Examination of exfoliation mechanism in tunnel lining joints

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Deformation of a tunnel lining is caused by external and internal factors, which may also result in the partial exfoliation of concrete lining. To reduce this type of exfoliation risk, it is necessary to shed light on the mechanism of exfoliation phenomenon, which, however, has yet to be done because of the use of plain concrete for concrete lining. In this study, the authors focus on the eluviation of calcium hydroxide in concrete, collected concrete cores from a sound part and a damaged part of a tunnel lining that had served for 40 years, and measured the amount of calcium hydroxide and calcium carbonate contained in the cores collected. As a result, the damaged part with water leakage was found to be experiencing the eluviation of calcium hydroxide. Based on the experiment results obtained, the authors propose the exfoliation process of concrete pieces activated by eluviation of calcium hydroxide in concrete lining.

1. Introduction

The longer the service life of a tunnel, the more often its concrete lining suffers partial exfoliation. For example, there have been several reports on the incidents of partial exfoliation from construction joints in concrete lining[1)]. Because the exfoliation of concrete pieces is an operational risk, when it occurs, the repair costs, compensation for an accident resulting in injury or death or any other expenses incurred as a result could mean a huge loss to the tunnel administrator. To reduce the risk of concrete exfoliation, it is necessary to shed light on the exfoliation mechanism and develop a prediction technique.

In this study, the authors formed a hypothesis about the concrete exfoliation mechanism. Figure 1 outlines the hypothesis, which holds that a concrete lining starts experiencing concrete exfoliation as it undergoes the following continuing and progressive phases:

Phase 1: Calcium hydroxide is eluviated[2)3)4)] by water infiltrating from ground through concrete lining cracks created by certain unknown causes.

Phase 2: The eluviation of calcium hydroxide makes the vicinity of cracks porous, which further accelerates cracking.

Based on this hypothesis, the authors focused on the eluviation of calcium hydroxide in the concrete lining of road tunnels. The amount of calcium hydroxide and calcium carbonate in a sound part

Photo.1 Exfoliation of concrete on inner lining

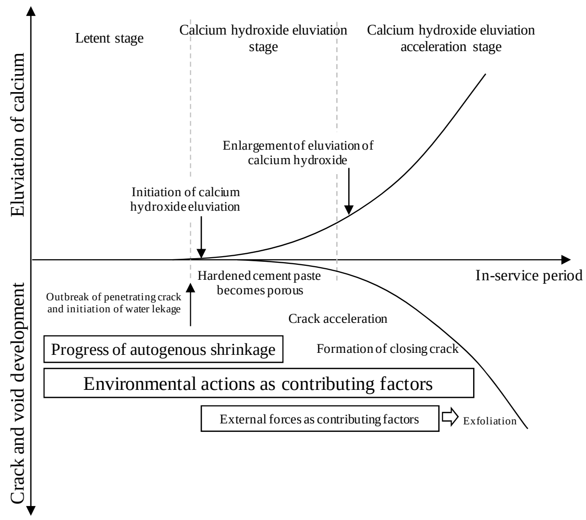

Fig.1 Eluviation of calcium hydroxide and crack development

(i.e. without any damage such as cracking) and a damaged part (i.e. with penetration cracks causing water leakage) were measured and compared to study the difference, which clearly showed the eluviation phenomenon of calcium hydroxide.

2. Calcium hydroxide eluviation theory and deterioration of concrete lining

2.1 Calcium hydroxide eluviation theory and progress of concrete lining deterioration

In this study, the "eluviation of hydrates" means a phenomenon where hydrates in concrete dissolve into soft water, causing the concrete formation to become coarser."[5] The calcium hydrate in cement paste is largely consisted of calcium hydroxide and calcium silicate hydrate,[6] as outlined in Fig.2.[7] According to Minagawa, et al,[8] calcium hydroxide undergoes calcium eluviation before calcium silicate hydrate does, as outlined in Fig.3. When calcium hydroxide disappears from cement paste, calcium silicate hydrate dissolves as shown in Eq.1, and new calcium hydroxide is generated inside the voids. When calcium hydroxide dissolves from calcium silicate hydrate and the calcium concentration in cement paste is reduced, calcium silicate hydrate undergoes rapid decomposition and forms Silicagel.

