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RESEARCH ACTIVITIES RELATED TO MAINTENANCE OF CONCRETE STRUCTURES

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The paper reviews recent inspection and research activities related to the maintenance of concrete structures. The main issues considered are codes for the maintenance of concrete structures in Japan, maintenance systems (including the concept of maintenance categories, total cost, uncertainty), prediction of structure life spans, methods of inspection and judgement, and repair and strengthening techniques. Finally, topics requiring active development to heighten the future engineering level of maintenance will be noted.

Keywords: performance, functionality, deterioration, service life, preventive maintenance, prediction, inspection, assessment, judgement, countermeasures, repair, strengthening,

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1. INTRODUCTION

It was thought that concrete structures would be maintenance-free and would retain their functionality semi-permanently. The concrete blocks making up the breakwater at Otaru Port, for example, were carefully constructed with appropriate materials and were expected to have considerable durability[1]. On the contrary, though, some structures have been found to not match their planned functionality. Changes of structural functionality can be caused by inadequate materials, inadequate mix-proportioning or construction methods, severe environmental conditions, or a change in loading conditions.

Just one century has passed since civil engineers constructed with first began using concrete, and there is no guarantee that concrete structures will have long-term durability under the actual environmental conditions experienced on earth. Given this understanding, it is rational to accept that: concrete structures generally suffer from reduced performance as time elapses and need maintenance work if the required functionality is to be maintained.

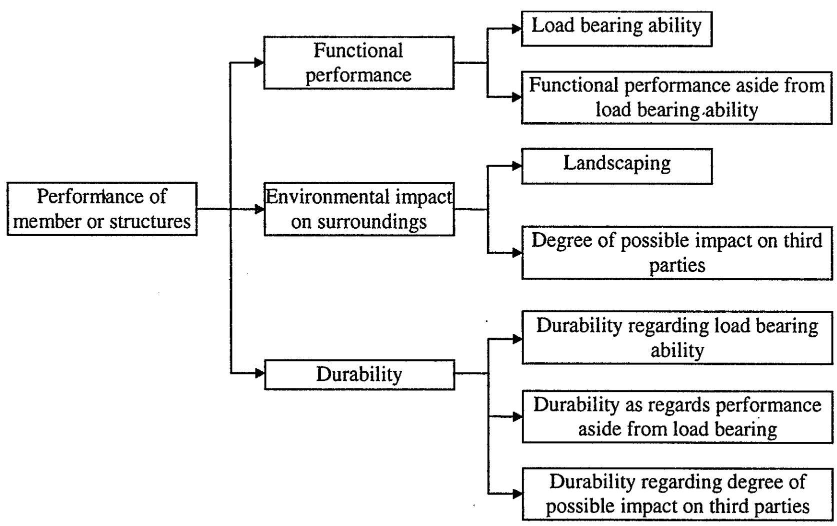

Fig. 1 Classification of Performance of Concrete Structures

There are three kinds of performance required of a concrete structure, as shown in Fig.1. Functionality and environmental impact on surroundings relate to performance at the present point in time, while durability relates to the decrease in functionality (performance) and the increasing environmental impact on surroundings with time. It is therefor necessary to predict durability and consider the future decrease in performances in these areas.

The deterioration of concrete structures is caused by various factors. In this paper, certain types of factor are ignored: disasters (fire, earthquake, etc.) and changes in loading conditions. Still, any comprehensive implementation of maintenance work must incorporate the following processes:

① prediction of deterioration
② methods of inspection and survey
③ assessment and judgement of deterioration
④ measures against deterioration

2. CODES OF MAINTENANCE

This section lists codes of maintenance for concrete structures that have been proposed so far in Japan. Codes published by official organizations are generally more practical.

(1) Recommendations for Maintenance of Concrete Structures – Draft (Japan Society of Civil Engineers)[2] (1995.10)
(2) Recommendations and Commentaries for Inspection, Assessment, Repair of Buildings (Japan Society of Architects) (1988)
(3) Recommendations for Inspection, Repair, Strengthening of Concrete Cracking (Japan Concrete Institute (JCI)) (1987.2)
(4) Guidelines for Inspection and Repair of Structures Damaged by Alkali-aggregate Reaction (JCI) (1989.7)
(5) Recommendations for Repair of Concrete Structures Damaged by Chloride Attack and Recommendations for Repair and Strengthening of Concrete Structures Damaged by Alkali-aggregate Reaction (Ministry of Public Work)[6](1988.11)
(6) Manual for Protection of Deterioration and Repair of Deteriorated Concrete Structures (Coastal Development Institute of Technology) (1989.9)
(7) Standards and Commentaries for Maintenance of Structures (Research Institute of Japan Railway) (1987.9)
(8) Guide for Maintenance and Repair of Bridges(Japan Highway Bureau) (1988.5)
(9) Guide for Repair of Road Concrete Structures(Hanshin Highway Bureau (1990.6)
(10) Guide for Repair and Strengthening of Bridge Structures (Metropolitan Highway Bureau) (1993.7)

3. Consideration of Maintenance Systems

3.1 Classification of Maintenance

Maintenance systems vary according to the product in question, and depend on the control method, the scale of the product, whether the product is manufactured on site or in a factory, and so forth. When an electrical appliance, for example, goes out of order, it is often easier to replace it rather than expending effort to repair it. In the case of airplanes, certain parts are replaced at particular intervals in addition to routine inspections. Concrete structures, however, differ from factory products and are generally constructed on site according to design and construction documents.

