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Post Peak Behavior of Carbonated Concrete Structure - A Case Study of the Former Shime Mining Office Vertical Derrick in Japan

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Abstract. *This paper is a report on the investigation results of the Former Shime Mining Office Vertical Derrick, which was built in 1943 and was 75 years old at the time of the investigation. The building suffered from serious deterioration including rebar corrosion, which led to large area of concrete spalling. In this report, aggregation data of concrete spalling has been presented along with the investigation results of cover thickness. According to the investigation results, concrete spalling occurred in places where cover thickness was less than 25 mm. And According to the aggregation data, concrete spalling flakes increased by approximately 200 pieces per year, with the average size of 10 cm in diameter. Also, a possible relation between concrete spalling and rainfall was observed during the investigation. Equations using the proportion of wet area affected by rainfall to estimate the area of spalling are proposed, although the value of empirical coefficient* α *needs further discussion, including collecting data from other buildings where spalling occurs.*

Keywords: *Durability, Historical Buildings, Concrete Spalling, Concrete Moisture, Rebar Corrosion.*

1 Introduction

Concrete moisture is known to be a key parameter of rebar corrosion which leads to spalling and deterioration of the concrete structure. While reports on evolution of water content in real structures are still scarce, This paper is a report on the investigation results of the Former Shime Mining Office Vertical Derrick, which was 75 years old at the time of the investigation and had suffered from severe deterioration including rebar corrosion, which led to large area of concrete spalling. In addition, a possible relation between concrete spalling and rainfall was observed.

The introduction and the photo of the Former Shime Mining Office Vertical Derrick are shown in Table 1 and Figure 1.

2 Approach

To monitor the inner relative humidity evolution where the concrete cover was thin, from June 1st to July 25th, 2018, several thermo-hygrometers were implanted inside the concrete with cover thickness of 10mm and 40 mm. Concrete spalling had been observed and calculated every 3 months since February 2011. Cover thickness was measured with an electromagnetic radar method or a scale according to the condition of the cover.

Table 1. Introduction of the Former Shime Mining Office Vertical Derrick.

Location	Shime town, Fukuoka	Structure	RC
Owner	Shime town	Completion	May, 1943
Size (m)	height	47.6	
	length	15.3	
	width	12.3	

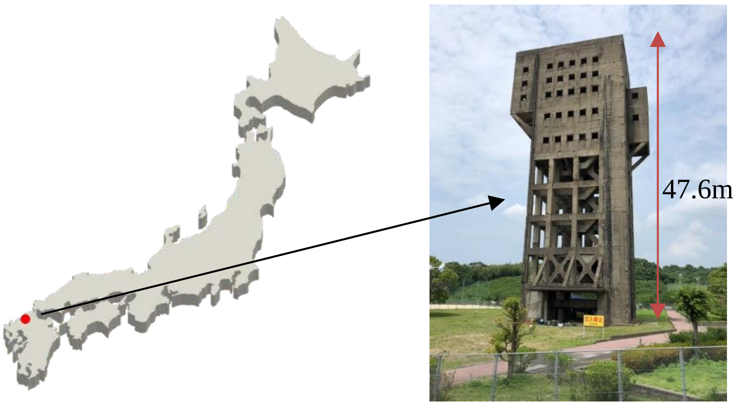

Figure 1. Photo of the Former Shime Mining Office Vertical Derrick.

3 Results

3.1 Results of Relative Humidity Monitoring

The results of relative humidity and temperature monitored during June 1st to July 25th, 2018, along with precipitation observed by Japan Meteorological Agency are shown in Figure 2. These results indicate that places with thinner cover thickness tend to be influenced by weather events such as rain.

