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서울시내 위치한 콘크리트 고가차도의 내구성능 조사 및 평가

Investigation and Evaluation on Performance of Durability for Freeway Concrete Viaducts in Seoul Metropolitan Area

이 창 수* / 윤 인 석**
Lee, Chang Soo / Yoon, In Seok

Abstract

The objectives of this paper were to obtain the fundamental data to analyze the causes of deterioration of 39 freeway concrete viaducts in Seoul metropolitan area. To investigate the degree of concrete deterioration, carbonation depth, soluble chloride concentration in hardened concrete and half-cell potentials of reinforcement were measured.

The number of structures which carbonation depth penetrates to reinforcement was 25% of total. The model of carbonation rate was induced to 3.92 $\sqrt{t}$, which was 5% faster than 3.727 $\sqrt{t}$ assumed 60% water-cement ratio, R=1 in that of kishitani. After measuring chloride concentration in concrete, it was concluded that about 24% of all readings on samples from concrete exceed the *critical content to minimize the risk* of chloride-induced corrosion. About 31% of the freeway viaducts structures had a value lower than -350mV(vs. CSE), so it could conclude that the excessive chloride concentration was the major cause of reinforcement corrosion. Among the structures which measured half-cell potentials less than -350mV, about 50% exceeds the maximum acceptable limit of chloride concentration.

Key words : Carbonation of concrete, Chloride concentration, Deterioration, Durability, Half-cell potential

요 지

본 연구는 서울시내 위치한 39개 콘크리트 고가차도의 중성화 깊이, 가용성 염화물량 및 철근의 자연전위 등을 측정하여 열화의 원인을 분석하기 위한 기초자료를 얻고자 하였다.

전체 조사대상 구조물 가운데 철근위치까지 중성화 깊이가 진행된 구조물은 약 25%에 해당되었으며 중성화 속도는 물-시멘트비 60%, R=1의 조건인 kishitani의 제안식 3.727 $\sqrt{t}$ 보다 5%가 빠른 3.92 $\sqrt{t}$로 나타났다. 콘크리트의 염화물량의 조사결과에서는 전체 측정부위의 24%가 임계염화물량을 초과하였으며 철근의 자연전위는 -350mV(vs. CSE)이하로 측정된 것이 약 31%에 해당되는 구조물로서 과다한 염화물량이 철근부식의 주요 원인이 되는 것으로 조사되었다. 자연전위 -350mV 이하인 구조물에 한한 철근부식의 주요요인을 추정한 결과, 약 60%에 해당하는 부위가 최대 허용염화물량을

* Member, Professor, Dept. of Civil Engineering, University of Seoul, South Korea
** Graduate Student, Dept. of Civil Engineering, University of Seoul, South Korea

초과하였기 때문으로 분석된다.
핵심용어 : 콘크리트의 중성화, 염화물농도, 열화, 내구성, 자연전위

1. INTRODUCTION

The reliability of deteriorated concrete structures has now become an important problem. Although concrete has traditionally been regarded as a durable material requiring little or no maintenance, many concrete structures have been showing signs of deterioration. That reason is the decrease of durability performance by frequent loading, increasing traffic volume and CO_2 gas content in atmospherics, acid rain, and so on.

As a case of structures in Seoul metropolitan area, using marine sand, de-icing salt such as calcium chloride, and concrete chemical admixture was the cause of reinforcement corrosion and the decrease of service life. In this situation, in order to maintain performance by nature and to increase the service life of concrete structures, the selection of construction materials, the insurance of good concrete quality and careful maintenance should be performed. Fortunately, as the concern for the lack of durability was perceived as a threat to the glory of concrete, modern codes have put emphasis on the durability of concrete structures.[(1)~(2)]

To obtain the countermeasure of the decrease of durability, the condition analysis of structures in service must be performed. While we have not done any systematic research on it yet, the advanced nations finished it.[(3)]

This paper has concentrated on the data collection and the analysis of durability performance of studied 39 freeway concrete viaducts in Seoul metropolitan area at random. The analysis has been conducted to determine how much freeway concrete viaducts have been deteriorated, why they are being deteriorated and, if possible, how rapidly they are being deteriorated. The purpose of this paper is to comprehend the condition of freeway concrete viaducts in Seoul metropolitan area so that the reasonable long-term maintenance method could be made. It has also been hoped to decrease maintenance cost and to develope deterioration model of freeway concrete viaducts in Seoul metropolitan area.

