Repair and Rehabilitation of Concrete Structures

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Abstract: Repair of concrete structures has been a focus of attention in recent years not only in Japan but also worldwide. Concrete structures have fallen short of expectations at the time of construction—they should have been perpetual and maintenance-free. However, investigation into their premature deterioration reveals the primary causes: Concrete was made using inadequate materials and/or inadequate mixture proportions due to insufficient consideration and was placed inadequately under insufficient execution control. The secondary causes include insufficient consideration at the time of construction for the environmental conditions to which the structures were to be exposed. In any event, in the current economic climate, structures cannot be demolished and rebuilt as soon as they are damaged, but instead are expected to continue to be in service as long as possible with appropriate repair or retrofitting. This paper analyzes the causes of deterioration requiring repair and introduces relevant repair techniques. At the end, the repair project of the Sanyo Shinkansen Line in which the author was involved through committee activities is reported.

1. Introduction

Many years have passed since the durability issue of concrete, particularly in relation to repair and retrofitting of concrete structures, emerged as a research topic and a phenomenon of actual structures. As a testament to this, the triennial international conference titled the "Durability of Building Materials and Components" organized by RILEM has already been held nine times while the fourth conference on Concrete under Severe Conditions (CONSEC) on is slated to be held in South Korea later this year. However, it can also be regarded as a relatively new topic when viewed from the history of cement concrete stretching back thousands of years, the development of modern cement over the past 180 years, reinforced concrete over the past 150 years, or the 120-year history of prestressed concrete. This is because the concept of design service life required for concrete has not been firmly established. Whereas the Pantheon of Rome, for instance, retains its majestic beauty even after 2,000 years, it is said that the designer assumed only 80 years for its service life. In fact, the public baths of Rome built in the same era with similar materials now exist only as ruins.

Also extant in present-day Rome are a number of castle walls and arch bridges as old as the Pantheon. These conflicting examples tell us that some structures outlive their design service lives, while others last only as long as intended.

Ignoring this fact, numerous concrete structures have been built under a misconception that cement concrete is immortal and maintenance-free, partly because the service lives of modern structures have not been determined by the durability of their materials and components. Instead, they have had to be terminated while being structurally intact by their functional limitations to meet increasingly demanding requirements. They have been replaced with higher buildings with more sophisticated infrastructure, wider bridges meeting increased design loads, and increased pavement thickness to withstand increased loading requirements. The service lives of structures have thus been made shorter than their termination by deterioration.

Over the last one or two decades, however, reports have circulated on premature deterioration or damage that terminates the service lives of structures, causing confusion and provoking discussion worldwide. This paper relates to this topic.

2. What is repair/retrofitting? Why is it a focus of attention?

The term "repair" is defined as follows: to restore the functions of a concrete structure to the as-constructed level when they have degraded over time ("functions" here referring to load-bearing capacity, durability and serviceability and being limited to the so-called structural functions). On the other hand, "retrofitting" is defined as the operation to raise the functions required of a structure, particularly the load-bearing capacity in this case, to a level higher than the as-constructed level. This includes an increase in the thickness of pavement slabs due to an increase in the design load requirement (in Japan, the wheel load requirement was increased from 20 t to 25 t), but is outside the scope of this paper, as most retrofitting in Japan is for earthquake resistance.

Why is retrofitting such a much-discussed subject in Japan nowadays? The following three reasons may be given:

(i)Concrete structures built during the construction rush in the late 1960s to 1970s have reached an age when their functions have degraded, requiring repair as part of maintenance. Had the robust economic growth of those days continued, these structures might have been demolished and reconstructed, but the social consciousness has changed toward longer use of such buildings.

(ii)Structures built at the same time as those above but having significantly diminished functions due to the construction work being carried out beyond the abilities of material procurement and execution, which caused inadequate quality and execution control, including an insufficient cement content, high water-cement ratio, and defective execution.

(ⅲ)Damage to structures by events unexpected at the time of construction, such as chloride attack and alkali-aggregate reaction (AAR); or damage by expected factors but at a rate higher than expected.