3.2 Results of Concrete Spalling and Cover Thickness

Concrete spalling had been observed every 3 months since February 2011. The Figures used below are based on the observation record. Figure 3 shows the accumulated number of concrete flakes, which increased by the rate of approximately 200 pieces per year. However, the influence of weather events or earthquake was still unclear. Figure 5 shows the size and numbers of the flakes, which are around 5~10 cm in diameter. In addition, cover thickness and level of rebar corrosion in relation to concrete spalling were also investigated. The subjects investigated included pillars and beams of 4 directions from 1st floor to 3rd floor. The aggregated results of cover thickness by are shown in Figure 6. According to the results, rebar exposure induced by concrete spalling occurred when cover thickness was less than 25 mm.

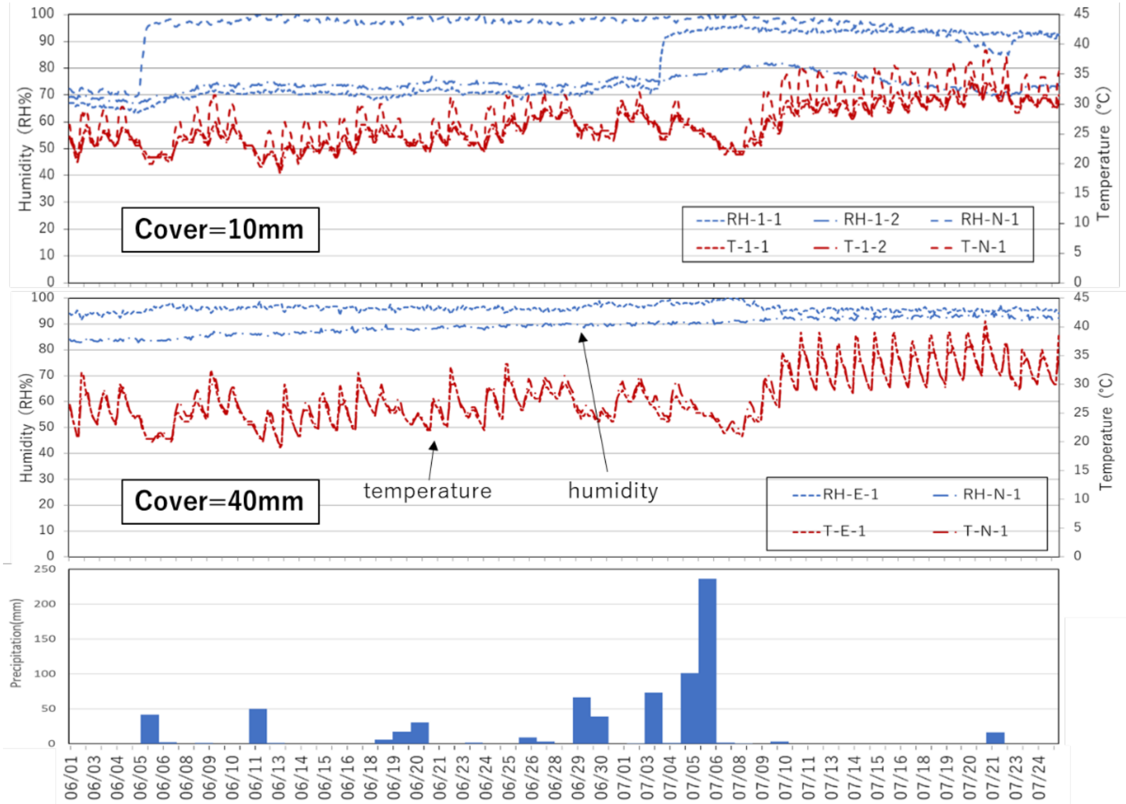

Figure 2. Evolution of Relative Humidity and Temperature (Upper: Cover=10mm, Middle: Cover=40mm) and Precipitation.

