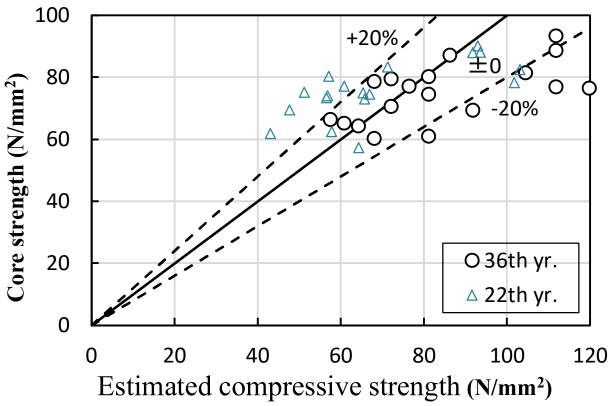

Figure 4. Accuracy of equation proposed by Shiba, et al.

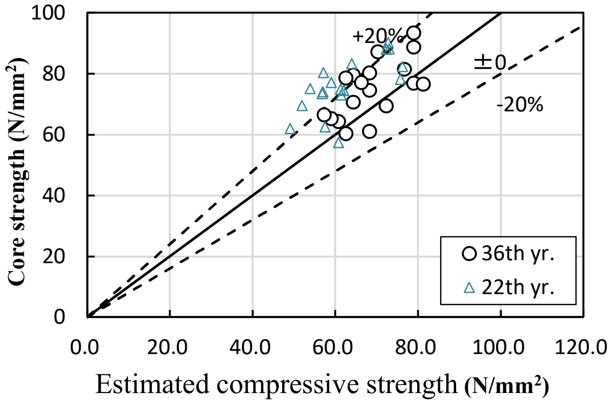

Figure 5. Accuracy of PCCV equation

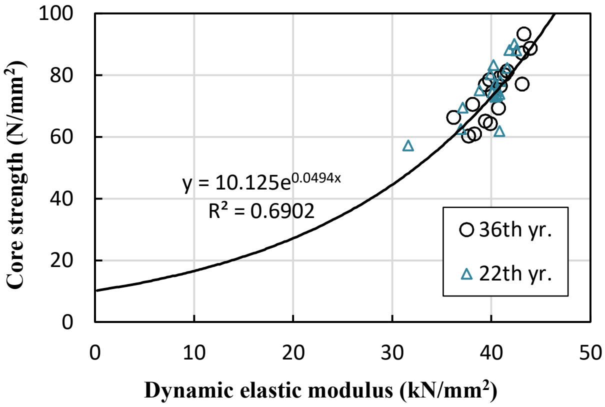

Figure 6. Relationship between dynamic elastic modulus and core strength