The soundness of a structure can be classified as follows: ①Completely sound condition with no limitations; ②no visible deterioration on the surface though deterioration has begun within; and ③deterioration is visible and the performance of the structure has begun to decrease. In most cases countermeasures are introduced at stage ③, but for some structures maintenance is required at stages ① or ②. These might be called the preventive maintenance stages, whereas ③ represents ex post facto maintenance. Reference[2] classifies the component of a maintenance system as follows: A: preventive maintenance; B: ex post facto maintenance; C: observational maintenance, and D: maintenance without inspection. The type of maintenance applied to a structure depends on the importance of the structural members, the influence of deterioration on third parties, the required service life, environmental conditions, and the difficulty of maintenance work.

3.2 Total Cost and Maintenance

It is necessary to consider the total cost of maintaining the expected performance of a structure over its service life. This total cost comprises the cost of construction plus the maintenance cost. At present, construction cost only is considered.

Miyamoto et al. proposed the Bridge Management System (BMS) to consider maintenance work in total[3]. Matsuhima et al. considered the optimum inspection interval for piled piers, in which the problem was defined as a trade-off problem between inspection cost, repair cost, and the cost of lost performance[4]. The optimum interval was calculated so as to minimize the total expected cost by way of reliability theory.

3.3 Maintenance and Uncertainty

There are various uncertainties involved in executing maintenance work, and some researchers have been tried to treat these uncertainties in maintenance mathematically. Shiraishi et al. used Fuzzy Theory to evaluate the degree of deterioration of concrete bridge slabs, and proposed an expert system for estimating the damage mode and degree of deterioration[5][6]. Miyamoto et al. also applied Fuzzy Theory to evaluate the soundness of concrete bridges[7] and furthermore estimated the safety of actual structures based on statistical data[8]. Matsushima et al. proposed an evaluation technique in which Fuzzy Theory is applied to the deterioration of concrete structures based on visual inspection data[9]. Huruta et al. attempted to introduce Fuzzy Theory as an effective method of improving and maintaining a maintenance data base[10].

4. ESTIMATION OF LIFE SPAN AND MAINTENACE

4.1 Life Span of Concrete Structures

a) Determination of Service Life Duration
It is generally said that the service life of a structure depends on the following conditions: ①physical condition (loss of performance due to physical and chemical attack); ②functional condition (change of function or enhancement of function); and ③economical condition. It is difficult to allow for ② and ③ at the construction stage, and the following condition must be satisfied:

Design service life $<$ Design durable life

The design durable life is the period for which suitable performance is guaranteed in consideration of the structure's physical condition.

Various codes or suggestions have been proposed regarding the definition of service life.

- Wind force (in consideration of repeating period): 50 years
- Environmental force(mainly wave action): 100years
- Service life as determined by depreciation of national assets:
  - bridges: 15years; tunnels: 60years; railway sleepers: 20 years
- Governmental subsidy
  - piers and breakwaters: 50years; bridges: 60years

b) Estimation of Life Span of Structures
In estimating life span of a concrete structure, the following points have to be clarified: ①the performance requirements; ②the factors that reduce the performance; ③the changes in the factors' indexes; and ④the limits on performance loss. In addition, various considerations related to decrease in both safety and functionality must be summarized. A JCI committee report[11] summarizes the present state of research regarding analytical methods for predicting durable life, the prediction of life spans in other engineering fields, and models for predicting deterioration.

4.2 Deterioration Factors and Estimation of Life Span

a) Chloride-induced deterioration

1) Deterioration and performance loss: Salt damage is a phenomenon in which corrosion of reinforcing bars occurs as a result of chloride. Chloride is supplied with the concrete materials (sea sand, cement, admixtures) or from the environmental conditions (coastal areas, de-icing salt). The deterioration process is illustrated in Fig.2. Once chloride has accumulated in the concrete up to the corrosion limit, corrosion of the reinforcing bars begins. Ultimately, the corrosion products expand and apply pressure to the surrounding concrete, causing cracking in the direction of the reinforcing bars.

2) Penetration and distribution of chloride: Chloride ions penetrate into the inner concrete through transport of liquid water and by diffusion of ions in aqueous solution. Bazant initiated an analytical approach to this phenomenon[12][13]. Many other experimental and analytical approaches have also been reported. Otsuki et al., for example, proposed an apparent coefficient of diffusion using actual chloride data from concrete structures in the field[14]. Takewaka et al. solved a diffusion equation that included a term for the chloride concentration in the surface layer of the concrete[15]. Maruya et al. analyzed the accumulation of chloride in concrete in consideration of such factors as diffusion of chloride ions, diffusion of water through pores in concrete, type of chloride (soluble or fixed), and the influence of wetting and drying [16]. Oshiro et al. considered the chloride present in the surface layer as a function of time, and proposed an analytical technique for estimating the chloride distribution in concrete[17]. Kobayashi et al. discovered a phenomenon in which chloride ions concentrate at the carbonation front[18]. Maekawa et al. analyzed the process of chloride ion transport accompanying water movement due to drying[19]. Goto et al. discussed the movement of various ions dissolved in concrete pore water, taking into account the concrete pore size and the electrical charged condition of hardened cement[20].