This chemical reaction theory is applied to the case of concrete lining. Based on a number of past exfoliation case examples and exfoliation observation data, an assumption was made that damage to a concrete lining would be accelerated in a manner shown in Fig.4. Because construction joints in a tunnel lining involve more complicated execution processes than other parts of the lining, they are prone to inherent quality variations and defects, such as cavities and micro cracks. Draining channels, which discharge groundwater from ground, are often provided in construction joints, which often reduces the lining thickness locally. In many cases, it is found that these minor defects eventually develop into penetration cracks and cause water inflow. This objective evidence indicates that construction joints are greatly affected by the eluviation of calcium hydroxide caused by groundwater inflow.

3. Verification test on calcium hydroxide eluviation in concrete lining

3.1 Overview of the tunnel and cores collected

Concrete cores were collected for analyisis from the concrete lining of a road tunnel that had served 40 years. Table 1 describes the tunnel. Two types of concrete cores were analyzed: concrete cores ol-

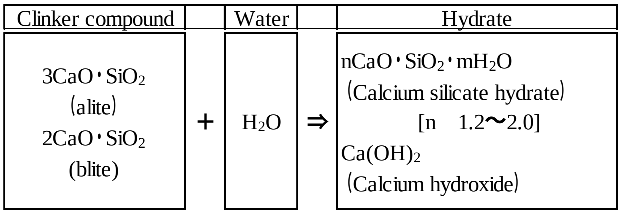

Fig.2 Cement components [7]

$$xCaO \cdot SiO_2 \cdot (x+0.8)\,H_2O \rightarrow (x-y)CaO \cdot SiO_2 \cdot (x-y+0.8)\,H_2O + yCa(OH)_2 \quad \text{(Eq.1)}$$

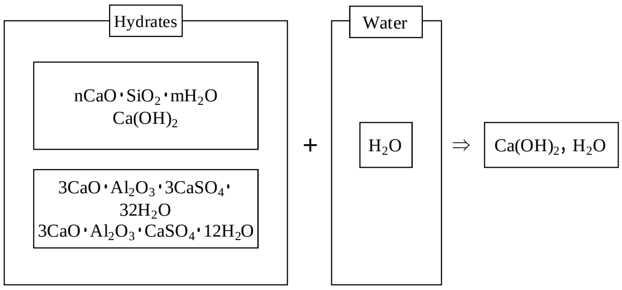

Fig.3 Dissolution of hydrates

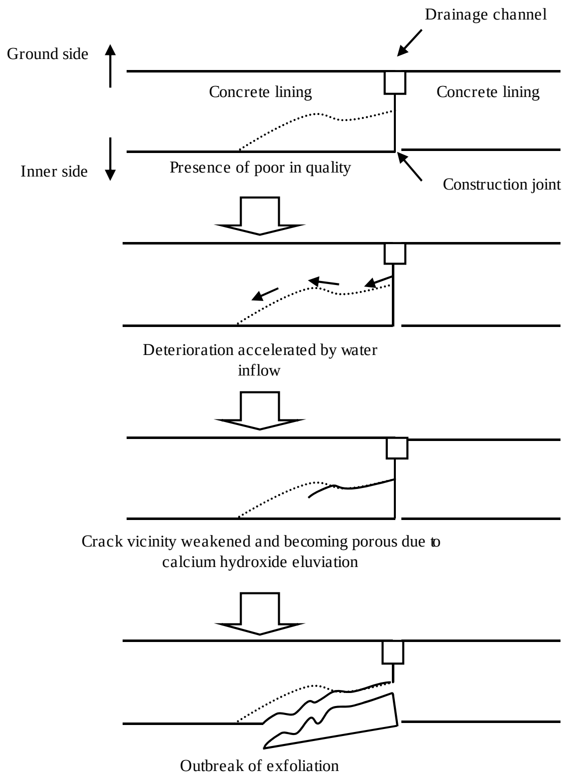

Fig.4 Exfoliation process of lining concrete

Table.1 Outline of the tunnel

Tunnel type	Road tunnel
Year completed	1957
Lining thickness	Arch 45cm
Ventilation	JF Mechanical ventilation (vertical)
Design speed	50km/h
Traffic configuration	Two lanes
Tunnel length	1220m
Geological condition (West side)	Schist (140m, highly to moderate weathering)
Geological condition (East side)	Granite (120m, highly to moderate weathering)