The Japan Concrete Institute has established a system for improving the technical level of engineers involved in the materials, production, execution, and design of concrete by carrying out qualification tests for certified concrete engineers and senior concrete engineers for a long time. The institute recently established a system of qualification for certified concrete repair diagnosticians. An unexpectedly large number of engineers applied for this qualification, forcing the organization to prepare additional examination locations. This indicates the extent to which the repair work is attracting attention in Japan.

3. Durability of concrete and reinforcement corrosion

The factors impairing the durability of concrete include the following: (1) carbonation, (2) chloride ion ingress, (3) freezing and thawing action, (4) chemical attack, (5) AAR, and (6) others. This section gives a brief explanation of these factors, though they are commonly known.

(1) Carbonation of concrete

Carbonation is a chemical reaction in which calcium hydroxide in concrete reacts with carbon dioxide in the air, generating calcium carbonate.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

Concrete is alkaline owing to the effect of $Ca(OH)_2$ present in it and neutralized when $Ca(OH)_2$ is carbonated to $CaCO_3$. The effect of this reaction is not so significant on concrete, including shrinkage, slight increases in the strength, increases in the elastic modulus, and possible slight increases in the brittleness. However, when steel reinforcement is embedded, this reaction causes corrosion of steel by neutralizing its environment, thereby shortening the service life of reinforced concrete structures.

(2) Chloride ion ingress

When concrete contains chloride ions (Cl^-), steel reinforcement in the concrete is corroded even in an alkaline environment. Though the threshold value for corrosion onset is said to be 1.2 kg/m^3 as Cl^- equivalent, the chloride ion content of ready-mixed concrete is specified to be as low as 0.3 kg/m^3 or less at the time of shipment in Japan. Nevertheless, chloride ions derived from seawater can penetrate concrete in structures built in coastal areas, causing reinforcement corrosion. The chloride ion content in such structures can reportedly amount to 6 to 8 kg/m^3 as Cl^- equivalent. Chloride ion ingress does not substantially change the physical properties of concrete as such, but causes corrosion and concomitant expansion of reinforcing steel, thereby causing cracking in concrete. Such cracking readily allows air, water, and chlorides to reach steel reinforcement, accelerating its corrosion. The Japan Society of Civil Engineers currently specifies equations for estimating the rate of chloride ion ingress and requires concrete to be proportioned so that the accumulated chloride ion content does not exceed the specified limits within the service life of the structure.

(3) Freezing and thawing action

Freezing and thawing action on concrete under harsh climatic conditions can cause scaling and/or popout on its surfaces, as well as cracking in it, significantly aggravating its deterioration. This phenomenon is referred to as freezing and thawing action, and the performance to prevent such deterioration is referred to as resistance to freezing and thawing.

Fine air bubbles entrained in concrete with a spacing factor of 250 μ or less are known to resist fairly severe freezing and thawing. In such a case, however, it is essential that the aggregate phase be robust enough to resist the action. For this reason, the resistance of concrete made using lightweight aggregate or aggregate recycled from original concrete that is not air-entrained is known to be limited even with an increased entrained air content.

(4) Chemical erosion

Being alkaline by nature, concrete is vulnerable to acidic action. Therefore, concrete should not be used for the flooring of factories involving acids. There are a number of other chemicals that cause deterioration of the concrete phase. In Japan, concrete may be placed in volcanic areas where such chemicals can gain access to concrete. In such a case, it is necessary to compensate for losses in the durability of concrete by other materials. One such example is concrete bridge piers constructed in a volcanic area in Japan's southwestern main island of Kyushu.