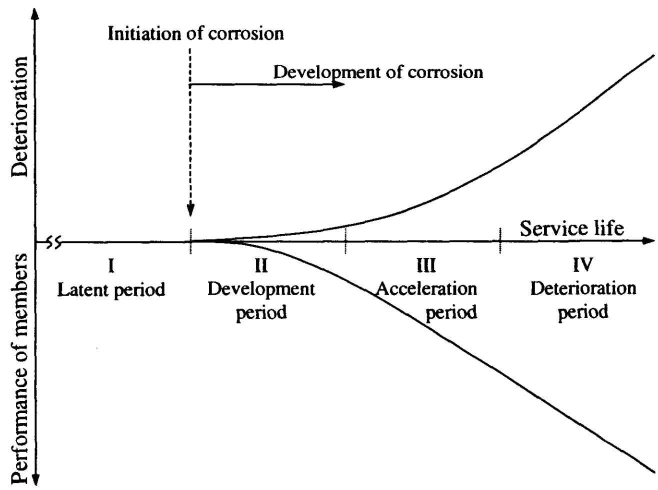

Fig. 2 Deterioration Process and Decrease in Performance

3) Limit chloride content for occurrence of corrosion: The limit content has been the focus of many research results. Otsuki et al. evaluated from electro-chemical experiments whether or not a passive film exists on the bar surface, and finally proposed a limit chloride content of 0.75 kg/m^3 (for 1 m^3 of concrete)[21]. Miyagawa et al. suggested a limit chloride content of 1.2~2.5 kg/m^3 based on tests of corrosion a bars embedded in concrete specimens[22]. Recommendations for Maintenance[2] proposes a limit of 0.4% (by weight of unit cement, or approximately 1.2 kg/m^3 for 1 m^3 of concrete)[2].

4) Control phase of corrosion and corrosion rate: Phase of macro corrosion are classified as anode control, cathode control, and electrical resistance control. Though corrosion of reinforcement has been considered to be controlled with diffusion of oxygen (that is, anode control), one paper[23] has suggested that electrical resistance might mainly control corrosion rate of bars.

5) Corrosion products and crack occurrence: The physical properties of corrosion products must be clarified in order that the expansion pressure applied by corrosion can be evaluated. The main crystallization of corrosion products is known to be Fe_3O_4 from X-ray analysis[24], but only one paper[25] has reported

experimental data relating to physical properties. An analytical approach has been used to obtain the time of corrosion occurrence and corrosion cracking, in which the corrosion model was assembled in consideration of such factors as the coefficient of chloride diffusion, the coefficient of oxygen diffusion, the water content in concrete, and the modulus of elasticity of corrosion products[26][27]. Actual structures generally have evidence peeling-off cracks in addition to longitudinal cracks, and the mechanism by which these cracks arise has been experimentally and analytically investigated[28]. Many researchers consider that when cracking is observed on the concrete surface then the limit of serviceability has been reached, while others believe that certain crack width must be allowed because tiny cracks have no damaging influence on load-bearing capacity.

b) Carbonation of concrete

1) Deterioration and decrease in performance: The JCI Research Committee on Carbonation of Concrete proposed strict definitions of 'carbonation' and 'neutralization'. 'Carbonation' is the process by which cement hydrates react with carbon dioxide and became either carbonic products or decomposition products. On the other hand 'neutralization' is defined as the phenomenon by which the alkalinity of cement hydrates decreases. Though neutralization can be caused by acid rain and fire in addition to carbonation, the main factor in neutralization is carbonation. It is therefore generally understood that neutralization due to carbonation is referred to 'neutralization'.

   Research activities on neutralization are in to two areas: ①the chemical mechanism and ②physical properties. A JCI committee report has scrutinized the mechanism[29]. Kobayashi et al.[18] discussed the movement of inner ion due to carbonation of concrete, and pointed out that the C-S-H gel would decompose in carbonated areas of concrete. Many papers have reported on the strength of concrete. Saeki et al.[30] reported that carbonation caused tightness of cement hydrates and an increase in strength.

   The most damaging result of neutralization is that concrete loses its anti-corrosion property with regard to reinforcing bars embedded in the concrete. Kashino et al.[31][32] carried out exhaustive experimental work to investigate various related factors and explained that the predominant factor in neutralization differed from that causing the corrosion of reinforcement bars. Saeki et al.[33] evaluated the relationship between neutralization and reinforcement corrosion by way of the measurements based on electro-chemical technique.

2) Prediction of neutralization: Various equations for neutralization depth have been deduced from the inspection of actual structures, and these are summarized in ref.[34]. An analytical based on developing a neutralized model was followed by Saeki et al.[35] and Fukushima et al.[36]. Their model included the diffusion of carbon dioxide and calcium hydroxide, the solution rate of vapor into liquid, and the reaction rate of neutralization.

