1. Introduction

In Japan, cast-in-place concrete poles started to be used in 1922, and were also adopted by the railways. In 1934 poles began to be factory made using centrifugal-molding. Then, since the cabinet (government) decision on timber supply and demand measures in 1951, the railways started to use concrete poles as catenary masts [1]. Although reinforced concrete poles (RC poles) were installed initially, in the 1960s these were gradually replaced by prestressed concrete poles (PC poles). After the 1970s most newly installed poles were PC poles. Concrete poles have been used as catenary poles on a wide scale for over 50 years; therefore, there is now a desire to determine criteria and standards that can be used to plan their replacement according to level of deterioration.

Concrete poles for electric railways are load-supporting members which support overhead contact lines and their fittings, etc., and their required mechanical strength is determined in consideration of the load which in turn depends on in-service conditions. To determine during maintenance whether a pole needs to be replaced due to deterioration it is important to be able to estimate its retained strength. Concrete catenary poles have been used on the railways on a wide scale for over 50 years. Therefore, there is a desire to determine criteria and standards that can be used to plan their replacement according to level of deterioration. This paper clarifies the main deterioration processes affecting concrete poles based on the results of field surveys on commercial lines, and bending and material tests on disused poles. This paper also proposes a method to determine whether a pole needs to be replaced or not.

Keywords: electric railway, pole, replacement, concrete, maintenance, strength, deterioration

2. Performance of concrete pole

Concrete catenary poles for electric railways are load-supporting members which support overhead contact lines and their fittings, etc., and their required mechanical strength is determined in consideration of the load which in turn depends on in-service conditions. To determine during maintenance whether a pole needs to be replaced due to deterioration it is important to be able to estimate its retained strength. Concrete catenary poles have been used on the railways on a wide scale for over 50 years. Therefore, there is a desire to determine criteria and standards that can be used to plan their replacement according to level of deterioration. This paper clarifies the main deterioration processes affecting concrete poles based on the results of field surveys on commercial lines, and bending and material tests on disused poles. This paper also proposes a method to determine whether a pole needs to be replaced or not.

Figure 1 shows an example of a cross-section diagram of a pole. Concrete is weak against tensile loads and is resistant to compressive loads; therefore, concrete mainly bears compressive strength. It also protects internal steel bars from corrosion. In complement, steel bars bear mainly tensile strength against which concrete is weak.

The criterion of mechanical strength for concrete catenary poles is described in the Approved Model Specifications related to Article 41 of “Ministerial Ordinance to Provide Technical Regulatory Standards on Japanese Railways” [2] which prescribes that the safety factor of the concrete pole shall be not less than two with respect to the breaking load. Further, JIS A 5373 [3] prescribes that the concrete poles should withstand twice the load of a crack test bending moment. For these reasons, concrete pole design adopted takes into consideration a crack test bending moment which exceeds the maximum. Since the crack test bending moment is called the “design bending moment” in the design of overhead contact line structures, it is also referred to in the same way in this paper.

3. Field survey of concrete poles on commercial lines

In order to research the deterioration of concrete catenary poles (hereinafter referred to as “pole”), field sur-
veys on commercial lines were conducted. A total of 475 poles with an age span of 1 to 56 years were surveyed. Figure 2 shows the age distribution of the surveyed poles. The survey was focused on lines that had poles with the most obvious ageing and which were scheduled for replacement, which, depending on the operator in question, were either along coastal areas or inland areas. For this reason, the predicted replacement rate of deteriorated poles in the survey was higher than what would be expected in a broader inspection, but this was not considered to be a problem since the evaluation was on the safe side.

Figure 3 shows the ratio of deteriorated poles observed in each pole age group. Figure 4 shows the ratio of deteriorated poles against the total number of the surveyed poles, 475. The most frequent type of pole damage was “crack around formwork joint”, which was observed in approximately 40 % of poles. The number of observed cases of “vertical crack,” “efflorescence,” “detachment,” “detachment and exposed steel bar,” “exposed steel bar (insufficient covering)” and “horizontal crack” came first, second, third, fourth, fifth and sixth, respectively. Figure 5 shows some examples of pole deterioration. Each deterioration is described below in descending order of number of observed cases.

1. Crack around formwork joint
2. Vertical crack
3. Efflorescence
4. Detachment
5. Detachment and exposed steel bar
6. Exposed steel bar (insufficient cover concrete)
7. Horizontal crack

In order to evaluate the bending strength of the poles, a bending strength test was conducted in the poles removed from these commercial lines [5].