(5) Alkali-aggregate reaction

Aggregates, particularly those derived from igneous rock, can react with alkali supplied from cement hydrates. The product of such reaction can expand in the presence of water, causing concrete to deteriorate. This phenomenon, which is referred to as alkali-aggregate reaction (AAR), is currently attracting attention in Japan as one of the factors impairing the durability of concrete. Alkali-aggregate reaction was not considered to exist in Japan until the 1980s , when reports revealed AAR-induced deterioration of concrete structures. This can partly be attributed to the shift in the major aggregate source from river gravel to crushed stone and the high percentage of alkali components in cement during a certain period in the past. Since the subsequent proposal for measures against AAR, this topic has not been actively discussed, but there have still been reports of newly found AAR-induced concrete defects. The measures against AAR currently adopted in Japan are as follows: (1) Maintain the alkali content (R_2O equivalent) to not more than 3.0 kg per m^3 of concrete; (2) use blended cement or required amounts of ground granulated blast-furnace slag or fly ash; and (3) use innocuous aggregates. The use of innocuous aggregates used to be the first priority, while measures against AAR were required when using aggregates that were not innocuous. However, the order of description was inverted in the 2003 revision of JIS A 5308, as innocuous aggregate is basically in short supply.

(6) Others

There are other factors depending on the conditions under which the structure is put in service, such as damage due to abrasion. However, (1) to (5) above may be regarded as major factors of deterioration.

Among these factors, (1) and (2) are of nationwide concern in Japan. These are distinguished from other factors by the corrosion of embedded reinforcing steel, which shortens the service life of the concrete structure while the performance of concrete remains intact. The use of epoxy-coated reinforcement is therefore permitted under harsh environment conditions.

4. Advances in repair techniques

Deteriorated structures have been frequently found in the past 10 to 15 years, leading to a large number of repair projects. The budget for repair work has accordingly been increasing in recent years while new construction has been stagnant. This has led to remarkable progress in repair techniques, with cutting-edge technologies being introduced.

(1) Deterioration-diagnosis techniques

Since defective events of concrete begins with cracking, the basics of deterioration diagnosis has consisted of estimating the cause of cracking from the shapes and dimensions of detected cracks—so-called visual judgment. Such judgment requires sufficient experience. Also, this technique provides no information on the internal deterioration, particularly as to the occurrence and progress of reinforcement corrosion, even to skilled examiners. Accordingly, infrared, ultrasonic, and electromagnetic measuring devices have been developed and made available in recent years, though with certain inaccuracy in measurement. This has enabled, for instance, continuous sensing of defects within tunnel concrete using sensors attached to trains, instead of conventional visual inspection and hammer tapping for checking voids in tunnel walls.

(2) Deterioration-repairing techniques

The techniques for repairing concrete structures to restore their performance to the as-built level have also made rapid progress in the past few years. Conventional repair of concrete comprised chipping away only the deteriorated concrete and filling new concrete or mortar. However, it is now known that it is necessary to completely remove the concrete around the reinforcement, otherwise the reinforcement will resume corrosion and expand, causing re-cracking of concrete. The technique of removing concrete behind reinforcement without damaging the reinforcement using a waterjet was developed for this purpose and has been widely used. The use of high quality concrete for patching and the use of a desalting agent are also proposed.

Electrical desalination and re-alkalization of concrete have also been proposed and proven to be effective, though requiring large-scale equipment. Cathodic protection to prevent reinforcement corrosion by micro-current is another option, with its effectiveness being proven.

5. The case of repair on the Sanyo Shinkansen Line

Along the Sanyo Shinkansen Line, which was constructed about 30 years ago, a series of accidents related to concrete have occurred in recent years, including falling of concrete lumps in tunnels and under bridges due to spalling and delaminatin of concrete. Though inflicting no casualties, they caused damage to trains and the roof of a parked car. West Japan Railway Company, which operates the Sanyo Shinkansen Line, had organized an in-house research committee to investigate this problem and formulate countermeasures since its takeover of the company from the former Japan National Railway Company. However, the Ministry of Land, Infrastructure and Transport took the matter seriously and organized a third-party research committee to address the problem, appointing the author to chair it.