lected from a part without any damage such as cracking (hereinafter, the "sound cores") and those collected from a part suffering penetration cracking and water leakage (hereinafter, the "damaged cores"). Photos 2 and 3 show the sound cores and damaged cores, respectively. The former showed no sign of progressive neutralization while the latter had progressive neutralization on the crack surfaces.

3.2 Analysis method

Differential thermogravimetric analysis (hereinafter, the "DTG analysis") was employed. The samples used for the DTG analysis consisted of the sound cores, namely A1, A2, A3 and A4 collected from a part without any neutralization (Photo.2), and the damaged cores, namely B1, B2, B3 and B4 from a part undergoing neutralization along cracks (Photo.3).

Platinum was used for a sample cell, and the analysis condition was established with a programming rate of 20 degrees Celsius/min and a target temperature of 1,000 degrees Celsius. The analysis temperature was set at 400 to 500 degrees Celsius and 600 to 800 degrees Celsius for calcium hydroxide and calcium carbonate, respectively. The amount of each component was obtained by mol conversion[9], as shown in Equations 2, 3, and 4.

Calcium hydroxide content(mg)

$$=X\times(Ca(OH)_2)/(H_2O)=W \quad \text{(Eq.2)}$$

where,

X: Mass decrease (mg)

$Ca(OH)_2$: Molecular weight of the calcium hydroxide

H_2O: Molecular weight of water

Calcium carbonate content(mg)

$$=X\times(CaCO_2)/(CO_2)=W \quad \text{(Eq.3)}$$

where,

X: Mass decrease (mg)

Ca CO_2: Molecular weight of the calcium carbonate

CO_2: Molecular weight of the carbon dioxide

$$\text{Content percentage}(\%)=(W/I)\times 100 \quad \text{(Eq.4)}$$

where,

W: Calcium hydroxide content (mg)

Calcium carbonate content (mg)

I: Initial sample mass (mg)

4. Results of DTG analysis and considerations

Figures 5 and 6 show the results of DTG analysis on the sound cores and damaged cores, respectively.

Photo.2 DTG Analysis sample collection locations for the sound cores

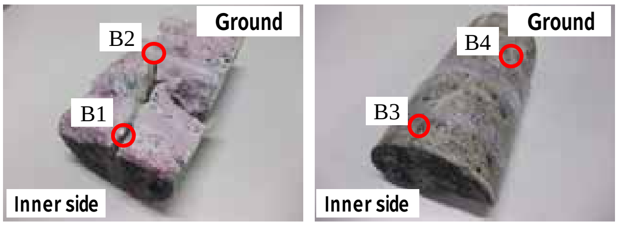

Photo.3 DTG Analysis sample collection locations for the damaged cores

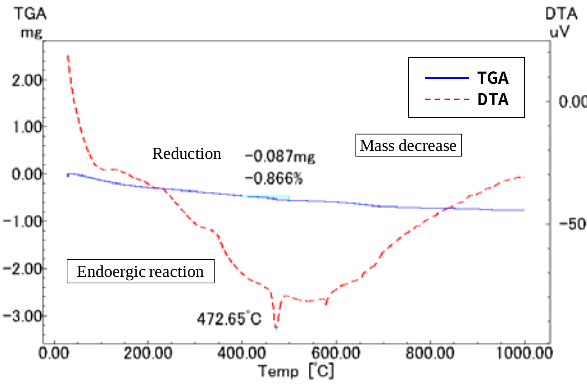

Fig.5 Example of DTG analysis results for the sound cores (A2)

