Committee Report : JCI- TC101A

Technical Committee on Diagnosis Methodologies of Structural Health of Concrete Structures by Utilizing Advanced Inspection Techniques

Junichiro NIWA, Noboru YASUDA, Tomoaki TSUTSUMI, Masaki TAMURA, Shigehiko SAITO, Toshiro KAMADA, Mitsuyasu IWANAMI, Hitoshi HAMASAKI, Takahisa OKAMOTO and Kazuo YOKOZAWA

Abstract

This technical committee was engaged in activities intended to clarify "How the various proposed semi-destructive and non-destructive testing methods should be applied to health diagnosis and deterioration prediction to minimize the LCC". The following WGs were established: (1) WG to study the change of health-related activities, (2) WG to identify the present condition and issues concerning semi-/non-destructive testing technologies, (3) WG to identify the present condition and issues concerning structural repairs/strengthening, and (4) WG for the application of semi-/non-destructive testing. Through the activities of these WGs, the present maintenance trends and issues, the technical level of semi-/non-destructive testing, etc. are clarified, and application methods of semi-/non-destructive testing to enable highly accurate prediction of deterioration, selection of reasonable repair time, and methods for repair are proposed.

Keywords: Semi-destructive testing, non-destructive testing, maintenance, life cycle cost, preventive maintenance

1. Introduction

In Japan, structures which were constructed during the high economic growth period to support the social infrastructure are about to enter an unprecedentedly heavy deterioration stage due to aging. On the other hand, as construction investment continues to be restricted, investment for maintenance is not expected to increase. Under such social conditions, innovative maintenance methods need to be established More specifically, there is a need for maintenance measures to restrict the increase of maintenance cost, as well as to enable the structures to continue to be used beyond the service life estimated at the time of construction. Concrete structures are not exceptional. In order to continue to use heavily aged concrete structures safely and comfortably to minimize the life cycle cost (LCC), it is indispensable to upgrade testing technologies, health diagnosis technology, deterioration prediction technology, and repair and strengthening technology.

Table 1: Committee members

Chairman	Junichiro NIWA	Tokyo Institute of Technology
Vice-chairman	Noboru YASUDA	Engineer.INC
Secretary-General	Tomoaki TSUTSUMI	Tokyo Electric Power Company
	Takahisa OKAMOTO	Ritsumeikan University
	Noboru YUASA	Nippon University
	Toshiro KAMADA	Osaka University
	Masaki TAMURA	Kogakuin University
	Mitsuyasu IWANAMI	Port and Airport Research Institute
	Takumi SHIMOMURA	Nagaoka University of Technology
	Shigehiko SAITO	University of Yamanashi
	Kazuo YOKOZAWA	Fujimi Consultants CO.,LTD
	Natsuki YOSHIDA	General Building Rsearch Corporation of Japan
	Shoichi OGAWA	Taiheiyo Cement Corporation
	Hitoshi HAMASAKI	Department of Building materials and Components, Building Research Institute
	Koichi KOBAYASHI	Japan Cement Association
	Kenichi ASANO	Hachiyo Consultant CO.,LTD
	Taku MATSUBAYASHI	Maeda Corporation
	Kazumasa MORIHAMA	Public Works Research Institute
	Yukihiro TANIMURA	Railway technical research Institute

There has been intense research and development on the above technologies so far; however, a satisfactory diagnosis of the degree of health or an accurate prediction of deterioration is still not possible.

In order to properly assess the present degree of health or to accurately predict deterioration of structures, the use of testing technologies to accurately grasp input data including concrete strength, infiltration depth of deterioration factors, corrosion degree of reinforcing bars, etc., is indispensable.

Progress of testing technologies in recent years is so remarkable that deterioration data can be grasped accurately at the structural component level through the practical application of semi-destructive testing technologies such as small size coring and drilling as well as non-destructive testing methods. The application of those testing technologies, however, remain at the level of “collection of deterioration data” at present, and such performance is far from sufficient for the intended diagnosis of “degree of health,” “deterioration prediction,” or “LCC minimization.”

The Japan Concrete Institute was actively engaged for two years from 2010 to 2011 when it established the JCI-TC101A "Technical Committee on Diagnosis Methodologies of Structural Soundness of Concrete Structures by Utilizing Advanced Inspection Techniques", with the theme of "How the various proposed semi-destructive and non-destructive testing methods should be applied to health diagnosis and prediction of deterioration to minimize the LCC". The committee was organized as shown in **Table 1**.

In order to properly perform a health diagnosis and predict deterioration of concrete structures, it is important to exploit the characteristics of semi-destructive testing and non-destructive testing, respectively. More specifically, while semi-destructive testing is appropriate for the analysis of the infiltration depth of deterioration factors such as core strength and neutralization depth through such methods as small size coring and drilling whose application is not very restricted, non-destructive testing is appropriate for grasping the state of construction such as the cover of reinforcing bars and internal defect exploration. The health diagnosis and prediction of deterioration should be performed by properly combining the information obtained from these testing methods. From such a perspective, the committee studied not only semi-destructive testing but also the application of non-destructive testing as its research objectives.

The committee defines the difference between semi-destructive testing and non-destructive testing as follows:

- Semi-destructive testing: A test to investigate concrete quality, deterioration factor infiltration depth, etc., by slightly damaging a concrete structure. The small size coring method and the drilling method are included in such testing.
- Non-destructive testing: A test to investigate the concrete quality, condition of reinforcing bars, etc., without damaging a concrete structure.

The committee consists of the following WGs: WG1 (WG to study the change of health-related activities, headed by Tamura) was chiefly engaged in activities to reveal the principal objective and remaining issues concerning the conventional durability assessment. It conducted (1) service life extension and stock management of concrete structures, (2) health assessment of concrete structures by semi-destructive testing, and (3) analysis of health assessment manual for facility managers. WG2 (WG to identify the present condition and issues of semi-/non-destructive testing technologies, headed by Kamada) was engaged in activities to investigate the actual results of semi-/non-destructive testing to recognize the state of the practice, future directions, and issues. It (1) sorted out the results (findings) related to semi-/non-destructive testing by academic societies, and analyzed mutual relations and roles; and (2) revealed perfection, actual application, and prospective application for health assessment by semi-/non-destructive testing technologies. WG2 also summarized and analyzed the questionnaire survey on semi-/non-destructive testing. WG3 (WG to identify the present condition and issues concerning repairs/strengthening, headed by Iwanami) investigated and analyzed repair/strengthening cases of actual structures, and presented issues in the present health diagnosis of concrete structures. WG4 (WG for application methods of semi-/non-destructive testing, headed by Yasuda) proposed methods to use semi-/non-destructive testing for efficient maintenance of heavily aged concrete structures which are expected to increase from now on in the light of the results of activities of WGs 1 to 3.

The results of the WG activities are summarized below.

2. Activities of the WG to study the change of health-related activities (WG1)

2.1 Trends of service life extension of concrete structures in Japan

This section discusses, among the activities performed by WG1, service life extension trends and maintenance of concrete structures in Japan which are shifting from conventional corrective maintenance to preventive maintenance.