3) Neutralization and prediction of deterioration: Izumi et al. surveyed the neutralization of concrete and corrosion of bars in actual structures, and proposed an estimation method for the deterioration of concrete members and remaining life span[34].

c) Other Deterioration factors

1) Alkali-aggregate reactions: Alkali-silica reactions (denoted ASR) cause expansive pressure on surrounding concrete and visible cracks occurs at the concrete surface. A JCI committee report[37] suggested that it might be possible to estimate qualitatively the progress of deterioration. Recommendation for Maintenance[2] proposes estimation method from a core specimen. If the specimen expands after being cured in the water, the limit volume expansion should be less than 0.1%.

2) Frost damage: The freezing and thawing of water in concrete leads to cracking, scaling of the concrete surface layer, coarse aggregate popping at the surface layer, and a damaged appearance. Though it is at present impossible to quantitatively predict the progress of deterioration, Recommendation for Maintenance[2] suggests the following indexes for making judgements regarding freezing and thawing action: ①physical test of aggregate (water absorption: less than 3%; weight loss due to soundness test: less than 12%), ②freezing and thawing test (relative dynamic elasticity: larger than 80%), and ③the frost damage ratio (depth of frost damage/concrete cover).

3) Fatigue: Cyclic loads act on such structures as railway bridges, road bridges, and breakwaters. Railway facilities are designed to cope with fatigue load by way of Miners' theory. The reinforced concrete slabs of road bridges suffer degraded load capacity according to the following process: ①cracking in one direction→②lattice cracking→③cracks passing through slab cross section→④transition from two-direction slab member to one direction beam member. Deterioration indexes might be crack density, amount of crack opening and closing, difference in level on two sides of crack, and deflection[2].

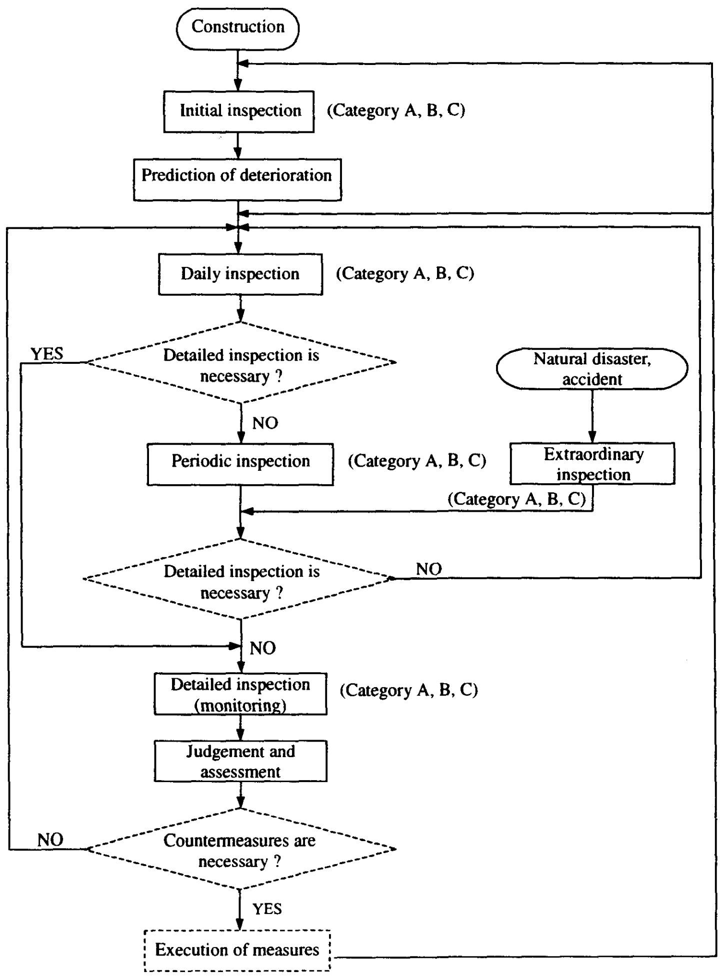

Fig. 3 Inspection Process

5. METHODS OF INSPECTION AND JUDGEMENT

5.1 Classification and Methods of Inspection

Inspection can be broken down into the categories of initial inspection, daily inspection, periodic inspection, detailed inspection, and extraordinary inspection[2]. Figure 3 indicates the general process of inspecting structures. The actual type of inspections and their intervals depend on the maintenance classification, the importance of the structure and the cost of inspections. Monitoring systems might be required for the purpose of preventive maintenance. Daily inspections are carried out with visually, while detailed inspections include the sampling of cores from the structures. It is recommended, from the point of view of minimizing costs for both inspection and repair, that periodic inspections be carried out at 4-year interval for the initial 20 years of service life and every 2 years thereafter[4]. The items checked during inspections are indicated in Tab.1[38]. Figure 4 shows the inspection process for chloride-induced deterioration[2].