1. Specimens and test method

A total number of 475 poles aged between 33 and 54 years were provided for the test. The bending strength tests were conducted according to JIS A 5363 [6]. Figure 6 illustrates how the poles were secured, by fixing at the bottom.
(1) Specimens and test method

Lead to corrosion. Needed, since if carbonation reaches the steel bars it can reduce pole strength, caution is needed. Although the strong alkaline properties of concrete at the time of manufacture are lost due to the influence of carbon dioxide, and other similar substances, in the atmosphere. Although this phenomenon does not reduce pole strength, caution is needed, since if carbonation reaches the steel bars it can lead to corrosion.

(2) Test results

The predominant failure mode was the cover concrete collapsing on the compressed side and bending failure due to buckling of the steel rebar.

Figure 7 shows the relationship between the age of the pole and the ratio of the failure bending moment $M_f$ to the design bending moment $M_d$ ($M_f / M_d$). In Fig. 7, the test poles are classified into three groups as follows:

- Nothing in particular: pole in which no deterioration was observed
- Deteriorated: pole in which deterioration was observed
- Repaired: repaired pole

Figure 7 indicates that values of $M_f / M_d$ in all the test poles were larger than two, which is the criterion value. There was no tendency for strength to decrease with age. Regarding the average values of $M_f / M_d$ for each category, “Not particular” was 2.96 (2.74 to 3.52), “Deteriorated” was 2.66 (2.19 to 3.49), and “Repaired” was 2.85 (2.62 to 2.97). This means that the average values for “Deteriorated” and “Repaired” were lower than for “Nothing in particular.”

5. Material property tests on removed poles

In order to investigate the degree of material deterioration in each type pole, material property tests were conducted.

5.1 Carbonation depth

The carbonation of concrete is a phenomenon where the strong alkaline properties of concrete at the time of manufacture are lost due to the influence of carbon dioxide, and other similar substances, in the atmosphere. Although this phenomenon does not reduce pole strength, caution is needed, since if carbonation reaches the steel bars it can lead to corrosion.

(1) Specimens and test method

A total number of 60 poles aged 33 to 54 years was used. The number of poles in each test was as follows:

- 10 poles: bending test (destructive part)
- 15 poles: steel bar investigation
- 35 poles: inspected for carbonation

Phenolphthalein solution was sprayed on the part of the pole to be examined and areas with no red-purple coloring were considered to have undergone carbonation.

(2) Test results

Figure 8 shows the relationship between the age of the pole and carbonation depth. Only one pole aged 52 years, had a carbonation depth of 5 mm, whereas other poles had a carbonation depth of less than 1 mm. Figure 8 also shows predicted results using a carbonation progression model [4]. The prediction results show that the water-cement ratio ($W/C$) greatly influences carbonation, and where the water-cement ratio is 40 % or less, there is almost no carbonation. Compared with common civil engineering structure concrete ($W/C$ 50 - 60 %), the $W/C$ in poles is low; the design ratio is approximately 35 % whereas the actual ratio is approximately 22 - 23 % [4]. Most measured values were under 1 mm, regardless of age.

5.2 Chloride ion

Chloride ion may permeate concrete after construction due to ambient salt from the sea, or be present in concrete due to the manufacturing process. This paper focuses on the former. When chloride ion concentration around a steel bar exceeds a certain threshold due to permeation this makes the steel bar susceptible to corrosion. This type of steel bar corrosion, crack due to cubic expansion of the corroded part, detachment of cover concrete, etc. are called “salt attack damage” [7].

(1) Specimens

Three poles were provided for these tests, from areas relatively close to the coast, with the cracks around their formwork joints.

- Pole No. 1: erected in the Higashi-Kaizuka station yard, approximately 2.2 km from the coast, 45 years of age.
- Pole No. 2: erected between Shioya station – Tarumi station, approximately 50 m from the coast, 51 years of age.
- Pole No. 3: erected in the Ichiki station yard, approximately 1.2 km from the coast, and 43 years of age.