In Japan, enormous social capital stock, including many concrete structures, has been accumulated. The stock, which was intensively developed particularly during the high economic growth period from 1955 to 1975, has entered a replacement time. They would be replaced by new construction without hesitation if the high economic growth period had continued. Due to stringent national finance and from the perspective of environmental protection in recent years, however, replacement by new construction is very difficult. Under such circumstances, we have to use the existing stock longer than the service life expected at the time of design. To enable this, it is important to firmly maintain the social infrastructure that supports the economy and life. **Fig. 1** shows the changes in construction investment in civil engineering projects and its ratio to GDP as an example. The investment ratio to GDP remains at approximately 5%[1)]. Given that the population and corporate capital investment, which are the largest factors for GDP growth, are obviously decreasing, there are concerns that it is difficult to secure the maintenance cost which is expected to rapidly increase in the future.

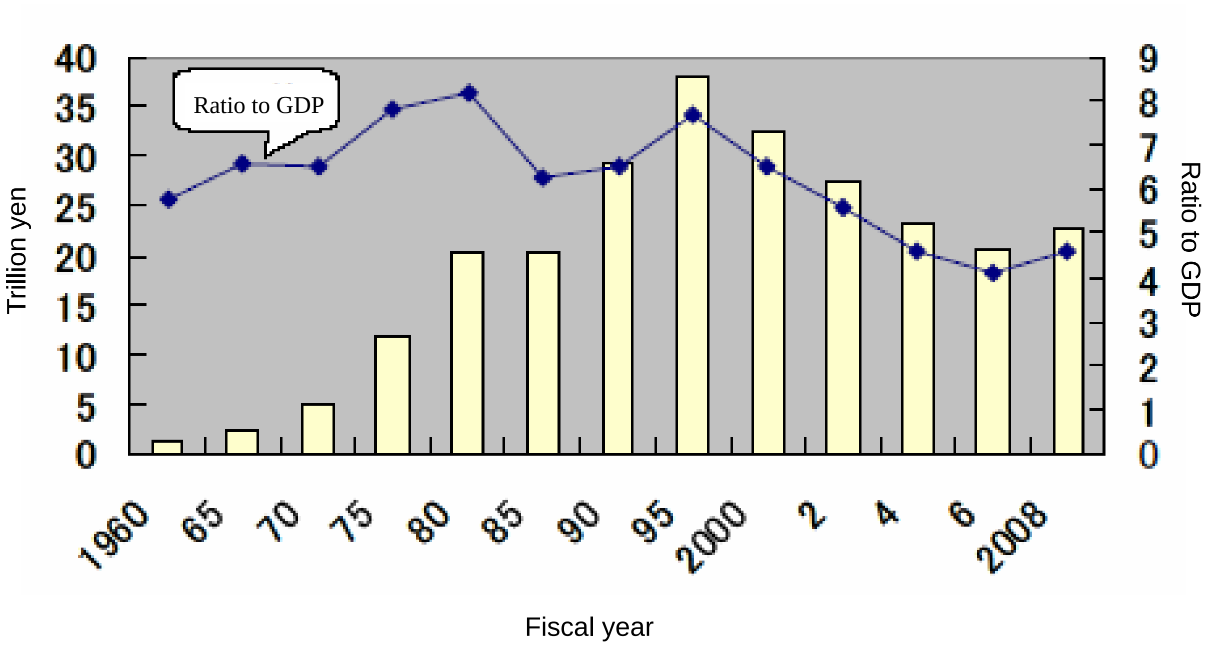

Fig. 1: Changes in civil engineering construction investment amount[1)]

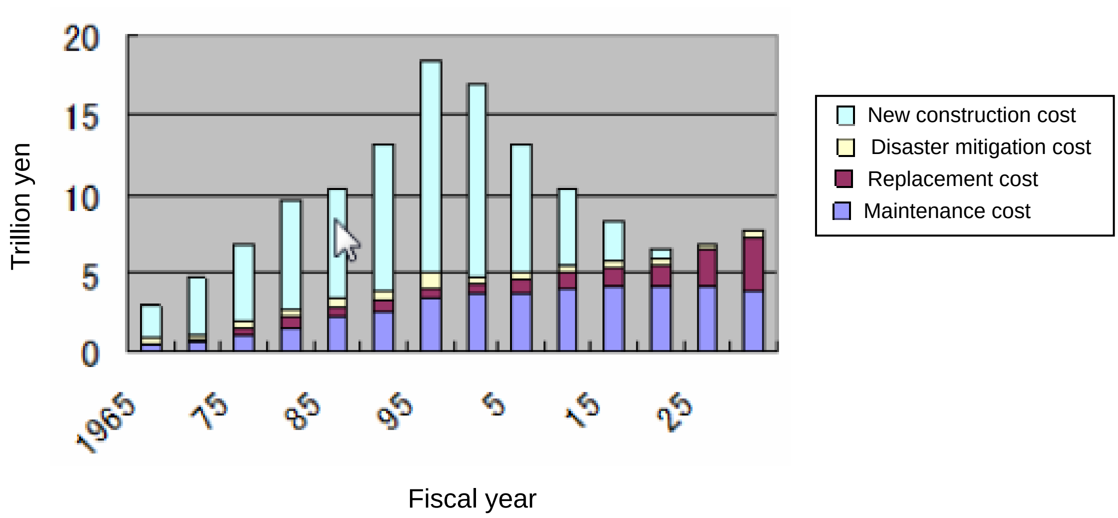

Fig. 2: Forecast of investment amount for maintenance/replacement [2)]

Fig. 2 shows the maintenance/replacement cost estimated on the assumption that the gross investable amount in FY 2005 onward will increase by -3% for the social capital managed by the national government or by -5% for the social capital managed by local governments[2)]. As shown in the figure, it is reported in the White Paper on Land, Infrastructure and Transport in Japan in FY 2005 that the gross investable amount required for maintenance and replacement will run short around FY 2023 at earliest. This estimate assumes that the service life of the structures is approximately 60 years, and that the structures beyond their expected service life will be replaced by new construction with the same functions.

This result indicates that the social infrastructure needs to be used beyond its expected service life. There is a real possibility that the social infrastructure will be used for more than 100 years. It should be always taken into consideration, however, that ensuring safety of the social infrastructure is directly connected with national economic activities and the safety of civil life.

2.2 From corrective maintenance to preventive maintenance

In conventional maintenance of civil engineering structures, corrective maintenance that “takes measures after an issue arises in ensuring safety due to the progress of deterioration” was a mainstream concept. In recent years, however, there is a need for the introduction of preventive maintenance that “takes measures before deterioration progresses” to minimize the life cycle cost and extend the service life of structures. The concept of preventive maintenance of civil engineering structures varies widely depending on facility managers with no definitive definition established.

Table 2 shows the changes in standards for roads and bridges and their background. It seems that there is strong recognition that we are facing an age of stock following the age of flow since the start of the 21st century.

2.3 Preventive maintenance and semi-destructive testing

Given that the mainstream of current maintenance is to take measures at a considerably deteriorated stage, coring investigation, which is a partial destruction testing, may be frequently used. While coring investigation such as for salt pollution can obtain many data such as strength, neutralization, salt penetration, and steel corrosion, non-destructive testing can obtain one item per test in general. If preventive maintenance to extend the expected service life is more frequently conducted, the current practice of coring investigation will damage, even only partially, the healthy parts of the structure and in extreme cases may lead to deterioration of the structure if repair of the coring is not well implemented.