Table 1 Items of Inspection

Classification	Inspection Items
Deteriorating action	Applying loading and cyclic loading. Supply of chloride. Dry and wet action (chloride damage). Temperature (alkali-aggregate reaction, chloride damage). Freezing and thawing action. Supply of water (alkali-aggregate reaction). Chemical action.
Materials	Construction records (type of cement, aggregate, mix-proportion, etc). Properties of concrete (strength, modulus of elasticity, ultrasonic wave, etc). Chloride ions contained in concrete. Corrosion of bars (natural potential, polarization resistance, decrease of cross-section). Depth of neutralization, Residual expansion.
Construction	Cover of bars. Arrangement of bars. Inner defects.
Structure	Design strength. Dimensions of cross section. Cracking (depth of crack, width of crack). Rigidity (deflection). Vibration. Support condition. History of repair.
Possible impact on third parties	Free lime. Leakage. Delamination of cover concrete. Looseness of cover concrete. Change of surface color (rust stains, etc).

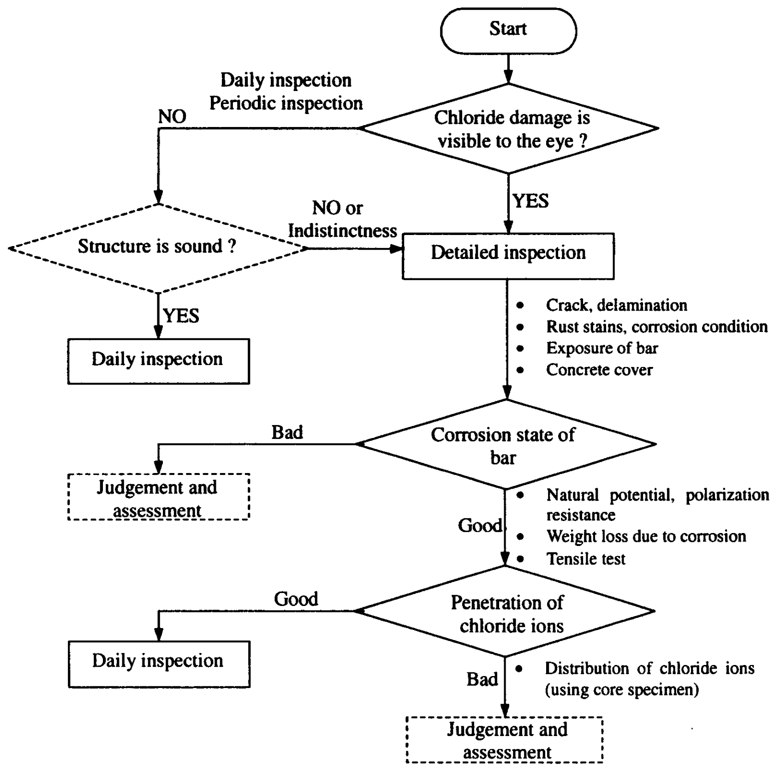

Fig. 4 Inspection Process for Chloride-induced Deterioration

5.2 Inspection Techniques

Various non-destructive inspection are available or on are trial. Some examples are noted below.

① General inspection of deterioration: visual methods, photographs

② Estimation of physical properties: surface hardness, ultrasonic methods, vibration methods

③ Estimation of inner defect of structure: hammering, infrared methods, AE methods, ultrasonic methods, microwaves

Test methods that entail damage to small areas are as follows.

① Measure of corrosion: natural potential, polarization resistance

② Estimation of physical properties: penetration resistance, pull-out resistance

Further, core specimens can provide the types of data listed below.

① Physical properties including actual strength of concrete

② Estimation of mix-proportioning

③ Depth of neutralization

④ Estimation of alkali aggregate reaction

The appendix of ref.[2] summarizes the selection of suitable techniques from those available according to the deterioration mechanism. Many books giving guidelines are in print.

Very few of the currently available methods offer high accuracy and applicability. As a result, there is a need for active research into new techniques such as ①measurements that are highly reliable and repeatable, ② equipment that is fast and easy to use, and ③inspection methods that yield two-dimensional data.

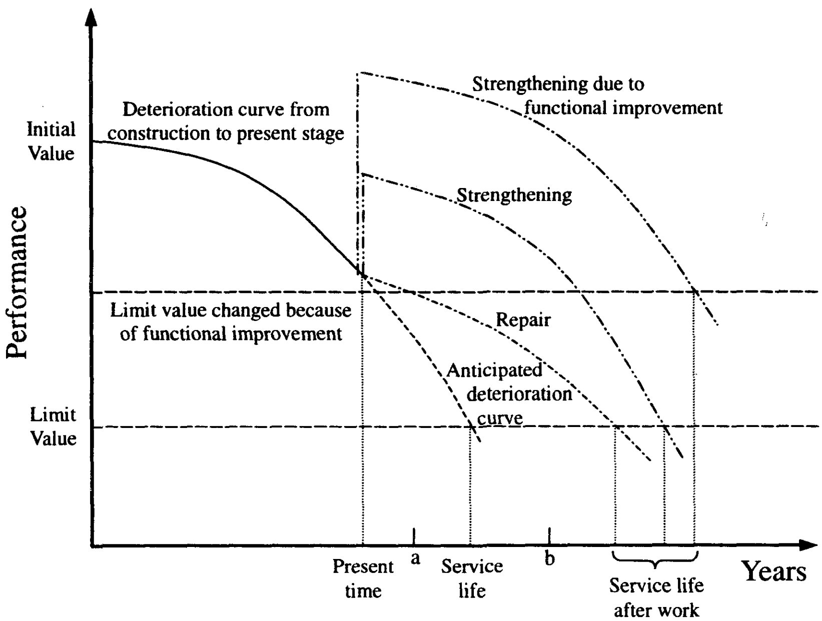

Fig. 5 Change in Performance and Repair/Strengthening Work

5.3 Judgement of Need for Repair

a) Concept of assessment and judgement

The decrease in a structure's functionality as time elapses is anticipated. Figure 5 indicates the change in load bearing capacity as a function of age. According to the degree of deterioration, a judgement has to be made regarding the measures to be implemented. With regard to load bearing capacity, the main items requiring inspection are as follows.