(2) Test method

The concentration of chloride ions was determined using ion chromatography according to the method described in JIS A 1154 [8]. Samples were collected from under the surface of each pole every 5 mm with a twist drill. The samples from each pole were collected from parts in sound condition where no deterioration had been observed, and from cracked formwork joints.
(3) Test result

Figure 9 shows the measured concentrations of chloride ions. The regression curve of the measured values by Fick’s diffusion equation is also shown in Fig. 9. Since the diffusion equation can only be applied where crack has occurred, a regression curve was adopted for the parts in sound condition. The chloride ion concentration \( C(x,t) \) [kg/m^3] for age \( t \) [year] at depth \( x \) [mm] from the pole surface is expressed by the following equation [7].

\[
C(x,t) = C_0 \left( 1 - \text{erf} \left( \frac{x}{2 \sqrt{D_{ap} t}} \right) \right)
\]

(1)

where \( C_0 \) : Chloride ion concentration at the surface [kg/m^3]

\( D_{ap} \) : Apparent diffusion coefficient of chloride ion [mm^2/year]

\( \text{erf} \) : Error function

The values of \( D_{ap} \) identified from the regression curve expressed by (1) were 0.10, 0.07, and 0.07 mm^2/year for the poles No. 1, No. 2, and No. 3, respectively. For \( C_0 \), 2.5 kg/m^3 [7] was adopted which corresponds to the value obtained at 100 m from the coast. The predictions for permeation of chloride ions are shown in Fig. 10. Predictions for an age of 100 showed that the chloride ion concentration around the steel bars would not exceed 1.2 kg/m^3 [7] which is the value at which steel bars tend to corrode. This therefore confirmed that, although chloride ions permeate the concrete, problems related to salt attack damage did not occur in parts in sound condition.

Where cracks have appeared however, steel bar corrosion is likely to occur regardless of the chloride ion concentration. In two out of three poles with cracks around the formwork joints chloride permeated to the steel bar. Hence, in areas close to the coast, early action to prevent crack would be effective to prevent steel bar corrosion.

5.3 Steel bar investigation

The covering concrete on poles was removed to examine the steel bars inside. A total of 15 test poles were investigated. Figure 11 shows that there was no deterioration, corrosion did not occur on the steel bars. The results of this examination however confirmed that in cracked poles the steel bars directly beneath the damage endured corrosion; corrosion elsewhere however, was only slight.

6. Examination of maintenance procedures

6.1 Predominant concrete pole deterioration mode

Field surveys on commercial lines revealed that apart from “Crack around formwork joints”, “Vertical crack” was most frequent. Cracks have been classified here into the following three types [9]:

(1) Crack preceded by steel bar corrosion

Crack due to the cubical expansion of a steel bar corroded by carbonation, chloride ions, etc.

(2) Spontaneous cracking

Crack due to drying shrinkage etc. at first, followed by material deterioration, such as steel bar rod corrosion, which occurs because of the crack.

(3) Crack due to deterioration

Crack due to deterioration of the concrete material itself, such as an alkali-silica reaction.

Results from field surveys and material property tests indicate that carbonation and chloride ion permeation in poles progresses very slowly compared with other common civil engineering structures. Although one pole was found with cracks due to an alkali-silica reaction, no information on this type of case was found in the literature [4]; it can therefore be assumed that cracks observed in the remaining poles were due to other factors. The conclusion drawn from these results was that almost all the crack found in poles was of the “spontaneous” type.

Regarding “vertical cracks,” another factor considered to be a major cause of this type of crack, aside from shrinkage from drying and temperature fissuring, is the formation of voids inside the poles during manufacturing. Moreover, it can be assumed that “efflorescence” and “detachment and exposure of steel bars” appear after vertical crack, since in the field surveys, this type of damaged was frequently observed after “vertical crack” had been observed in poles.

6.2 Residual mechanical strength of concrete poles

Six poles were modified for bending strength tests: three were modified to create covering concrete detach-
have a high tolerance to carbonation and permeation of chloride ions. In material evaluation it is possible to measure the water-cement ratio to determine the level of tolerance to carbonation and permeation of chloride ion. This is difficult to measure however in poles on a commercial line. A suitable method was therefore devised for determining the water-cement ratio by measuring the carbonation depth.

Several methods exist to measure carbonation depth, namely using a drill, or concrete core cutting, etc. However, it is important to minimize damage when taking measurements, since poles are bearing members. Measurements showed that the carbonation depth was approximately 1 mm whereas the thickness of the covering concrete was approximately 15 mm, this means that the pole surface investigation to a depth of 1 mm must be accurate. The drilling method was examined. Commercially available impact drills only have a maximum cutting depth which is greater than 1 mm because the tip forms an acute angle and it is difficult to make a steady cut to the required depth each time. Therefore, as shown in Fig. 13, a specially designed drill was developed for “carbonation testing,” with a flat tip and stopper to adjust the depth of the cut. Phenolphthalein solution is sprayed onto the area being examined, and if it turns a reddish-purple it is considered that carbonation has not commenced. The specially designed drill can be used to accurately cut into the surface of the pole to a depth of approximately 1 mm. For poles displaying a carbonation depth in excess of 1 mm, a detailed inspection is required because material deterioration is suspected. The characteristics of the drill are that it offers “high judgment accuracy,” “no need for post-inspection treatment,” “good portability,” and “is little different from human judgement.”