2. SURVEY METHODS

2.1 Selection of Freeway Concrete Viaducts

In view of the wide variety of freeway concrete viaducts, as large a sample as possible is required for the survey. The method of selection of freeway concrete viaducts in Seoul metropolitan area considered geographical distribution, environment, and the approach to structures. The prepared inspection and on-the-spot survey were performed and 39 structures were selected at random.

The construction years of studied freeway concrete viaducts is shown in Table 1. The vast majority of studied freeway concrete viaducts were built in the 1960s and 1970s.

Table 1 Construction years of studied freeway concrete viaducts

Construction years	~1969	1970s	1980s	1990s	unknown
Number	8	17	9	4	1

2.2 Techniques of Investigation

A computer database have been used to assist the analysis of the mass of information arisen from the freeway concrete viaducts. For each structures, three sets of data were entered : The first is structures the data describing location, type, and construction years, the second is the visual inspection data describing the condition, and the third is the durability data giving the half-cell, carbonation depth and chloride concentration.

2.2.1 Selection of Studied Part on Members

The whole of each freeway concrete viaducts was investigated from the slabs, the abutments and the piers. The most deteriorated parts which were regarded as potentially dangerous portion were selected and tests were concentrated on the corresponding portion..

2.2.2 Visual Inspection

The method of visual inspection was based on the department of construction & transport's requirements in Table 2. On each element of the structures the presence of defects such as spalling, rust, cracks, efflorescence, or water rust was noted and the extent and the severity of each type of defects was estimated. Photographs were taken to supplement and illustrated the inspection records.

Table 2 Guide of visual inspection grade

Grade	Definition of grade and condition
1	Excellent without any problem
2	Good with minor defect
3	Fair with the damage of secondary member
4	Poor requiring urgent repair due to aging of main member
5	Out of service

2.2.3 Concrete Cover

Within each test area, the cover depth to reinforcement was measured using concrete cover meter(ferro-scan) in each 600㎜×600㎜ grid square.

2.2.4 Chloride Concentration in Concrete

The chloride concentration in concrete had been investigated on structures grouped with elements. The powder and core specimen which were made by drilling into concrete were taken. The chloride concentration(%, Cl^-) was estimated by the measurement method of soluble chloride concentration in hardened concrete as JCI's requirements. After chloride solution was extracted, it was measured using ionic electrode. In accordance with ACI building code 318, 0.04% was regarded as acceptable concentration, and 0.052% as critical concentration causing reinforcement corrosion.

2.2.5 Carbonation of Concrete

At surface, the hole was drilled a short distance into concrete. The 1% phenolphthalein - alcohol indicator was then sprayed onto the broken surface, so the depth to the color change could be measured using a depth gauge in accordance with the technique described in RILEM.[4]

2.2.6 Half-cell Potential of Reinforcement

The surface of concrete was dampened at the contact points with water. The connection to reinforcement was made and tests which were carried out to ensure that reinforcement were electrically continuous with the negative terminal of the voltmeter. The half-cell potential was measured using a copper/copper sulfate electrode in accordance with the technique described in ASTM C 876-80.[5]

2.2.7 Reinforcement Corrosion Grade

Taken a partial reinforcement embedded in concrete, rust form and color were inspected and reinforcement corrosion grade was estimated in Table 3.

Table 3 Guide of reinforcement corrosion grade

Grade	Definition of grade & condition
1	No corrosion in all the reinforcement in concrete
2	Minor corrosion of reinforcement surface in concrete
3	Normal degree of rust or crack due to reinforcement corrosion at concrete surface

4	Thick expansion rust at reinforcement surface but slight spalling or reduction of cross section of concrete
5	Excessive expansion rust at reinforcement surface and significant reduction of reinforcement in concrete

3. RESULTS AND DISCUSSION

3.1 Visual Condition

Visual condition was accomplished especially considering cracks, spalling and rust staining. The extreme damage input into the database of computer brought the results shown in Fig. 1. 19 structures with 3 grade were 49% of all. These structures have no problem in common service, if they were repaired with suitable method. However, 5 structures with 4 grade were 13% of all, which were built in 1960s and 1970s, have little possibility to keep their service life even if they were repaired. 24 structures over 3 grade whose percentage was 62% were very slightly deteriorated and a countermeasure should urgently be accomplished. Structures with 4 visual condition grade have the spalling or the cracking of cover concrete caused by reinforcement corrosion. In those structures, deterioration rate would be rapidly increased. Such spalling or cracking has usually been followed by rust staining. Thus, in visual condition of structures, it was an important problem. However, the commonest cause of cracking was early thermal movement or shrinkage. The cracking can usually be minimized by careful detailing, design of concrete mix, and construction procedures.