Deterioration action (loading conditions, and cyclic loading)
Materials (construction records, properties of concrete and reinforcing bars)
Construction work (bar arrangement, internal defects)
Structural items (design strength, dimensions of cross section, cracking, flexural rigidity, support condition)

It is difficult to carry out a comprehensive and quantitative assessment of such data, and judgement is usually a qualitative process based on some limited subset of these items.

Table 2 Methods of Repair

Mechanism of Deterioration	Repair Concept	Repair Method
Chloride-induced deterioration	- Removal of chloride-contaminated concrete - Protection againt intrusion of Cl^-, water, and oxygen after repair	- Restoration to original cross section - Surface protection
	- Give bars less noble potential - Removal of chloride-contaminated concrete	- Cathodic protection - Desalination
Neutralization	- Removal of neutralized concrete - Protect for intrusion of CO_2 and water after repair - Realkalization of concrete	- Restoration of original cross section - Surface protection - Realkalization
Frost damage	- Removal of deteriorated concrete - Protect against intrusion of water after repair - Higher resistance to freezing and thawing action	- Restoration to original cross section - Injection into crack - Surface protection
Alkali-aggregate reaction	- Protect against intrusion of water - Acceleration of water discharge from inner concrete - Protect against alkali supply	- Injection into crack - Surface protection
Chemical erosion	- Removal of deteriorated concrete - Protect against intrusion of detri-mental chemical ions	- Restoration to original cross section - Surface protection
Fatigue (RC slab of road bridges)	- Protect against widening of crack (strengthening in most cases)	

b) Practical assessment and judgement

1) General judgement: A trial method has been proposed for the quantitative determination of judgements[2], in which each inspection item has its own grading (weighted value) and the total grade is compared with some allowable figure. If the allowable value is exceeded, a detailed inspection becomes necessary. In the case of railway structures, judgements are classified (Class AA~Class S) on the basis of an initial visual inspection, and measures for each classification are proposed. For instance, a Class AA judgement requires that use of the structure be halted or a replacement structure be used, while Class S means that the structure remains in sound condition. Yonezawa et al. has proposed an idea[40] based on two categories of visible deterioration: one is the width and length of cracks, and the other relates to the area of peeled cover concrete. A final categorization is made by considering the two categories, and the level of performance, such as load bearing capacity, is judged on the basis of this value.
2) Judgement of chloride-induced deterioration: In ref.[2], the stages of deterioration are classified from I (latent period) to IV (aggressive deterioration period) using indexes of corrosion and cracking. Limitations on performance (as shown in Fig.1) are defined for each classification.
   A more practical approach has been applied to reinforced concrete slabs at piers. The process is as follows.

First, the degree of bar corrosion observed at the concrete surface and the deterioration of the cover concrete are inspected visually, and then the degree of deterioration of each member is classified. Finally, the degree of deterioration of the structure is comprehensively evaluated[41]. According to this method,

Degree of deterioration 0 and I: no repairs needed

Degree of deterioration II: no repairs (though repairs are necessary in some cases)

Degree of deterioration III and IV: repairs needed

Degree of deterioration V: repairs needed (and in some cases, strengthening)