Based on these research results, a procedure was developed to assess whether a concrete catenary pole needs to be replaced, as shown in Fig. 14.

(1) Since the predominant deterioration mode of concrete poles is “spontaneous crack,” visual inspections are carried out.

(2) In cases where no deterioration is detected, the material is evaluated to detect carbonation, using the specially designed drill.

(3) If deterioration is observed, the strength of the pole is evaluated according to the “strength evaluation sheet,” which shows the relationship between the

![Fig. 13 Equipment for carbonation testing](image)

6.4 Procedure to determine whether a concrete catenary pole needs to be replaced

Concrete poles are manufactured by centrifugal molding and have a low water-cement ratio ($W/C$), they therefore
7. Conclusions

Clarification was obtained to identify the predominant deterioration mode affecting concrete catenary poles through field surveys. Bending and material tests were conducted on poles removed for replacement. A procedure was then proposed to determine whether a pole needs to be replaced or not. The results of this study can be summarized as follows:

1. Results from a field survey of 475 poles on commercial lines, showed that the most frequent type of damage to poles was “crack around formwork joints.” Other forms of damage observed, in order of frequency were: “vertical crack,” “efflorescence,” “detachment,” “detachment and exposed steel bars,” “exposed steel bars (insufficient covering)” and “horizontal crack.”

2. Bending strength test results showed that the ratio of the breaking bending moment to the design bending moment of all the test poles was larger than two, which is the criterion value. There was no tendency for strength to falter with age.

3. Carbonation progression and permeation of chloride ions in the poles was very slow compared with other common civil engineering structures.

4. It was found that the predominant deterioration mode of poles was “spontaneous crack,” where crack occurred first, followed by the deterioration of materials, such as steel bar rod corrosion, and other consequences of crack.

5. A procedure was proposed to assess the need to replace a concrete pole. Since the predominant deterioration process was “spontaneous crack,” visual inspections are carried out first. When there is no visible deterioration, the material is evaluated using the specially designed drill “for carbonation testing.” If visible deterioration is found, strength is evaluated using the “strength evaluation sheet.” If the residual strength is lower than the required value, the pole has to be replaced or reinforced.

Acknowledgement

The authors would like to express their sincere gratitude to staff at the Kyushu Japan Railway Company and the West Japan Railway Company, for their active involvement in field tests.

References

[1] Railway Electrification Committee of Japan, “Concrete pole handbook,” 1958 (in Japanese).
[2] Railway Bureau, Ministry of Land, Infrastructure, Transport and Tourism of Japan, “Ministerial Ordinance to Provide Technical Regulatory Standards on Japanese Railways,” 2012.
[3] Japanese Industrial Standard, “JIS A 5373 Precast prestressed concrete products,” 2016 (in Japanese).
[4] Ueda, H., Kudo, T., and Sasaki, T., “Deterioration Diagnosis and Maintenance of Concrete Poles,” RTRI Report, Vol. 18, No. 10, pp. 3-8, 2004 (in Japanese).
[5] Tsunemoto, M., Shimizu, M., Kondo, Y., and Yokouchi, K., “Flexural Strength Evaluation of Deteriorated Concrete Pole,” J-RAIL2016, No. S2-1-5, 2016 (in Japanese).
[6] Japanese Industrial Standard, “JIS A 5363 Precast concrete products – General rules for methods of performance test,” 2016 (in Japanese).
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[7] Japan Society of Civil Engineers, “Standard specifications for concrete structures-2013, Maintenance,” 2013 (in Japanese).
[8] Japanese Industrial Standard, “JIS A 1154 Methods of test for chloride ion content in hardened concrete,” 2012 (in Japanese).
[9] Japan Concrete Institute, “Concrete diagnostic techniques,” 2016 (in Japanese).
[10] Miura, I., “Breaking Bending Moment PC Piles Axially Loaded,” Cement and concrete, No. 293, pp. 25-32, July 1971 (in Japanese).