Many freeway concrete viaducts have problem which is caused by poor drainage facility, pond water on deck slabs, and stain on substructure. It would be the major cause of rapid deterioration rate of freeway concrete viaducts. It should not be disregarded that the material of concrete is chosen because of its ability to resist water, low initial cost, and low maintenance cost. When concrete loses its watertightness in service, it becomes vulnerable to a variety of deterioration process. Generally, it is not lack of compressive strength but the lack of soundness that the cause of decreasing serviceability of concrete structures.[6] Therefore, designers and managers must recognize that moisture is critical to concrete durability, and that it is needed to be cautious about drainage, joining, and other design details to keep minimum of moisture content.

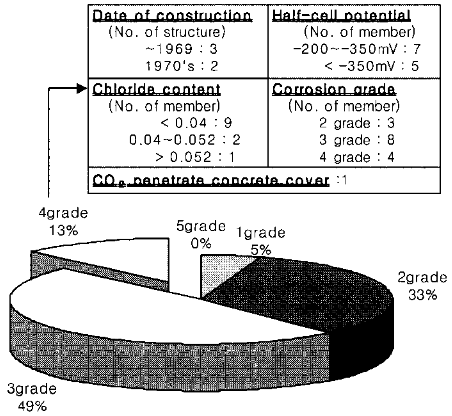

Fig. 1 Visual condition grade

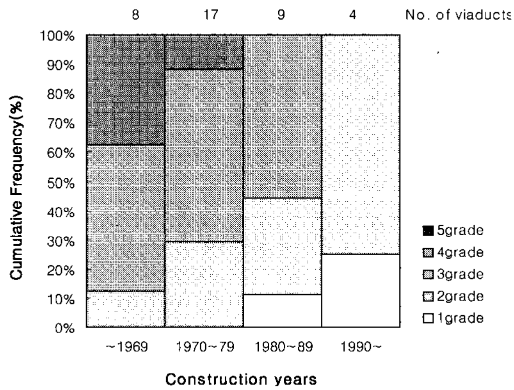

Fig. 2 Visual condition with construction years

The visual condition of studied freeway concrete viaducts with construction years is depicted in Fig. 2. Structures with the 4 visual inspection grade, assumed to be damaged a lot, were constructed in 1960s and 1970s. It can be seen that the structures were deteriorating as far back as 1970s. Thus, it can be concluded that the cause of deterioration of freeway concrete viaducts with 4 visual inspection grade was insufficient maintenance. The corresponding structures must be urgently repaired with a suitable method to eliminate the cause of deterioration.

3.2 Carbonation of Concrete

The comparison of carbonation depth and concrete cover depth is shown in Fig. 3. Carbonation depth is mainly distributed less than 10㎜ but some 10~40㎜ region. The result of carbonation depth relative to concrete cover is presented in Table 4. In 25%(38 readings) of studied structures, carbonation depth penetrates cover depth. Therefore, it is concluded that many concrete structures are deteriorated by carbonation of concrete. If the diameter of flexural reinforcement is supposed as 20㎜, there are 6 readings (5% of total) in which carbonation depth penetrates over lower part of reinforcement.

The regression analysis result of carbonation depth and square root time($\sqrt{t}$) is presented in Fig. 4. The regression model is 3.92 $\sqrt{t}$, which is 5% larger than 3.727 $\sqrt{t}$ by Kishitani's model(7) which is assumed water-binder ratio, R for 60%, 1, respectively. It is observed that carbonation of concrete progressed totally fast because of highly carbon dioxide concentration in air, gas by car, acid rain and so on. For this reason, consideration about concrete cover depth is more needed so that carbonation effects severely on reinforcement corrosion.[8] For concrete cover depth, the Korea Bridge Specification(KBS)'s requirement[9] is 25㎜ at the slabs in moderate weather, while CEB code's requirement[10] is 30 ㎜, Cnom = Cmin(25㎜) + tolerance(5~10㎜) considering durability design concept. More cover depth need to prevent deterioration by reinforcement corrosion.