Under such circumstances, what is expected to be applied increasingly in the future is semi-destructive testing that is considered to be positioned between coring investigation and non-destructive testing. Semi-destructive testing includes small size coring method with a core diameter of approximately 25 mm and the drilling method with a drilling diameter of 10 mm to 20 mm. Since these semi-destructive testing methods have started to be used relatively recently compared to other testing methods, it is not well known “for what” and “to what extent" they should be used. As there is not sufficient data about the drilling method at present, data from the Soft Coring Association were analyzed (**Fig. 3**)[3].

Table 2: Changes and history of standards for roads and bridges

Year	Establishment and background of standards	Disaster/incident	
1950 - 1969	◆ 1952: Article 42, paragraph 2, "Road Law" stipulates that "the technical standards and other requirements relating to the maintenance or repair of roads shall be stipulated by government ordinance" ◆ 1962:"Road Technical Standards Maintenance and Repair Edition", supplemental "Guidelines on Maintenance and Repair under Direct Control", and "Road Maintenance and Repair Guidelines" were notified in place of the government ordinance which has not yet been enacted. ◆ 1966: "Road Maintenance and Repair Guidelines" was published by Japan Road Association as a uniform technical guidebook for maintenance and repair.	◆1967: The Silver Bridge (suspension bridge) in the United States fell down	Lacking in recognition of the need for maintenance
1970 - 1999	◆ 1970: The Road Structure Ordinance (government ordinance) was established to provide "Technical Standards for Road Structures" stipulated in Article 30 of the Road Law. No maintenance-related government ordinance has been established yet, however. ◆ 1978: "Revised Road Maintenance and Repair Guidelines" was published in response to the enactment of the road structure ordinance. ◆ 1988: For maintenance of bridges, "Bridge Inspection (Draft)" was published by the Public Works Research Institute. It provides inspection points and the method of determining severity of damage for the first time.	◆ 1984: The concrete crisis became a social problem ◆ 1995: The Great Hanshin and Awaji Earthquake	⇓
2000 -	◆ 2003: Ministry of Land, Infrastructure, Transport and Tourism "Proposal by review committee on how road structures should be managed/replaced in the future" (chaired by Mr. Okamura). Seven proposals were made including the introduction of asset management and human resources development. ◆ 2004: Notification by the Head of the Disaster Prevention Department, Ministry of Land, Infrastructure, Transport and Tourism, Development of "**Periodic Bridge Inspection Guidelines (Draft).**" Inspection frequency, inspection scheme, assessment of damage severity, need for repair, etc., were indicated. ◆ 2004: Notification by the Head of the Disaster Prevention Department, Ministry of Land, Infrastructure, Transport and Tourism, Development of "**Bridge Maintenance System and Guidelines on Preparation of Bridge Management Record (Draft)**." Uniform management of inspections and records relating to bridges. ◆ 2008: The Ministry of Land, Infrastructure, Transport and Tourism "Proposal for Preventive Maintenance of Roads"(chaired by Mr. Tazaki) was issued. Five measures were proposed for **minimization of LCC and service life extension of structures**, as well as ensuring safety and peace of mind of citizens and reliability of networks by early detection and early response.	◆ 2004: Niigata Chuetsu Earthquake ◆ 2006: Collapse of de la Concorde Overpass (concrete slab bridge) in Montreal, Canada ◆ Corrosive destruction of diagonal bracing was detected in an inspection of the Kisogawa Ohashi Bridge (truss bridge) and the Honjo Ohashi Bridge (truss bridge) ◆ 2007: A truss bridge fell down in Minnesota with 50 vehicles ◆ 2011: East Japan Great Earthquake	Recognition of age of stock

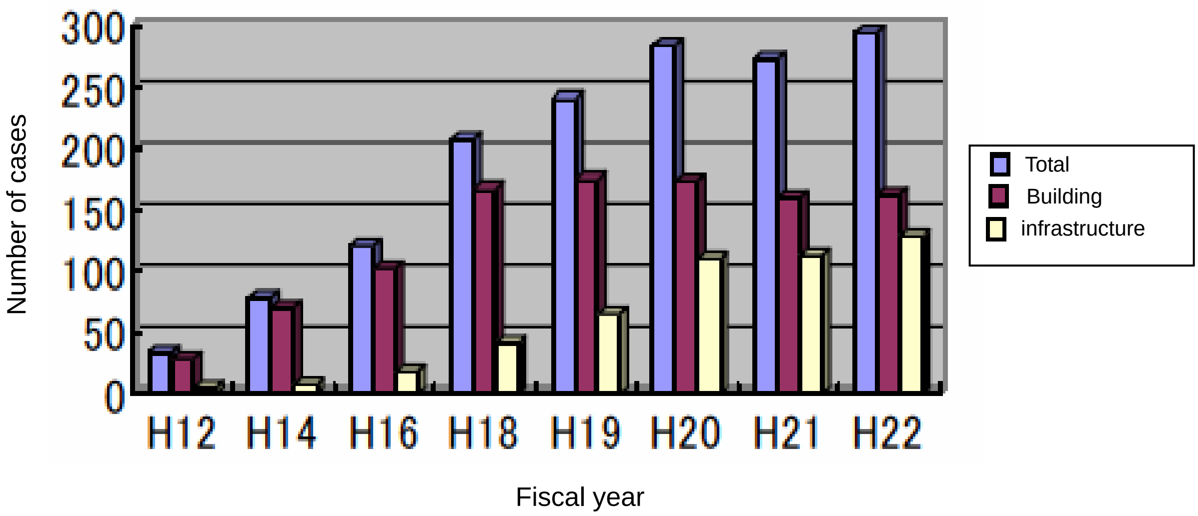

Fig. 3: Number of application cases of small size coring[3)]

As shown in the figure, the number of semi-destructive tests (small size coring) is still quite small although it has been increasing year by year.

As preventive maintenance is a measure to be taken if reinforcing bars rust during the latent stage or if splitting cracks occur inside the concrete due to corrosion of reinforcing bars in the developmental stage, the structures do not seem to be damaged from outside. Since preventive maintenance is implemented in such a condition, discovery of damage is often delayed so it may be subject to the criticism that it is a wasteful project.

Under such circumstances, the use of semi-destructive testing techniques such as small size coring and drilled powder may enable preventive maintenance to be performed at a proper time.

3. Activities related to the present condition and future prospects of concrete structure health diagnosis technology (WG2)

3.1 Actual application of health diagnosis technology

(1) Analysis of Certified Concrete Diagnosis Survey Report A (2009)

With the objective of grasping the present status of how semi-/non-destructive testing methods are applied to actual structural diagnosis, an analysis of FY 2009 Certified Concrete Diagnosis Survey Report A was conducted. In this activity, all reports of Survey Report A except for reports on participation in symposia, etc. were statistically analyzed with respect to what test methods were used and what was assessed in the diagnosis. Details of the selected test methods, assessment subjects, and counting rules can be found in related reports of this committee.

The FY 2009 Certified Concrete Diagnosis Survey Report A contains 735 reports in total, of which 619 reports discuss the diagnosis of structures and the remaining 116 reports discuss participation in symposia, etc. Thus, 619 reports were analyzed.

Fig. 4 shows the number of reports on the diagnosis of structures by category of surveyed structures. In the construction/civil engineering category, civil engineering structures accounted for 75% or more. The reports on survey of road structures are the largest in number, and account for 45% of all reports (280 reports), followed by reports on buildings, railroad structures and river structures.