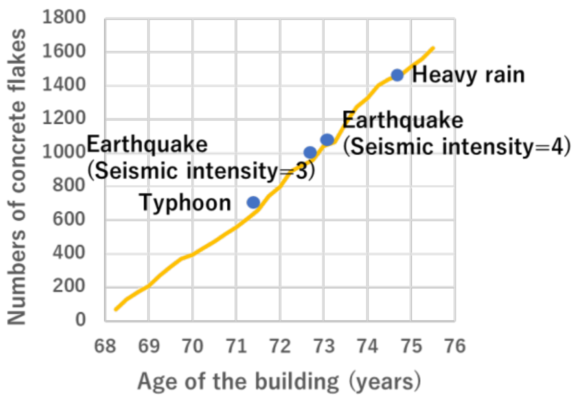

Figure 3. Accumulated number of concrete flakes.

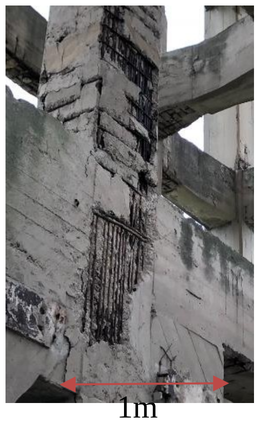

Figure 4. Rebar exposure due to spalling.

3.3 Results of Air Permeability Test and Carbonation

The results of the relation between the coefficient of carbonation and the coefficient of air permeability are shown in figure 7, along with previous investigation results of other buildings. The coefficient of carbonation is calculated by $C/\sqrt{t}$, where C stands for the depth of carbonation and t stands for years of use. The depth of carbonation is measured by applying phenolphthalein solution to concrete cores following the instructions in JIS A 1152. The coefficient of air permeability is calculated by the Torrent method (double chamber method). According to previous investigations, the coefficient of air permeability increases when the coefficient of carbonation increases. According to Figure 5, the results Vertical Derrick are within the range of previous results.

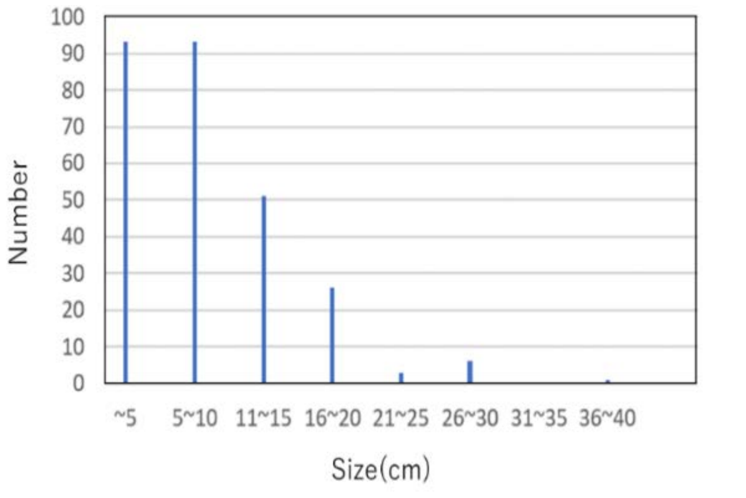

Figure 5. Size of concrete flakes.

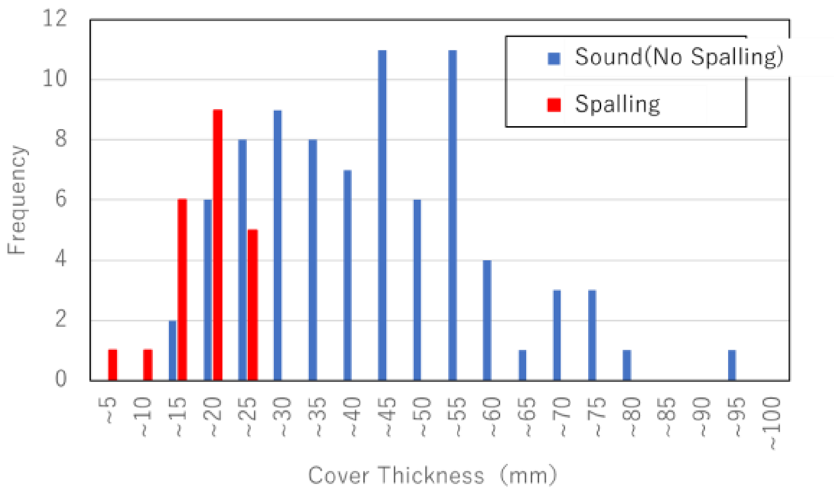

Figure 6. Cover thickness and rebar expose. (Tomotaka Ide, 2019)