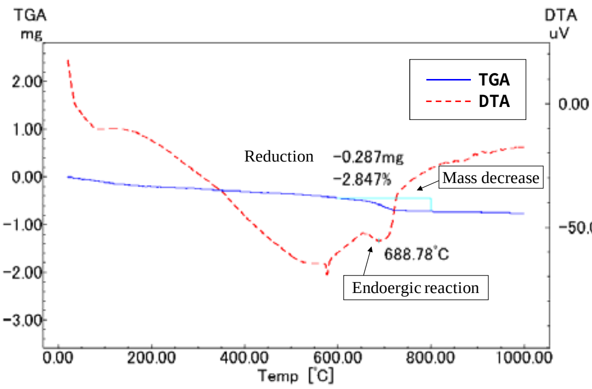

Fig.6 Example of DTG analysis results for the damaged cores (B2)

Tables 2 and 3 and Tables 4 and 5 show the amountof calcium hydroxide and calcium carbonate with endoergic reaction temperature for the sound cores and damaged cores, respectively. As seen from Fig.5, the sound cores show an endoergic reaction temperature of approximately 470 degrees Celsius with the confirmed existence of calcium hydroxide, an observation which was common to all the samples, i.e. A1, A2, A3 and A4. On the other hand, as seen from Fig.6, there was no sign of an endoergic reaction between 400 and 500 degrees Celsius in the damaged cores, which then underwent an endoergic reaction between 600 to 800 degrees Celsius with the confirmed existence of calcium carbonate. This was common to all the samples, i.e. B1, B2, B3 and B4.

These results show that at least the damaged cores with water leakage were experiencing the eluviation of calcium hydroxide. Generally speaking, the eluviation of calcium hydroxide produces many apertures, which accelerates crack development in concrete.

5. Conclusions

The tests on cores collected from a concrete lining that had served for 40 years confirmed the eluviation of calcium hydroxide in concrete with water leakage. It is assumed that when calcium hydroxide underdoes eluviation, the hardened cement paste in concrete becomes porous and the cracking process accelerated, causing the partial exfoliation of concrete. These results, however, do not constitute the necessary and sufficient condition to prove the hypothesis about concrete lining deterioration caused by calcium hydroxide eluviation. Other contributing factors are also assumed to be at work, such as the autogenous shrinkage of concrete, environmental actions, and external forces such as earthquake.

The authors are planning to develop test specimens to simulate tunnel linings to quantitatively identify the level of calcium hydroxide eluviation and impacts of contributing factors.

Table.2 Calcium hydroxide content (sound cores)

Sample code \ Result	Endoergic reaction temperature (℃)	Initial sample mass (mg)	Calcium hydroxide: Contained amount (mg) / Content percentage (%)
A1	474.15	10.07	0.23 / 2.32
A2	472.65	10.05	0.19 / 1.84
A3	472.72	10.02	0.20 / 1.97
A4	468.42	10.03	0.12 / 1.23
Median			1.84

Table.3 Calcium carbonate content (sound cores)

Sample code \ Result	Endoergic reaction temperature (℃)	Initial sample mass (mg)	Calcium hydroxide: Contained amount (mg) / Content percentage (%)
A1	577.37	10.07	0.29 / 2.91
A2	577.91	10.05	0.28 / 2.81
A3	577.56	10.02	0.40 / 4.02
A4	577.45	10.03	0.26 / 2.62
Median			3.09

Table.4 Calcium hydroxide content (damaged cores)

Sample code \ Result	Endoergic reaction temperature (℃)	Initial sample mass (mg)	Calcium hydroxide: Contained amount (mg) / Content percentage (%)
B1	449.90	10.08	0.11 / 1.06
B2	450.44	10.00	0.23 / 2.34
B3	451.41	10.05	0.22 / 2.17
B4	450.59	10.09	0.20 / 1.99
Median			1.89

Table.5 Calcium carbonate content (damaged cores)

Sample code \ Result	Endoergic reaction temperature (℃)	Initial sample mass (mg)	Calcium hydroxide: Contained amount (mg) / Content percentage (%)
B1	688.78	10.08	0.65 / 6.48
B2	729.80	10.00	1.31 / 13.05
B3	705.15	10.05	0.79 / 7.85
B4	692.91	10.09	0.50 / 4.96
Median			8.08

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