Because service life was very sensive to cover depth, the 5㎜ differency between CEB and KBS can bring about over 10 years difference in service life prediction.

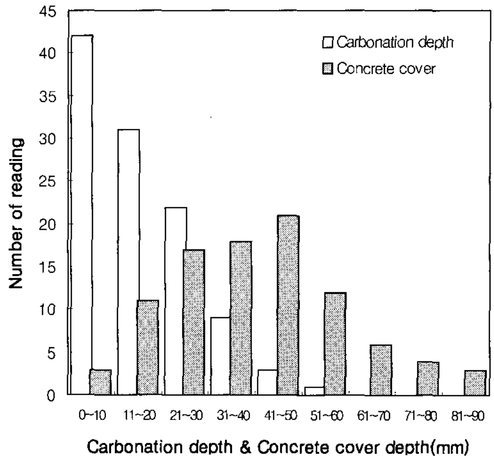

Fig. 3 comparison of carbonation depth and concrete cover depth

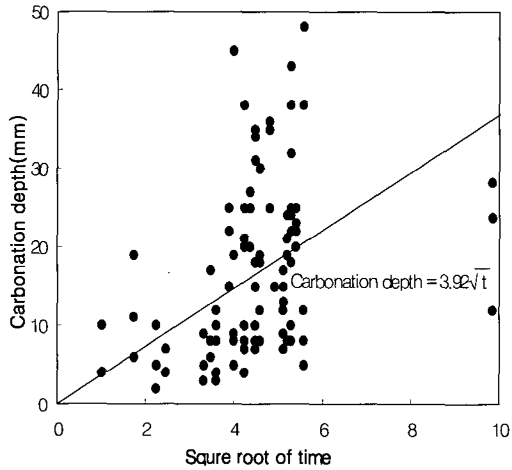

Fig. 4 Estimated carbonation rate with construction years

Table 4 Result of measured carbonation depth

Condition of carbonation depth	No. of readings (%)
Below concrete cover depth	95 (75%)
Over concrete cover depth	32 (25%)
Over concrete cover depth + 20㎜	6 (5%)

3.3 Chloride Concentration in Concrete

The free chloride ions had a most effect on reinforcement corrosion in concrete. The chloride concentration of in situ concrete structure was influenced by the quality of concrete, joint condition, traffic volume, service time, service environment, maintenance, and so on. The penetration of chloride and carbon dioxide was quickly increased when water-binder ratio was over 50%.[11] Consequently, the quality of in situ concrete should be more ensured.

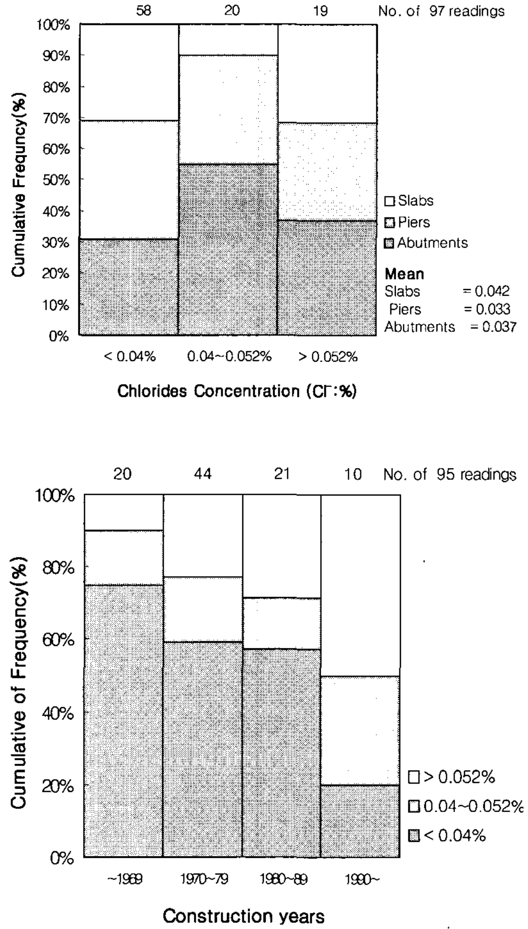

Fig. 6 Chloride concentration with construction years

The chloride concentration with members is shown in Fig. 5. It is seen that chloride concentration of concrete structure is very high. Many freeway concrete viaducts showed the trace of stain and water leakage due to poor inferiority of drain facilities. Especially the water leakage of joint accelerated the deterioration of freeway concrete viaducts. Thus, it is concluded that the quality of concrete structure was considerably influenced by joint conditions. The moisture content in concrete under service may lead to the deterioration of concrete structure. Consequently, designers and managers should consider reducing water content in drainage, joint and other facilities. The chloride concentration of freeway concrete viaducts in service time is presented in Fig. 6. The structures constructed in 1990s should be examined whether they are made of marine sand or not, because corresponded structures have highly chloride concentration in concrete.