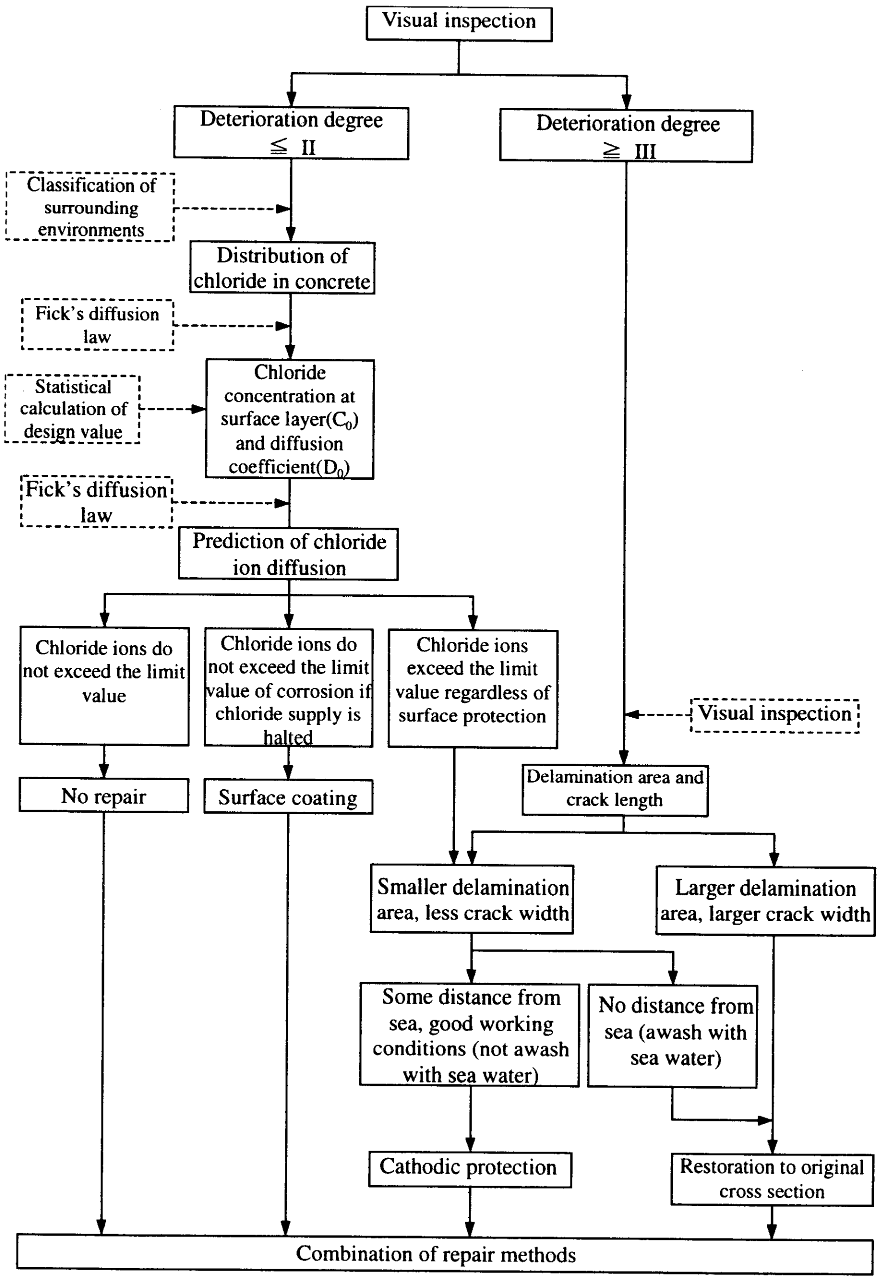

Fig. 6 Selection Process of Repair Methods for Piers

3) Judgement of neutralization: The neutralized depth is generally measured with an alcohol solution containing 1% phenolphthalein. If the neutralized depth is found to be larger than the concrete cover, then it is assumed that corrosion of the reinforcing bars has begun. An electro-chemical approach might be one effective alternative for judging directly whether or not the reinforcing bars have corroded.
4) Judgement of alkali-aggregate reaction: Ref.[35] suggests that the need for countermeasures has to be judged in consideration of the following factors: degree of damage, visual appearance of structure, importance of structure and expansion of sampled cores (residual expansion). A more practical judgement might be obtained by adding such factors as the gel ring surrounding coarse aggregate, and the width and length of cracks.
5) Judgement of crack width: Matsushima et al. analyzed the width of cracks that had been repaired, and proposed an allowable crack width by way of a statistical method[42]. Kaneko suggested an allowable crack width from the standpoint of appearance and angle, as follows.
   Allowable crack width for appearance: 0.4 mm
   Allowable crack width according to angle of crack to member axis where structural anxiety be felt :

Perpendicular to member axis	0.5mm(for RC)
	0.4 mm(for PC)
Some angle to member axis	0.25mm(for RC)
	0.15mm(for PC)
Parallel to member axis	0.1mm

6. REPAIR AND STRENGTHENING

The terms used in this section are defined as follows.

Repair: work carried out to recover or enhance durability and reduce possible impact on third parties
Strengthening: work carried out to recover or enhance load bearing capacity

6.1 Repair Methods

a) Selection of repair methods
Repair methods in actual use are crack injection methods, surface protection methods, methods that restore the original cross section, and electrical methods. Table 2 summarizes methods that apply to each deterioration mechanism. In surface protection methods, the particles causing deterioration are blocked by a concrete surface film. The surface layer of the concrete, which contains the harmful particles, is removed and a new concrete layer put in place. Figure 6 shows how a repair method is selected for the reinforced concrete upper elements of piers[44]. This section gives a full description of various electrical methods of repair.
b) Electrical methods
Electric methods use the reinforcement as a cathode and an anode is attached to the concrete surface. An electric current passes from anode to cathode, and the reinforcement forced into a non-corrosding state. Electrical techniques are used: ①to directly protect reinforcements from corrosion ('cathodic protection'), ②to remove chloride ions from the concrete (generally 'desalination methods'), ③to return concrete to high alkalinity ('realkalization methods'), and ④to close cracks with reaction products (generally called 'electrodeposition methods'). Cathodic protection requires only a small electrical current, so there is little influence on concrete properties. On the other hand, desalination and realkalization have the merit of completing the electrical treatment within a short time.
1) Cathodic protection: There are two types of cathodic protection, the outer battery system and the galvanic system. The current passing from anode to cathode is generally in the range 10~20 mA/m^2 (of concrete surface area) throughout the service life. A JCI committee report[45] summarizes in detail the research

carried out so far the and experimental results obtained. Large areas have been repaired using cathodic protection. Furthermore, Ishii et al. attempted to apply cathodic protection to PC members[46], testing for the hydrogen embrittlement of PC tendons in the laboratory and measuring the load-carrying characteristics of PC members. He concluded that the method presented no problems at the small currents usually used in practical cathodic protection work.