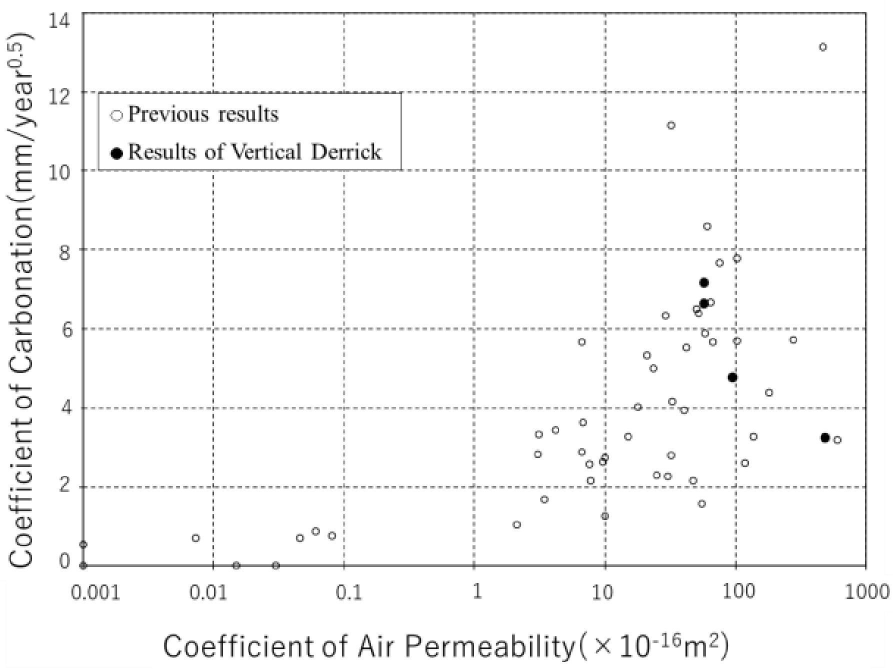

Figure 7. Relation between coefficient of air permeability and coefficient of carbonation. (Akio Tanaka; Kei-ichi Imomoto, 2013).

4 Discussion

4.1 Flying Distance of Flakes

Figure 8 shows the number and horizontal flying distance of flakes of each direction. According to Figure 8, concrete flakes mostly fell within the 7 meters range from the building. The height of the building was 47 meters. For the flying distance of 7 meters, the falling degree was 21.7° and the horizontal flying distance was 0.15 times the height of the building. Concrete flakes that fell out of this range needs further discussion concerning the windswept condition of this location. Table 2 shows the percentage of the spalling area of each direction. According to Table 2, the percentages of spalling area are between 5~10%.

Table 2. Spalling percentage of each direction. (spalling/total area of each side of the wall).