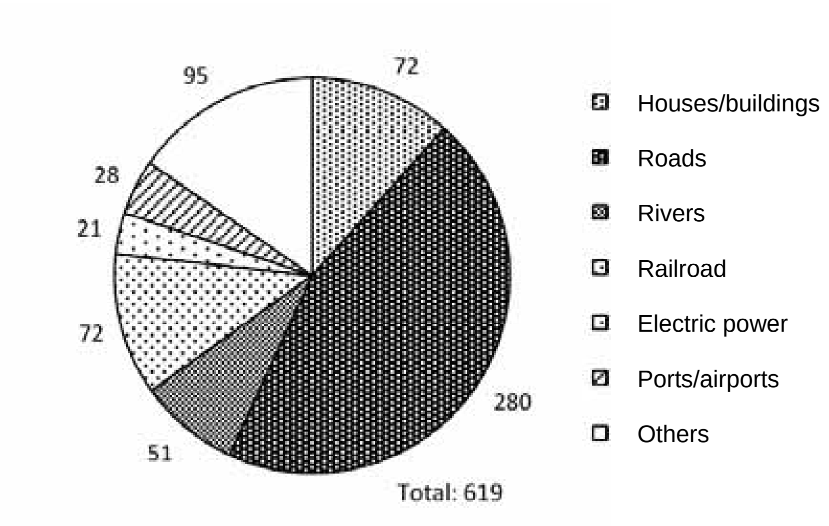

Fig. 4: Ratio of investigated structures in FY 2009 Certified Concrete Diagnosis Survey Report A

(2) Statistics by test items

Table 3 and **Fig. 5** show the statistics of test methods used to diagnose concrete structures and subjects of assessment. The results revealed the following:

(a) In general, cracks, neutralization depth, estimation of physical properties/strength, and reinforcing bar corrosion are mostly assessed.

(b) While conventional methods (destructive testing and visual observation) are used frequently, semi-/non-destructive testing methods are also used for some test items.

(c) Semi-/non-destructive testing methods are used for internal defects/spalling, estimation of physical properties/strength, reinforcing bar position/covering depth, neutralization depth test, and salt content test in many reports.

Table 3: Rank in number of reported cases of test item

Rank	All	Number of cases	Semi-/non-destructive testing	Number of cases
1	Cracks	413	Internal defect/exfoliation	125
2	Neutralization depth	230	Estimation of physical properties/strength	79
3	Estimation of physical properties/strength	218	Reinforcing bar position/covering depth	54
4	Reinforcing bar corrosion	188	Neutralization depth test	51
5	Internal defect/exfoliation	132	Salt content test	35
6	Reinforcing bar position/covering depth	115	Cracks	28
7	Salt content test	114	Reinforcing bar corrosion	14
8	ASR diagnosis	107	Structural component thickness	4
9	Diagnosis of freezing damage	41	Diagnosis of freezing damage	
10	Diagnosis of chemical deterioration	15	Grout repletion	3

While conventional methods (destructive testing and visual observation) are mostly used in general, semi-/non-destructive testing methods are used for some items. **Table 3** shows that general test items do not correspond to the items for semi-/non-destructive testing. In other words, it may be said that the application of semi-/non-destructive testing has not been used as much as expected to assess items highly needed in the general diagnosis of concrete structures (**Fig. 5**).

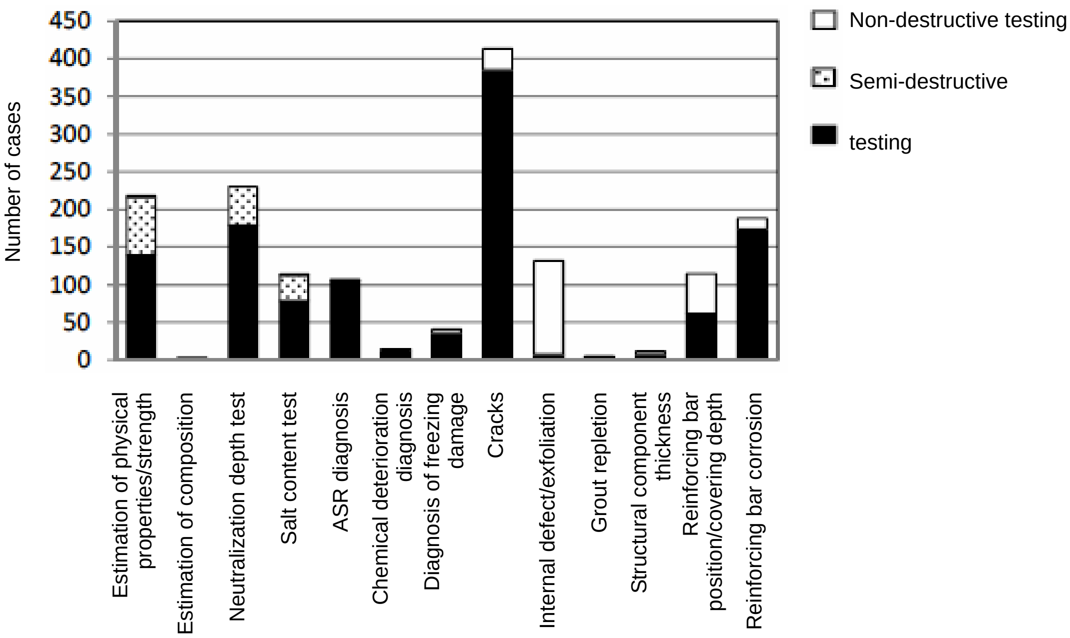

Fig. 5: Statistics by assessment subjects

(3) Analytical results of the questionnaire survey on JCI website

This section discusses the analytical results of the questionnaire survey on “The application of semi-destructive testing/non-destructive testing for concrete,” which was published on the JCI website during the period from November to December 2011.

See related reports of this committee for details of the survey results.

The analytical results showed that the number of respondents who have used semi-destructive testing such as small size coring and drilled powder in the setting of health diagnosis of structures accounted for as high as about 70% of all respondents. The analytical results also showed that non-destructive testing has been used by a higher percentage of respondents than semi-destructive testing, accounting for approximately 90% of all respondents.

As for reasons why semi-/non-destructive testing were used, the description in the specification, etc., and specific instructions from the owner/administrator both account for more than ten percent. This indicates that the dissemination of semi-/non-destructive testing method to structure administrators is still far from sufficient.

More than a half of the current survey respondents answered that they were satisfied (either much satisfied or slightly satisfied) with the result of semi-/non-destructive testing. We can understand that semi-/non-destructive testing technologies were accepted and used with a certain extent of appreciation in structural diagnosis in general despite several remaining issues. Efforts should be made in the future to enhance the satisfaction of users by further promoting research and development of such technologies.

A majority of respondents, who answered that they were satisfied with the results of semi-/non-destructive testing, stated that the reason is that they can obtain quantitative (objective) information or that they can obtain information that cannot be obtained from visual inspection or other conventional methods. The number of respondents, however, who evaluated semi-/non-destructive testing as extra informative in the setting of maintenance diagnosis was far from large, and further research and development may be required from the above perspectives.

On the other hand, the reason for dissatisfaction with the results of semi-/non-destructive testing was that “the expected information or accuracy could not be obtained.” While such a case may have been caused by insufficient implementation of measurement (due to such factors as the lack of skill of the test engineer), it may include misunderstanding resulting from excessive expectation or insufficient understanding of semi-/non-destructive testing technologies.

Lastly, some noteworthy views are introduced below from free opinions offered by the respondents.

[Activities]

(a) Previous knowledge about accuracy and actual cases (including failures) should be disclosed.