Freeway concrete viaducts in Seoul metropolitan area are not safe for chloride concentration because 24% of total readings pass over 0.052% which is regarded as critical chloride concentration.

3.4 Half-cell Potential of Reinforcement

In Fig. 7, half-cell potential of reinforcement at abutments is lower than others. Half-cell potential for substructure such as the piers and the abutments is lower than the slabs. The distribution of half-cell potential with construction years is shown in Fig. 9. There is not below -350mV(vs. CSE) for freeway concrete viaducts constructed in 1990s while widely distributed 1980s. The half-cell potential for freeway concrete viaducts constructed before 1970s is shown below -200mV.

However, half-cell potential is measured 51% for -200~-350mV and 31% for below -350mV. Therefore, many concrete structures have latently dangerous elements for reinforcement corrosion. Occasionally, the trace of rust stain is shown on structures which are measured below

-350mV and this condition suggests that it has been a long time since the reinforcement corrosion initiates.

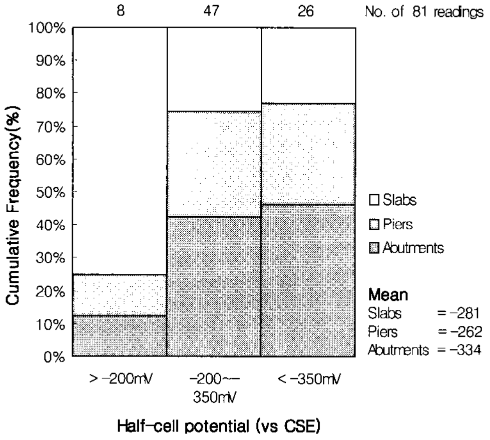

Fig. 7 Half-cell potential with members

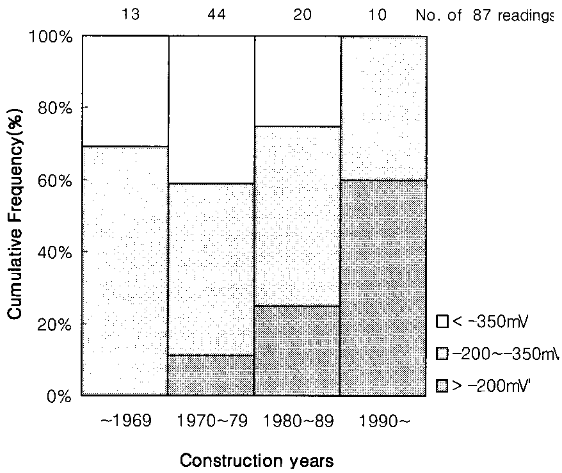

Fig. 8 Half-cell potentials with construction years

Fig. 9 depicts equipotential contour map about the bottom of the slab between No. 3 pier and No. 4 pier in moon-lae viaduct which is one of the investigated viaducts. The reinforcement corrosion is progressing from No. 4 pier to 7m, and the portion from 7m is passive condition. The reinforcement corrosion is in an active condition because the half-cell potential at portion from joint about 3m distance was -350mV~-550mV. However, reinforcement corrosion has just started since visual inspection doesn't represent clear stain of corrosion.