As shown in Fig. 1, tunnel and banking parts account for 50% and 12%, respectively, of the overall 600-km length of the rail line, with the rest consisting of bridges including rigid-frame bridges. Therefore, the committee investigated the prestressed concrete and reinforced concrete girders excepting steel girders, as well as the rigid frame bridges. The committee carried out a follow-up survey to analyze the phenomenon using the test data accumulated by the in-house committee, as well as information from additional test data. Figure 2 shows typical test results. Chloride ions are not recognized at the immediate subsurface, but their content tends to increase as the depth increases and then begins to decrease again at a deeper level. The depth of peak contents ranged between 30 and 40 mm, which happened to coincide with the depth where reinforcing steel was embedded. The chloride ion profiles in concrete suggested the following:

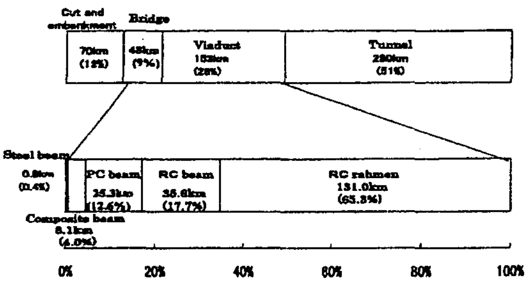

Fig. 1 Composition of facilities along Sanyo Shinkansen line

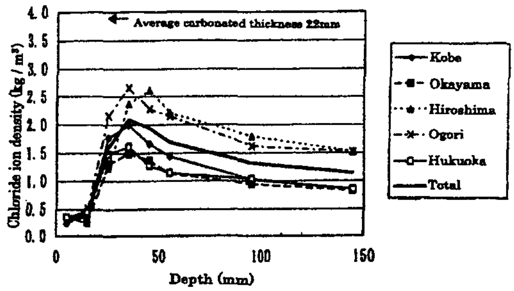

Fig.2 Chloride ion content distribution within concrete

The concrete used for the construction of the Sanyo Shinkansen Line was made using sea sand, which was mixed and placed without sufficient washing. Chloride ions are therefore considered to have been present in the concrete from the beginning at a content equal to that which remains at deep levels. Carbonation then began to proceed from the surfaces. This caused chloride ions to concentrate inward, resulting in peak contents at the boundary between carbonated and uncarbonated zones. The West Japan Railway Company struck off all the concrete showing cracking or delamination on the surfaces, excepting the segments within the company's premises and over rivers, as it could cause damage/injury to third parties. A relationship shown in Fig. 3 was recognized between the hammering down area and the uncarbonated cover depth {(cover depth) – (carbonation depth)}. Figure 4 shows the relationship between the degree of reinforcement corrosion and the hammering down area of concrete. This figure reveals a certain correlation, indicating that the surface area of struck-off concrete can be an index to the necessity for repair of concrete structures. Note that the criteria for reinforcement corrosion were proposed by the Japan Concrete Institute and are described in Fig. 5. Figure 6 shows the relationship between the mass loss percentage of reinforcement determined by investigation of reinforcement exposed by chipping and the uncarbonated cover depth. Figure 7 shows the relationship between the mass loss percentage and the chloride ion content at a depth of 95 mm (the content presumably representing the initial value).

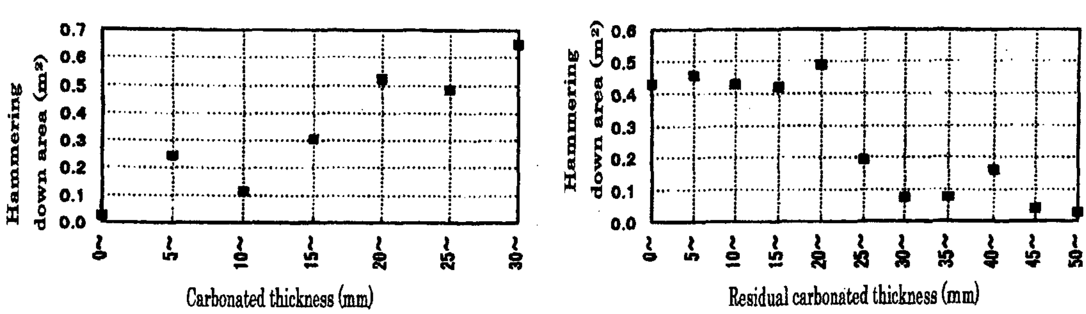

Fig.3 Carbonation depth and uncarbonated cover depth related to hammering down area of concrete