(b) The usability of various devices and methods developed so far cannot be assessed without referring to papers, technical reports, etc. Many claimed that specific items could be measured but their reliability or traceability is actually not sufficient. Corresponding improvement is required.

(c) It is often the case that conditionally impossible requirements are forced and incapability is recognized as a shortage of skill since service conditions, etc., of the test equipment are not grasped due to lack of knowledge and experience in investigation/test methods on the owner side. In addition, it is often the case that vendors provide their services without understanding the accuracy, conditions, etc., of the test/investigation method.

(d) Not only text-based tutorials but also movie-based tutorials are needed for explanation of the various test methods. In the case of the drilling method, for example, one may grasp the appropriate drilling speed, filter paper rotation speed, and so on just by watching a movie.

[Standards, etc.]

(a) Because concrete structures are uneven in quality, setting of the test position is important. The standards on the setting of the test position need to be improved.

(b) Because non-destructive testing alone cannot measure all defects, information about the applicability of other methods is required.

(c) There are cases where the owner does not accept the results due to vague evaluation criteria, etc. Improvement is required as regards this aspect.

[Technological innovation]

(a) A technology may be required that enables everyone to validate accuracy with minimum complicated functions.

(b) Devices, which always feedback some results even if the required measurement conditions are not met, may lead to false diagnosis by displaying a meaningless figure. A measurement device displaying an error accurately should be used.

(c) Test machine units are too expensive. Is it not possible for an academic society, etc., to develop a device that enables proper monitoring at a reasonable cost? In addition, research and development should not focus on concrete only. As structures are closely related to the ground and water, development activities should be performed jointly with relevant fields.

As mentioned above, all views are implicative and are very significant for the future research and development of semi-/non-destructive testing technologies, the development of associated mechanisms, etc. We hope that those views will be taken into consideration in future actions.

3.2 Future prospects of health diagnosis technology

(1) Usability of semi-destructive testing in health diagnosis

In order to clarify the significance of semi-destructive testing, destructive, semi-destructive and non-destructive testing are compared in **Table 4**. Significant differences among the three include the demerits of destructive testing as shown in a to f of **Table 4**, viz., damage to the structure, the inability to perform a repeat test at the same position, and the laboriousness of tests. It has, however, such merits as shown in g to j of **Table 4**, which are partly the consequence of a profusion of previous results during the development of the methods. On the other hand, while non-destructive testing has merits that it does not damage structures unlike destructive testing and that there are fewer restrictions on test positions thus enabling a repeat test at the same position; it has the demerit that few test methods have been established. Semi-destructive testing, on the other hand, is considered to be positioned between destructive testing and non-destructive testing, but it can be also regarded as non-destructive testing in the broad sense, with the merit similar to non-destructive testing such as fewer restrictions on application area due to less extent of damage. Semi-destructive testing, however, also has constraints such as being incapable of repeating a test at the same position as it damages structures. As described later, semi-destructive testing is expected to be applied to the same test items as destructive testing, and to assume the role of substitute for destructive testing in the future.

For the above findings, the details will be clarified by discussing each test item as described below. Comparison results for infiltration of deterioration factors (neutralization depth, chloride ion content), concrete strength, and reinforcing bar position/covering depth, which are important test items for examination/inspection, are shown in the three lower lines of **Table 4**. In order to inspect the infiltration of deterioration factors, destructive or semi-destructive testing will inevitably be conducted since there are no applicable non-destructive test methods at present. The table shows the three testing methods that exist for the test item of strength. As for reinforcing bar position/covering depth, non-destructive testing will inevitably be conducted because destructive/semi-destructive testing is almost inapplicable for the measurement of a large plane area.

Table 4: Comparison of destructive/semi-destructive/non-destructive testing (difference by concept/test method)

Code	Item	Destructive testing	Semi-destructive testing	Non-destructive testing
a	Damage to structure	×	△	○
b	Applicable location (highly-dense arrangement of bar, etc.)	×	○	○
c	Repeated measurement at the same position (measurement of secular change)	×	×	○
d	Cost efficiency per measurement point	×	△	○
e	Grasping of condition of entire structure	×	△	○
f	Convenience of test	×	△	○
g	Future prediction	○	△	×
h	Variance in measurement	○	△	×
i	Effect of proficiency	○	△	△
j	Establishment of test method (standard)	○	△	△
k	Grasping of infiltration of deterioration factors	○	○	×
l	Strength	○	○	△
m	Reinforcing bar position/covering depth	×	×	○

○ Excellent △ Issue remains × Too many issues

(2) Expansion of semi-destructive test applications (use of concrete analysis technique)

Chemical analysis is useful if signs of chemical reaction are observed in concrete such as discolored or weakened concrete surface, cracks with seepage of white matter, and pop-out generated on the concrete surface, or if the chemical composition of concrete or the composition ratio of raw materials need to be studied in detail for such purposes as analyzing the neutralization depth or chloride content in concrete, or analyzing rough mixing conditions used for the placement of concrete. In the chemical analysis of concrete, test results obtained by analyzing a core with a diameter three to four times larger than the largest dimension of coarse aggregate (with a core of 100 mm diameter as standard) are relatively highly reliable, and are preferred in standard tests, etc., because the component ratio of aggregate and cement is similar to the actual concrete.

On the other hand, is a sample collected by a semi-destructive testing method such as small size coring or drilled powder unsuitable for analysis? No, it is not. Because the sample size required for the actual test is approximately several grams in most cases, the quantity of sample collected by a semi-destructive testing method is sufficient for the test. In addition, it is advantageous compared with standard coring as regards many aspects such as labor effectiveness and lower cost in core sampling. It is moreover advantageous in that it can obtain sufficient information from test results obtained with a small sample size depending on the purpose of diagnosis. In recent years, a method to obtain favorable test results from a small sample size has been proposed along with the progress in analytical techniques and research.

Table 5 summarizes the diverse methods to analyze chloride content by dividing the analytical methods into destructive testing, semi-destructive testing, and non-destructive testing.

While the use of a concrete core with a standard size of approximately 100 mm diameter and 200 mm length may be predominant in testing chloride content, it has been become more diversified in recent years with a small size coring and non-destructive testing methods. Each technique has both merit and demerit, and it is apparent that the use of the standard core is not always the best option. It may be desirable to select a method in accordance with the purpose.

Table 5: Merits and demerits of test methods for chloride content

Type		Test method	Merit/demerit
Destructive	Concrete coring	JIS A 1154 (test method for chloride ion contained in hardened concrete) (2003-) JCI-SC-4 (analytical method for salt content of hardened concrete)(1987-) JCI-SC-5 (simple analytical method for salt content of hardened concrete)(1987-) JSCE-G-573 (Measurement Procedure (Draft) for analysis of total chloride ion contained in actual concrete structure)	[Merits] ・Test standard available ・Infiltration status can be grasped ・Can be used in combination with compression, neutralization (JIS method) [Demerits] ・Careful planning of sampling point is required ・Repair is needed after sampling ・Test results not immediately available at site ・Requires much cost and time
Semi-destructive	Small size coring/drilled powder	JIS A 1154 (drilled powder), JCI-SC-5, portable fluorescent X-ray analysis	[Merits] ・Entails very little damage to structure and is easily repairable. Many samples can be obtained in a short period of time ・Enables sampling even at a place where standard core cannot be sampled ・Test results immediately available at site for some methods. [Demerits] ・Subject to the influence of weather during sampling ・Drilled powder method tends to yield overestimated test value ・Portable fluorescent X-ray analysis has a low precision for low concentration
Non-destructive		Portable fluorescent X-ray analysis	[Merits] ・Measurable at site with no repair required ・Enables extensive measurement in a short period of time ・Enables measurement of aging deterioration in the same position [Demerits] ・No standards available ・Limited measurement location (limited to surfaces if fluorescent X-rays are used) ・Infiltration status inside the structure cannot be grasped ・Has a low precision for low concentration

3.3 Summary of WG2 activities

As discussed in the former section (**3.1 Actual application of health diagnosis technology**), while survey results showed that semi-/non-destructive testing receives much attention with a relatively high percentage of respondents (semi-destructive testing: approximately 70%, non-destructive testing: approximately 90%) having experience of using some semi-/non-destructive testing methods for health diagnosis as far as the questionnaire survey conducted on the JCI website is concerned, the results of the detailed analysis of the Certified Concrete Diagnosis Survey Report showed an aspect where it is not always used effectively enough.