West	South	North	East
9.91%	5.20%	9.35%	3.71%

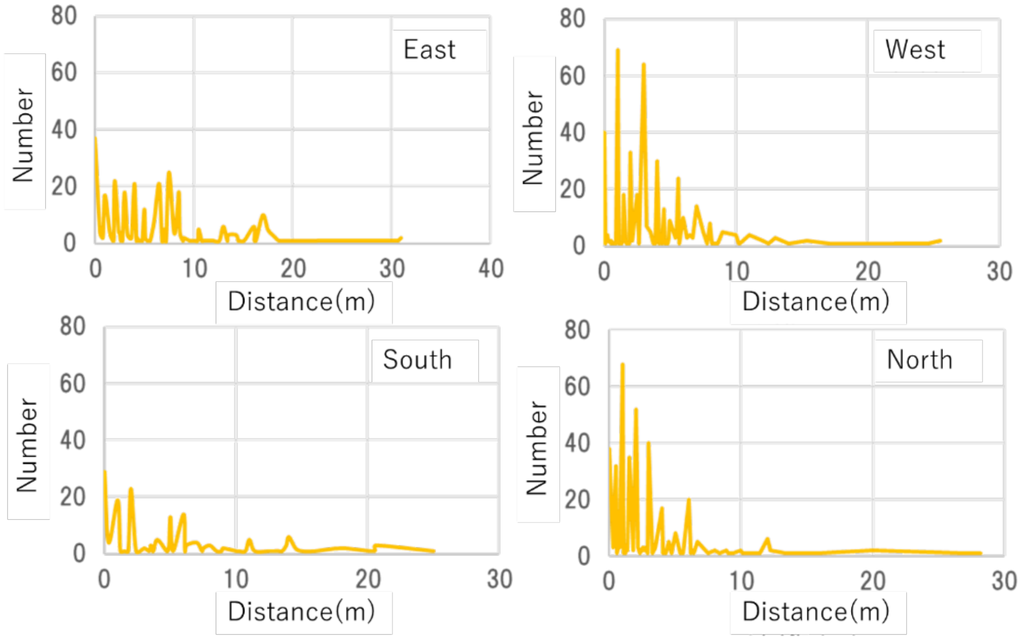

Figure 8. Number and horizontal flying distance of concrete flakes.

4.2 The Relation between Rainfall and Spalling

Figure 9 shows the percentage of wet area after rainfall. The percentages were calculated by wet /total area of each side of the wall. The calculation of wet areas from photos involved the image processing software, ImageJ. By circling the target areas, ImageJ automatically calculated the pixels of the selected areas. The manual selection of the wet areas brought an uncertainty to the results. To increase accuracy, image processing method should be further discussed in future researches. According to the results, the north and the west side with higher number of concrete flakes also showed higher percentage of the wet area. At this location, due to northwest wind blew throughout the year, the north and the west side of the building were more possible to be affected by rainfall than the south and the east side. This observation indicates that there might be a relation between spalling and rainfall. The following equations are proposed considering the relation between the two.

$$\textit{Coefficient of Rainfall} = \textit{Percentage of Wet Area} \times \textit{Number of Days with Precipitation over 10mm} \quad (1)$$

$$\textit{Percentage of Spalling Area} = \textit{Years after Carbonation reaches 25mm} \times \textit{Coefficient of Rainfall} \times \textit{Percentage of Cover Thickness Less than 25mm} \times \alpha \quad (2)$$

Table 3 shows the results of the *Coefficient of Rainfall* and the empirical coefficient α by applying equation (1) and (2) to the north and the south side. When the value of α is 0.006, according to the *Coefficient of Rainfall* in Table 3, the estimated values of spalling area along with measured spalling area are shown in Table 4.

Table 3. Results of the coefficient of rainfall and the empirical coefficient α of the south and the north side.

	South	North
Coefficient of Rainfall	1.231	4.537
α	0.0062	0.0012

West, 78% wet   South, 19% wet   North, 70% wet   East, 36% wet

Figure 9. Percentage of wet area (wet/total area of each side) after rainfall.

Table 4. The estimated value and measured value of spalling area of the east and the west side.

Percentage of Spalling Area	East	West
Estimated Value	3.63%	5.45%
Measured Value	3.71%	9.91%

5 Conclusions

Post peak behaviors of carbonated concrete structures are as follows.

- Concrete spalling flakes increased by the rate of 200 pieces per year while the influence of climate events was still unclear. The sizes of the flakes were around 10 cm in diameter.
- The horizontal flying distance of concrete flakes were approximately 0.15 times the height of the building.
- The sides of the walls with higher proportion of concrete spalling also present higher proportion of wet area during rainfall.

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