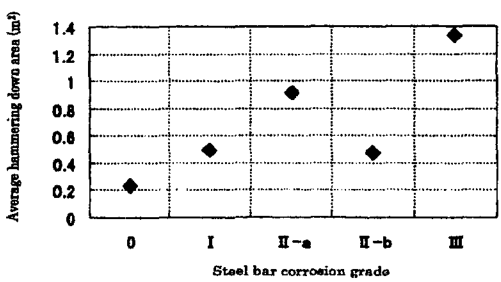

Fig.4 Hammering down area of concrete related to degree of reinforcement corrosion

Corrosion rate	Evaluation standard
0	Conditions when constructed are hold and there are no corrosion afterward.
I	There is a slight corrosion locally.
II a	There is corrosion on most of surface.
II b	There are sectional defects locally.
III	There are sectional defects all around steel bars.
IV	There are defects in more than a sixth of steel bar sections.

Fig.5 Evaluation criteria for degree of reinforcement corrosion

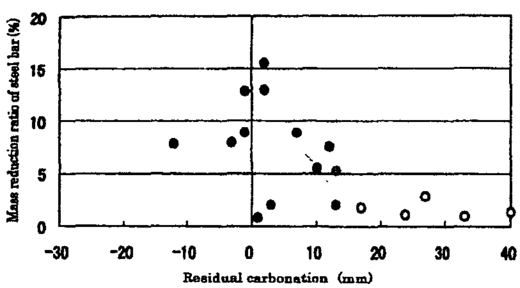

Fig.6 Relationship between uncarbonated cover depth and mass loss ratio of rebars

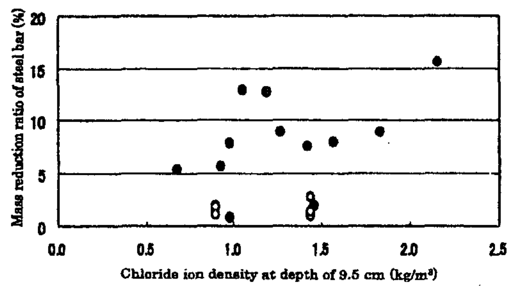

Fig.7 Realationship between chloride ion content and mass loss ratio of rebars

From these figures, it was found that the mass loss of reinforcement is negligible when the uncarbonated cover depth is 15 mm or more; an uncarbonated cover depth between 5 and 15 mm can be a risk depending on the chloride ion content; and the concrete should be chipped off to expose reinforcement for investigation of the degree of corrosion when the uncarboanted cover depth is 5 mm or less. In regard to the chloride ion content at a deep level, 0.6 kg/m^3 was found appropriate for the threshold value. Based on these data, the committee proposed flow chart for selecting the repair work as shown in Fig. 8. The types of repair work given at the bottom of Fig. 8 and the terms used in Fig. 8 are explained in Fig. 9. Referring to these flow charts, the West Japan Railway Company has prepared a survey sheet for each of about 10,000 units of structures along the line, with one unit being, e.g., a 3-span rigid frame bridge, and carries out repair work necessary for each unit. Fortunately, it is reported that the number of structural segments with a nominal safety factor of less than 1.2 is limited to only a few. The committee believes that Sanyo Shinkansen Line will continue to achieve its purpose as an important structure, if the current repair project is successfully completed.