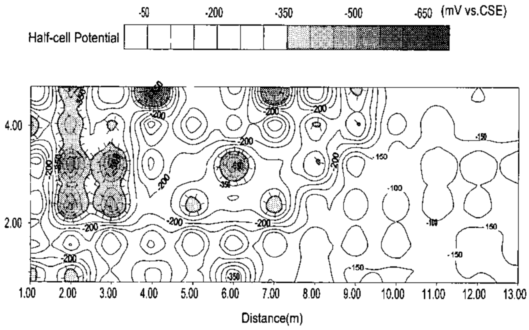

Fig. 9 Equipotential contour map at slab of Moon-lae viaduct

3.5 The Reinforcement Corrosion Grade

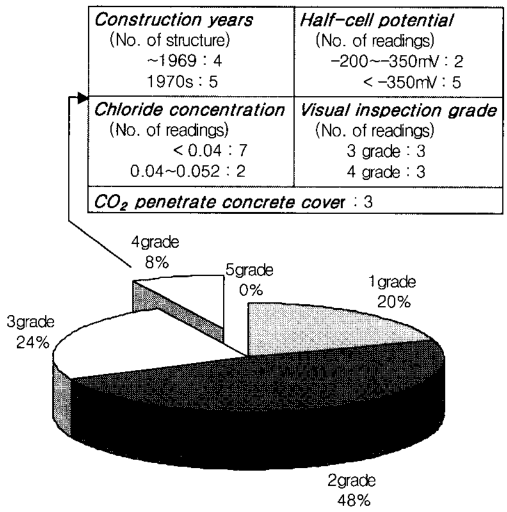

Fig. 10 Reinforcement corrosion grade

In Fig. 10, the reinforcement corrosion grade distributes from 1 grade with 23 readings(20% of total), 2 grade with 56 readings(48%), 3 grade with 28 readings(24%), 4 grade with 9 readings (8%), and 5 grade doesn't exist. It is concluded that freeway concrete viaducts with 4 grade need to be urgently repaired.

3.6 Comprehensive Analysis

The estimation of deterioration rate is not easy at situation in which chloride concentration is very high and carbonation depth progresses over cover depth. The reason is because the deterioration of concrete is related to carbonation, chloride binding capacity, free chloride concentration, the supply of oxygen, temperature, humidity, ohm resistance of cover concrete and so on. The chloride concentration can be corrode reinforcement in 0%~1% by cement weight.[(12)~(13)] The BRE(14) proposed that chloride concentration of 1.0% by cement weight could be a cause of reinforcement corrosion at situation which carbonation depth does not penetrate to reinforcement.

To depict the condition in which chloride and CO_2 attack simultaneously, Fig. 11 shows corrosion risk which is associated with carbonation depth / cover depth ratio, acceptable chloride concentrations and critical chloride concentrations. In most structures, the durability hazard degree is low or moderate.

The Fig. 12 represents the occasion of corrosion of members which were measured less than -350mV of the half-cell potential, more than 0.04% of chloride concentration, and carbonation depth reaches the cover depth and poorly visual condition. It is concluded that chloride ions from de-icing salt and marine sand is cause of reinforcement corrosion.

Generally, the corrosion propagation period is 2~5 year in the U.S.A.[(15)], while 10 years in Denmark[(16)]. Thus, it could be that rapid corrosion rate by synergy effect due to simultaneous injurious action. Accorded structures must be taken careful maintenance and management. The literatures proposed that 10~25% section loss of reinforcement can cause danger in service, while serious corrosion current density has been assumed more than 1.0 μA/cm².[(17)~(18)]

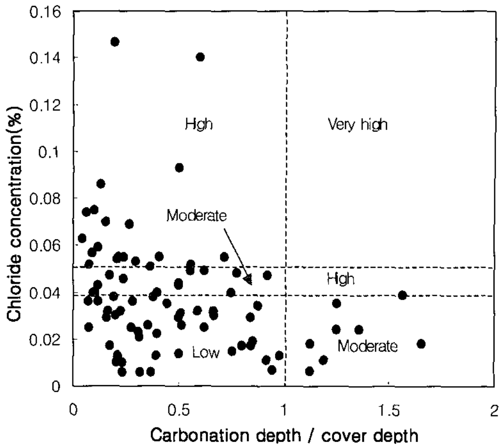

Fig. 11 Corrosion risk from relation between chloride concentration and carbonation depth / cover depth