2) Desalination methods: The electrophoresis is used in order that the ions in the concrete move under the driving force of an electrical potential difference. In electrophoresis, the current required ranges from 1.0 to 5.0 A/m^2 (of concrete surface area), and the treatment generally lasts 4~8 weeks.
Certain problems have been pointed out with the method. Cement paste in the vicinity of the reinforcement tends to soften under the influence of the high current applied. In the actual work, the cumulative current must be held below a certain value which ensures no effect on bond strength[47]. Nishibayashi et al.[48] evaluated the accumulation of alkaline ions in the cathode area and the possibility of inducing an alkali-aggregate reaction. Hisada et al.[49] reported that chloride ions moved toward the anode area, thus effectively to protecting the reinforcement from corrosion.
3) Realkalization methods: Electrical osmosis is used in order that the liquid contained in concrete moves and concrete realkalizes. The liquid phase in the concrete pores moves to the cathode. This alkaline solution, which is generally combined with sodium carbonate and lithium carbonate solution, builds up in the anode area and approximately 1 A/m^2 of electric current is applied between the anode and cathode to cause it to migrate. After immersion in the alkaline solution, the neutralized concrete returns to higher pH within several days.
4) Electrodeposition methods: An electrical current is passed between the anode (sea water) and the cathode (reinforcement), and $CaCO_3$and $Mg(OH)_2$ from $Ca^{2+}$and Mg^{2+} ions solved in the sea water. Yokota et al.[50] reported that cracks in sea wall were filled with crystalline reaction products after application of 0.5 A/m^2 for 5 months.

c) Outstanding issues regarding repair methods

It is not that many years since civil engineers realized the importance of repair work, and effective information relating to repair methods is limited in quantity. There are many issues remaining to be resolved, such as the following:

① The durability of repair materials remains uncertain.
② When structures are designed, post-completion maintenance work is not taken into consideration. This places severe maintenance work, such as the need to erect scaffolding.
③ How to introduce robotic systems where working conditions are particularly severe.

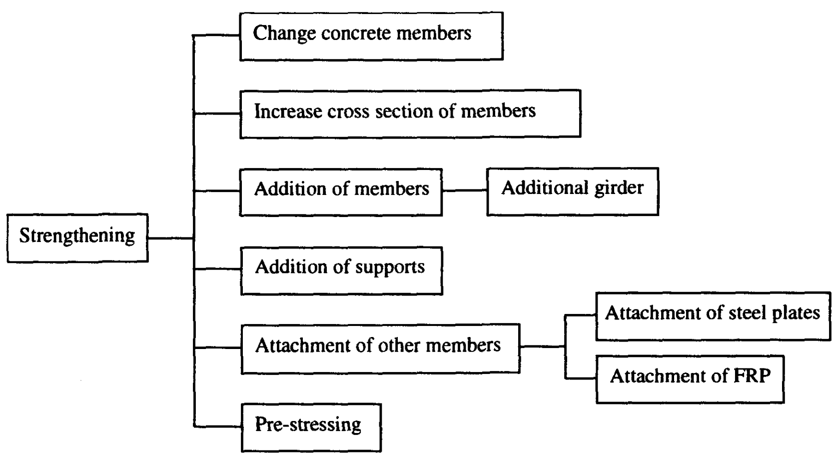

Fig. 7 Methods of Strengthening

6.2 Strengthening Methods

Figure 7 indicates methods of strengthening structures[2]. Few papers have reported on such methods as compared with repair methods, as it might be reasoned that most measures taken to counter structural deterioration relate to repairs. From now on, however, more research and technical development might are likely to became necessary.

7. AFTERWORD

This paper summarizes the present state of technology for the maintenance of concrete structures. The idea that concrete structures must be carefully maintained has now been firmly grasped by most civil engineers. Various issues relating to maintenance now require active investigation from the standpoint of technical engineering and maintenance systems, including the following:

(1) When structures are designed, post-completion maintenance must be taken into account such as by: ① introducing structures less susceptible to deterioration, ②developing structural types that are easy to maintain, and ③carrying out durability design in consideration the deterioration of members.

(2) Further research work is required regarding the prediction of deterioration.

(3) Most inspections and research work has so far related to concrete materials and concrete members. More discussion from the structural standpoint is required, such as the effect of changes in loading conditions during the service life, the decrease in structural performance, and methods for the maintenance of structures themselves.

(4) Little information is available on which to base a comprehensive judgement of loss of functionality. Further work to quantitatively establish the limits of performance is needed.

(5) Maintenance systems must be developed to incorporate such concepts as ①to apply Fuzzy Theory and Neural Network Theory to the uncertainties in maintenance and ②consideration total cost over the service life of a structure.

(6) It is necessary to clarify the durability of maintenance materials, to establish judgement criteria for their performance, and develop testing methods.

(7) Newly developed non-destructive test equipment is eagerly awaited.

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