A summary of requirements which seem necessary for semi-/non-destructive testing to play its role more effectively in health diagnosis, and future prospects, are discussed below.

Specifically, comparative results were summarized as to the roles, merits, demerits, etc., of destructive testing, semi-destructive testing, and non-destructive testing in the assessment of neutralization depth, chloride ion content, strength, reinforcing bar condition, and covering depth in a manner of responding to the question, "from what perspectives can semi-/non-destructive testing become an effective tool in health diagnosis?" The results revealed that the semi-destructive testing method is quite applicable as a substitute for conventional destructive testing methods, and is expected to be applied to health diagnosis in the future, so there is a high probability that it will impart its merits, including its applicability to grasping the entire structural condition with fewer restrictions applicable locations because it causes less damage to structures.

In addition, although it is not discussed here due to limitation of space, information that is useful to consider what is lacking and what action should be taken in the future by comprehensively summarizing the actual situation of standards from the perspective that it is indispensable to develop standards and criteria for respective techniques to further improve recognition of semi-/non-destructive testing is also provided.

Subsequently, we also discussed the method of using small size coring and drilled powder for the analysis of chloride content in concrete, diagnosis of alkali-silica reactions, etc., as a specific measure to expand application of semi-destructive testing, from the perspective of how it can be useful, and whether or not some merit can be expected, in the light of the latest findings.

The roles of semi-/non-destructive testing in health diagnosis will become more and more important with better understanding and recognition of the impact of the uncertainty of semi-/non-destructive testing for the reliability of the measurement.

4. Activities of WG to identify the present situation, and issues regarding repairs/strengthening of concrete structures (WG3)

4.1 General trends observed in collected cases

This WG investigated cases of repair/strengthening in ports and harbors, electric power plant, railroads, road structures, etc., from the literature, etc., and identified maintenance issues for the purpose of establishing a health diagnosis method for concrete structures based on semi-/non-destructive testing. Specifically, this WG conducted an analysis focusing on issues regarding health assessment and prediction of deterioration, the basis for determination of repair/strengthening, the stage of deterioration where repair/strengthening was implemented, the actual application of semi-/non-destructive testing, and so on. On the other hand, detailed investigation and health diagnosis were implemented in the building constructions at a less significant stage in the progress of deterioration than in civil engineering structures, and preventive maintenance measures were taken based on the above results with the aim of maintaining and improving the asset value of buildings. Accordingly, the WG also intensively investigated the actual applications of semi-/non-destructive testing in the construction field. This section, however, discusses the analytical results of repair/strengthening cases in the civil engineering field. The cases were collected from articles on recent cases of repair/strengthening of concrete structures mostly found in technical journals. In particular, cases of repair/strengthening of civil engineering structures were selected in which preventive maintenance efforts seem to be delayed, with a relatively low level of semi-/non-destructive testing application.

As the cases were mostly collected from those in technical journals, they represent relatively large-scale repair/strengthening or specific construction methods or materials. Accordingly, it should be noted that these cases do not always show the general trends of repair/strengthening in Japan.

Fig. 6 shows the number of years elapsed from the start of service to repair/strengthening with regard to the collected cases. Although the database includes cases of re-deterioration after previous repair, the figure shows only elapsed years before the repair/strengthening cases cited in the database was conducted.

As shown in the figure, 30 to 35 years from the start of service accounted for the largest percentage in the database, followed by more than 35 years. Cases with the above years combined, viz., 30 years or more, represented approximately 40% of the all cases.

Fig. 7 shows the degree of deterioration at the time of repair/strengthening. The degree of deterioration was determined in conformity with the concrete standard specifications [maintenance edition] established in 2007 by the Japan Society of Civil Engineers. According to this, approximately 60% of the repair/strengthening in all cases were implemented during the acceleration stage.

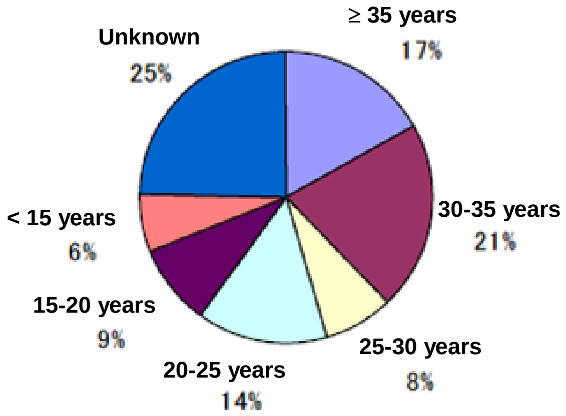

Fig. 6: No. of years that elapsed before repair/strengthening

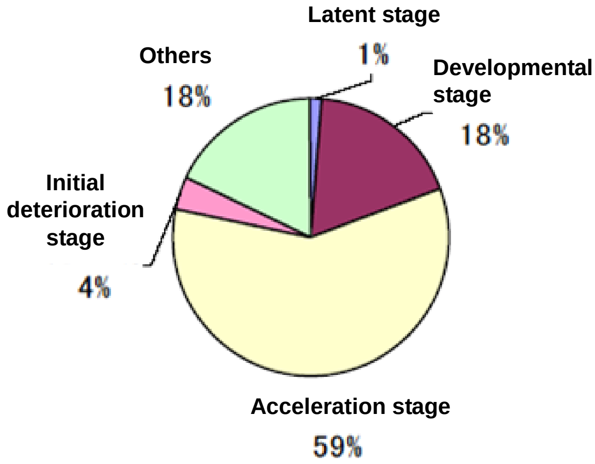

Fig. 7: Degree of deterioration

4.2 Detailed analysis of repair/strengthening cases

Efforts were made to highlight effectiveness and issues of health diagnosis by identifying and analyzing in details the cases in which the life cycle cost (LCC) might have been reduced if semi-/non-destructive testing had been used, and those in which re-deterioration might have been prevented if semi-/non-destructive testing had been used, It should be noted, however, that the case studies here in which semi-/non-destructive testing could have been used are so-called fictional case studies in that they are not intended to assess the appropriateness or validity of the investigation/diagnosis or repair/strengthening actually implemented in the various cases, but only to validate the effectiveness of semi-/non-destructive testing.

Six cases were used for detailed analysis as shown in **Table 6**.