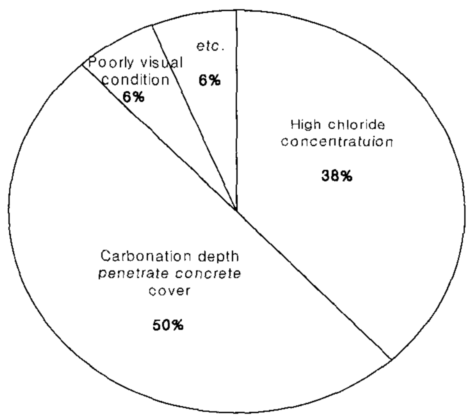

Fig. 12 Estimated cause of reinforcement corrosion

In the early stage of deterioration, a damage is not always distinct on the surface of concrete. Until chloride or carbonation depth does not penetrate to reinforcement, the surface of concrete keeps fine visual condition. However, if reinforcement occurs corrosion, it can be the cause of crack, spalling, and rust stain. The pitting corrosion of reinforcement is the most noticeable form which is appeared in reinforcement corrosion caused by chloride. If simultaneous deterioration such as chloride, carbonation of concrete, and acid attack acts, it must be more dangerous because synergy effect may be occurred.

In the results, this paper is very effective to comprehend the durability condition of freeway concrete viaducts in Seoul metropolitan area. However, the comprehensive analysis by quantitative research must be performed to predict service life and to form relationship between datums.

4. CONCLUSIONS

The conclusion of this paper on the durability of 39 viaducts in Seoul metropolitan area is following.

(1) The number of structures which CO2 penetrate to reinforcement is 32 readings.(25% of total) The model of carbonation rate is induced to 3.92 $\sqrt{t}$, which is 5% faster than 3.727 $\sqrt{t}$ assumed 60% water-cement ratio, R=1 in that of kishitani.

(2) The chloride concentration is high and highly estimated in the slabs than others. The 24% readings more than 0.052% chloride concentration which causes the corrosion of reinforcement must need to be repaired against chloride.

(3) The 26 readings(31% of total) measured below -350mV(vs. CSE) half-cell potential with more than 90% corrosion probability and accorded structures widely exist before 1980s. The structures over 3 reinforcement corrosion grade which need urgently repair are 32% of total.

(4) The causes of reinforcement corrosion of freeway concrete viaducts in Seoul metropolitan area are chloride(50% of total) and carbonation of concrete(38% of total) respectively.

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REFERENCES

1. ACI Building Code 318/318R-36
2. A.M. Neville (1997) Maintenance and Durability of Concrete, *Concrete International*, November
3. E.J. Wallbank (1989), The Performance of Concrete in Bridges, London, Her Majesty's Stationery Office
4. RILEM Draft Recommendation CPC-18 (1988), Measurement of Hardened Concrete Carbonation Depth, Materials and Structures, Vol.21, No.126, pp.453-455.
5. ASTM C 876 (1993), Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Reinforcement in Concrete, V 04.32, S4, pp.626-629.
6. P.K. Mehta (1997), Durability - Critical Issues for the Future, *Concrete International*, July
7. K. Kishitani (1964), Über die Beständigkeit von Stahlbeton unter dem Einfluß von CO2, Zement-Gips, Nr.4, S.158-159.
8. C.S. Lee, and I.S. Yoon (1999), An Investigation on Performance of Durability for Concrete Bridges in Seoul Metropolitan area, *Proceedings of KSCE*
9. Department of Construction and Transportation of Korea (1996), The Korea Bridge Specification
10. CEB Bulletin 238 (1997), New Approach to Durability Design
11. I.S. Yoon (1998), Reinforcement Corrosion Behavior according to Accelerating Experiment, Master of Science, Dissertation, University of Seoul
12. H. Grube, E. Kern and H.P. Quitmann (1990), Instandhaltung von Betonbauwer-

ken, Betonkalender, Ernst & Sohn
13. RILEM Report 12 (1995), Performance Criteria for Concrete Durability, E & FN SPON
14. Building Research Establishment (1982), The Durability of reinforcement in Concrete : Part 2. Diagnosis and Assessment of Corrosion - Cracked Concrete Digest 264
15. P.D. Cady & R.E. Weyers (1984), Deterioration Rates of Concrete Bridge Decks, Journal of Transportation, Vol.110, pp.35-44
16. M.R. Geiker, C. Henriksen, N. Thaulow (1993), Design for Durability : A Case Story, Concrete 2000 Vol.1, E & F N SPON, pp.63-70
17. Comité Euro-International du Béton (1983), Assessment of Concrete Structures and Design Proceedings for Up grading, Bulletin d'information, No.162.
18. J.P. Broomfield (1997), Corrosion of Reinforcement in Concrete, E & F N SPON
19. ACI Committee 201, Guide for Making a Condition Survey of Concrete in Service
20. ACI Committee 222, Corrosion of Metals in Concrete