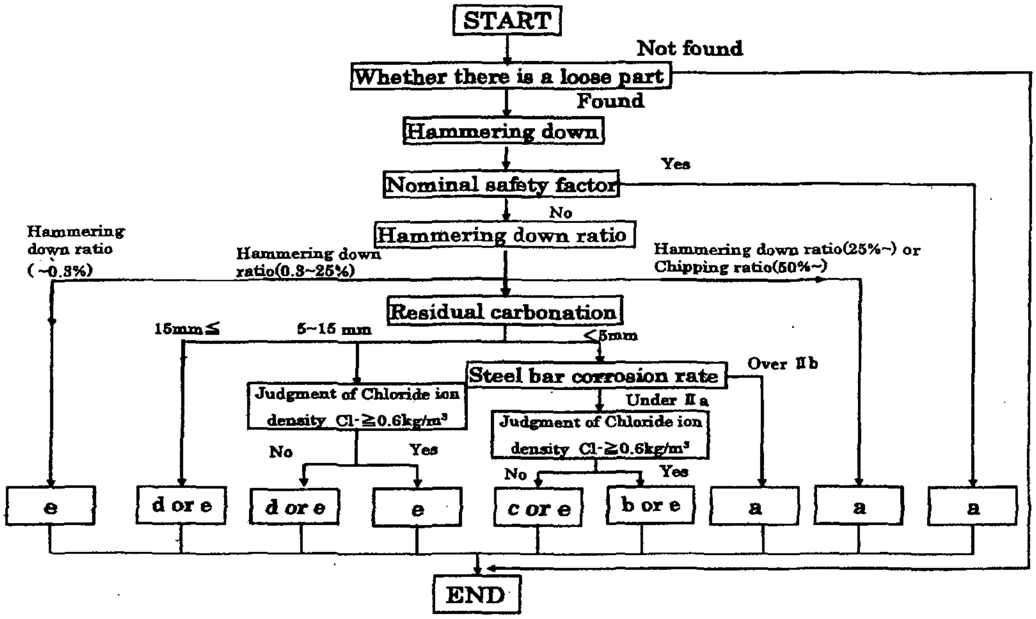

Fig.8 Flow chart for selecting repair method

	Repair characteristics	Applicable methods
a	To control the progress of steel bar corrosion caused by carbonation and chloride ions by replacing the concrete.	Restoration of entire cross sections
b	To control the progress of steel bar corrosion caused by carbonation and chloride ions by adopting electrochemical methods.	Desalination / Re-alkalinization, Electrolytic protection
c	To control the progress of steel bar corrosion mainly caused by carbonation by adopting electrochemical methods.	Re-alkalinization
d	To totally control the infiltration of steel bar corrosion factors such as oxygen, carbon dioxide and water.	Surface treatment on the entire surfaces
e	To control the progress of steel bar corrosion at locations suffering local damages.	Local restoration of cross section

Terms	Descriptions
Official safety ratio	The value obtained by dividing the actual strength, which is estimated from the measured steel bar diameter or other relevant values, by the design strength
Hammering down ratio	The ratio of the area hammered down with a hammer or other relevant tools in an inspection to the sectional area of the member.
Chipping ratio	The ratio of the area that has been chipped off, which is performed after hammering-down using electric chipping hammers or other relevant tools until the corrosion of steel bar is reduced to pitted corrosion, to the sectional area of the member. Note that the chipped-off area is the cumulative total of all the areas that have been chipped off in the past.
Residual carbonation	The value obtained by subtracting the carbonated thickness from concrete cover.

Fig.9 Descriptions of repair methods and terms

6. Afterword

I recall reading a book written by Prof. Tokujiro Yoshida in which he wrote the following:

(i) Workers in the field of civil works have conventionally been in the habit of thinking that specifications for concreting and other works are usually unobserved. Therefore, contractors win the bid at an unreasonably low price assuming nonconforming execution, preventing the proper and necessary execution from being carried out due to financial restrictions.

(ii) Due to the lack of sufficient knowledge about reinforced concrete, workers and supervisors may not do their best to conform to the specifications, though not intentionally,

(iii) The fact that it is difficult to judge the level of the execution of a concrete structure once it is completed inevitably influences the mindset of workers and others concerned, inducing them to think of sparing their efforts all the time.

These passages were written some 50 years ago. We are now struggling to cope with significant damage to concrete structures built by our and earlier generations due to deterioration and nonconformity during construction as pointed out by Prof. Yoshida. Though I am a researcher and educator with no experience in the field, I feel deeply responsible for this as a contemporary civil engineer. Reflecting on this situation, I think that it is the duty of engineers from now on to construct structures so that they can at least fulfill their design service lives while requiring repair only within the range permitted at the design stage.

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