Table 6: List of cases for detailed analysis

	Name of literature
Detailed analysis case 1	Investigation of Viaduct Damaged by Salt, and Study of Repair Method
Detailed analysis case 2	Preventive Measures against Reinforcing Bar Corrosion near the lower surface of RC Viaduct Floor Slab
Detailed analysis case 3	Survey of Concrete Bridge Located Along the Shore of the Japan Sea in Aomori Prefecture Significantly Deteriorated due to Salt Pollution
Detailed analysis case 4	RC Floor Slab Renewal Work at Okubi River Bridge on Okinawa Expressway (Part 1)
Detailed analysis case 5	Coating Method for PC Simple T Girder Bridge Deteriorated due to Salt Pollution - Daikeiji River Bridge on Hokuriku Expressway
Detailed analysis case 6	Optimization of Repair Time and Repair Method for Civil Engineering Facilities Based on Quantitative Assessment of Deterioration Risk

An example of the test cases is shown below.

[Detailed analysis case]: Survey of a concrete bridge located along the shore of Japan Sea in Aomori Prefecture significantly deteriorated due to salt pollution[4)]

(a) Overview

This bridge is an 11.1 m wide, 33 m long post-tensioned T girder bridge put into service in 1976. In an inspection performed in 2003, serious damage to the lower flange of the external beam on the mountain side, partial spalling of concrete cover, and corrosive destruction of the internal sheath and steel parts were found. The cause of damage was attributed to salt pollution due to airborne salt particles wafting inland from the Japan Sea.

Given that it was a prestressed concrete (PC) bridge with corrosion found in the embedded steel, it had been decided to demolish and replace it due to apparent safety issues.

(b) Repair history

Table 7 shows the previous repair history of the structure.

Table 7: Repair history of the structure

Year	Observed damage	Repair/strengthening construction method
1976	Start of service	
1992	Cracks emerged, concrete cover expanded and partially spalled (estimated)	Surface coating and partial surface repair
2003	Damage observed on the lower flange of the beam on the mountain side, concrete cover partially spalled, internal sheath and steel damaged due to corrosion	Dismantling, removal, replacement

(c) Deterioration status in 1992

The first repair was made 16 years after the start of service for the damage due to airborne salt particles wafting inland from the Japan Sea as well as use of antifreeze agents. Despite the lack of descriptions, it is inferred that part of the concrete cover had been spalled from the fact that the bridge was provided in the repair with a surface coating to prevent infiltration of corrosive substances, and that some trace of repair for part of the cross section was observed.

Given that it is a PC structure, it might have been diagnosed as being in the latent stage to developmental stage because it seemed to have less cracks and less apparent damage. Therefore, application of a surface coating and repair coating for the partially damaged area might have been selected to prevent infiltration of further deterioration factors.

Given the partial spalling and the later accelerated deterioration, part of the bridge was already somewhere between the early phase to the late phase of the acceleration stage.

(d) Application of semi-destructive testing

Fig. 6 shows that repair/strengthening cases increased after the elapse of about 10 years. Accordingly, it may be effective to perform inspection within five years after the start of service. However, because apparent damage can hardly be observed during the latent or the development stage, damage inside the concrete is always overlooked. In the current case, if semi-destructive testing had been applied by drilled powder or small size coring, demolishment of the bridge after 27 years of service might have been prevented.

(e) LCC

In reality, the deteriorated bridge was demolished and replaced with a new bridge after 27 years of service. To compare LCCs, a LCC was calculated on the assumption that an organic surface coating was provided every 10 years so that the chloride ion concentration surrounding the PC strand did not exceed 1.2 kg/m^3, and that, if the chloride ion concentration increased in excess of 1.2 kg/m^3, the chloride ion concentration would have been lowered by electrochemical desalination. The assumptions adopted in calculating the LCC are shown in **Table 8**.

Fig. 8 shows the comparison of LCCs. While actual measures will be taken for 90 years from the start of service at a cost of approximately 190 million yen including maintenance cost, the maintenance model used for comparison will cost approximately 140 million yen for the same period including electrochemical repair. The LCC in the maintenance model is lower than that in actual maintenance by approximately 25%. If the cost of demolishment, traffic control and other potential cost due to factors such as traffic congestion in the reality is further considered, the LCC difference will become much greater.

(f) Summary of case study

The study result for the case of the bridge that was demolished and replaced due to deterioration caused by salt pollution 27 years after construction indicates that the LCC could have been significantly reduced and the reconstruction of the bridge could have been avoided if preventive measure had been taken when signs of degradation appeared, which can be detected in-depth survey using semi-/non-destructive testing, etc.

Table 8: Assumptions used in LCC calculation

[Actual measures]
- ◆ Initial construction cost: Given that PC superstructure work costs 2.5 million yen/m, 2.5 million yen/m×33m= 82.5 million yen
- ◆ Reconstruction cost: Given that PC superstructure work costs 3 million yen/m (countermeasure against salt pollution), 3 million yen/m×33m= 99 million yen
- ◆ Maintenance cost: 5% of construction cost. No repair cost included.

[Maintenance model used for comparison]
- ◆ Surface coating cost: Given that surface coating costs 8,000 yen/m^2, 8,000 yen/m^2 × 3m × 33m × 6 units= 5 million yen, 82.5 million yen+ 5 million yen/time×8 units= 122.5 million yen
- ◆ Electrochemical corrosion prevention cost: Given the limited area for application, the cost is assumed to be approximately 20 million yen including the maintenance cost for corrosion prevention.

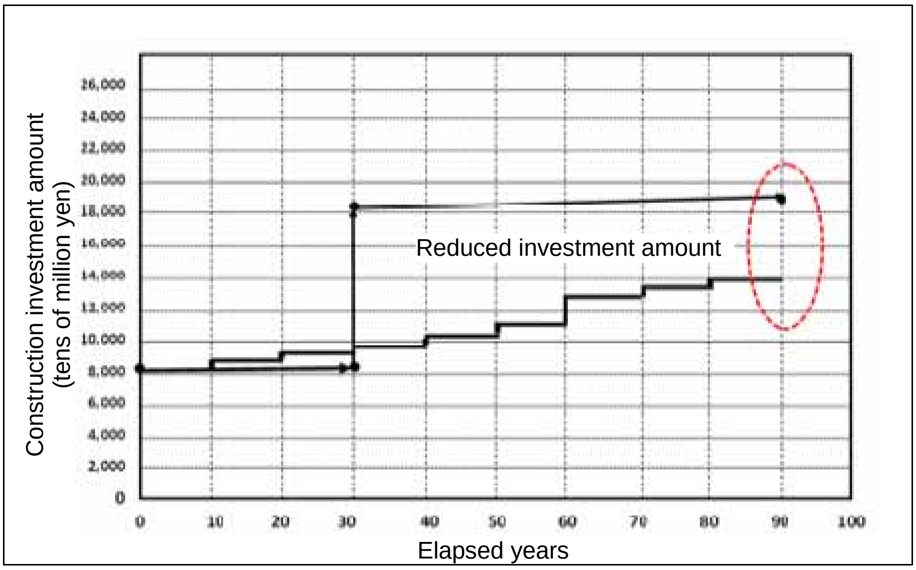

Fig. 8: LCC comparison

4.3 Summary of WG3 activities

The database of repair/strengthening of concrete structures mostly in the civil engineering field reported in articles in recent technical journals revealed the following:

(a) Repair/strengthening was performed mostly in the acceleration or later stages of the deterioration process of concrete structures, indicating that repair/strengthening is not performed before deterioration reaches a considerably serious level in most cases.

(b) The number of semi-/non-destructive test cases is smaller than that of visual inspection or core sampling. As a result, the soundness of the entire structure is mostly estimated based on local data obtained from core sampling and visual inspection.

(c) Repair/strengthening methods are mostly determined without grasping the deterioration status of the entire concrete structure in detail.

On the other hand, it was highlighted that semi-/non-destructive testing has already been used effectively with preventive maintenance for building structures because of aesthetic concerns. In some aspects, the implementation of a detailed inspection including semi-/non-destructive testing is motivated by the provision of a mandatory periodical building inspection under such laws as Building Standard Law, Housing Quality Assurance Act, and Law for Execution of Warranty against Housing Defects. In addition, the UR (Urban Renaissance Agency) aims to implement repair/strengthening and to efficiently allocate repair costs based on preventive maintenance by providing a building diagnosis service on the occasion of seismic capacity evaluation, reconstruction of vacant buildings, and so on, and assessing the need for framework renovation with a building record, in addition to the routine inspection work as a regular maintenance service.

5. Activities of the WG for application methods of semi-/non-destructive testing (WG4)

WGs 1 to 3 revealed the trends in service life extension of concrete structures, the movement toward preventive maintenance, the actual state of maintenance, the actual application status of semi-/non-destructive testing methods in health diagnosis, etc. The result shows that while semi-/non-destructive testing offers great expectations, it is far from being sufficiently used yet.

Use of semi-destructive testing, however, to periodically measure the chloride ion concentration in concrete, for example, will permit an understanding of the conditions in which chloride ion penetrates, and thus enable the prediction of infiltration and an estimate of the time when measures need to be taken. Grasping a sign of chloride ion penetration before the deterioration of the structure enters the development stage will enable appropriate measures to be taken based on preventive maintenance. In this case, repair methods of relatively low cost such as surface coating can be used, and that will help to reduce the LCC and prevent the deterioration of structures. Thus, structures can be expected to be used in a healthy state for a long period of time.

In the implementation stage of preventive maintenance, it will become more and more important in the future to grasp the degree and progress of deterioration in structures in more detail so as to take appropriate measures with less waste. In the future, it will be necessary to grasp the spatial distribution in a structure such as chloride ion concentration instead of collecting information about limited points for core sampling. In order to make this possible, it is necessary to investigate the structure without damaging it or with minimum damage to it, and therefore further application of semi-/non-destructive testing is desired.

Prediction of deterioration with higher accuracy and selection of a more reasonable repair time/method will be enabled by grasping the spatial distribution of deterioration factors through investigation of the entire structure by making the most of the convenience of semi-/non-destructive testing, and by periodically conducting tests to grasp infiltration of deterioration factors including chloride ion with time.

In the civil engineering field, in particular, the severity of deterioration has been assessed only by investigating the most deteriorated region. Semi-destructive testing is useful for prediction of deterioration by considering the spatial distribution of damage in a partially deteriorated structure or for assessment of structures with latent deterioration. In the meantime, repair/strengthening itself may not be welcomed at a stage with no apparent damage such as the latent stage or the developmental stage, because it entails damage to an apparently healthy structure. In such a case too, semi-/non-destructive testing may be useful.

For building structures, while there are many cases where semi-destructive testing was effectively used, there are some other cases where semi-destructive testing was not permitted as a substitute for coring. Efforts should be promoted from now on to increase the application of semi-destructive testing more than ever within the framework of deterioration diagnosis and earthquake resistance diagnosis.

The way in which semi-/non-destructive testing is used is important for accurate health diagnosis of concrete structures, and its success holds the key to preventive maintenance and reduction of the life cycle cost of concrete structures.

Through the above discussions, WG4 considered specific application methods to utilize the merits of semi-/non-destructive testing. As a result, the following methods were proposed. The important point of application is to utilize the convenience of semi-/non-destructive testing to:

- Grasp the spatial distribution of deterioration factors by investigating the entire structure;
- Grasp the progress of infiltration of deterioration factors by periodic tests; and
- Make future predictions using the obtained data.

The above methods will permit highly accurate prediction of deterioration and selection of a reasonable time and methods for repair, and may be effective in grasping the effectiveness of repair on structural life extension.

More specifically,

(a) For a new structure, non-destructive testing can be performed to make sure that structural properties (concrete strength, reinforcement, concrete covering, etc.) comply with those specified in the design.

(b) For an existing structure, infiltration of deterioration factors (chloride ion and neutralization depth), deterioration depth in concrete, etc., can be measured by semi-destructive testing such as drilling method, small size coring, etc, and the measured values can be set as initial values for future maintenance. In addition, the measured values can be compared with the deterioration levels predicted in the design stage. If prediction of deterioration has not been made at the designing stage, deterioration prediction can be made based on the measure values obtained in such survey. An important point in this procedure to include the entire structure in the investigation.

(c) If the prediction differs from the actual measured value, deterioration can be re-predicted by correcting the parameters used for the previous prediction.

(d) Procedures (a) to (c) should be periodically repeated.

(e) As a result of procedure (d), if the chloride ion concentration has reached the threshold of rusting reinforcing bars, or if neutralization depth or deterioration depth on the concrete surface is considered to have reached the reinforcing bar position, the corrosion status will be grasped by performing a partial chipping test on the concrete surface, and the spread and progress of corrosion will be evaluated using the natural current method or polarization resistance method.

(f) If the test result reveals that repair is required, repair will be performed.

(g) The post-repair infiltration depth of deterioration factors and deterioration depth on the concrete surface will be continuously investigated by semi-destructive testing.

Preventive maintenance can be implemented by taking appropriate measures and grasping the signs of deterioration before it enters the developmental stage by exploiting semi-/non-destructive testing in procedures (a) to (g) as shown above. Such efforts will result in the service life extension of structures, and consequently contribute to LCC optimization.

6. Conclusion

This report summarized the results of two years work of the technical committee on concrete structure health diagnosis based on semi-destructive testing. It is important to take measures before deterioration comes to the surface for the future maintenance of concrete structures in the age of sustainable built environment. Grasping the signs of deterioration before it enters the developmental stage will permit appropriate measures based on preventive maintenance, and may lead to LCC reduction and use of structures in a sound condition for a longer period. To this end, it is necessary to take repair/strengthening measures with less waste by accurately evaluating the distribution of deterioration and its variance along with time within the structure, and identifying appropriate time and locations, through active use of semi-/non-destructive testing that allows more data to be collected with relatively low cost.

We expect that further exploitation of various semi-/non-destructive testing methods, which are commercially available or have currently been proposed, will enable the ideal use of concrete structures and further recognition of the usefulness of these methods, thereby resulting in further improvement of semi-/non-destructive testing.

References

1) Ministry of Land, Infrastructure, Transport and Tourism : Ministry of Land, Infrastructure and Transport White Paper, 2006.part 2

2) Ministry of Land, Infrastructure, Transport and Tourism : Ministry of Land, Infrastructure and Transport White Paper, 2005.part 1

3) Softcoring Association : Company data

4) Ichiro IWAKI, Hiroaki TSURUTA, Akihisa UEHARAKO, Akitosi ARAKI, Motoki, AIHARA, and Motoyuki SUZUKI : A Research of Deterioration of Concrete Bridge due to Chloride Induced Seviere Damage in The Japan Sea Coast of Aomori Prefecture, Bridge and Foundation Engineering, 2007,Vol.41