Influence of superficial hygrothermal conditions on long-term deformation of RC & PC structures under natural environments

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1. Introduction.

Long-term deformation of RC & PC structures due to excessive shrinkage and creep is an important issue on assessments for structural serviceability. Nowadays, time-dependent deformation of concrete can be predicted through hygrothermal analysis [1] combined with mechanical analysis [2]. Following these, experimental verifications have been performed with concrete under assumptions of average environments [3], as well as monitored environments [4][5]. Furthermore, deformation behavior of concrete at long-terms has been reported for concrete structures with surfaces under different superficial drying-swelling conditions (superficial hygrothermability) by computing drying shrinkage [6]. However, the effect of superficial hygrothermal conditions on time dependent effects has not plenteous experimental studies yet, and its study is important to fathom on the long-term deformation phenomena.

The main objective of this study is to verify through experimental work, the time-dependent deflection of various types of concrete members having surfaces with different drying-swelling conditions to clarify the effect of superficial hygrothermability on prediction of long-term deformation behavior of concrete structures.

2. Experimental Study.

Reinforced (RC) and prestressed (PC) slabs were selected for this study and various types of specimens, varying its surfaces sealing conditions, were exposed to natural environmental conditions under a sustained load.

2.1 Specimen details.

RC and PC slabs with 100 mm (height)×300 mm (width)×3900 mm(length) of geometry, were adopted for this experiment, as it is described in **Fig. 1a**. RC slabs were fabricated with 4 reinforcement bars of 10mm of diameter and PC slabs with two PC rods of 11mm of diameter, both located in an effective height of 75 mm. Slabs were casted using the concrete mix of **Table 1** and cured for 28 days. The casted concrete was tested through a compression test, resulting in a compression strength (f_c) of 38.4 N/mm^2 and an elastic modulus (E_c) of 30400 N/mm^2. PC rods of each slab were post-tensioned with 10 kN after 25 days of specimens curing.

The cross sections of specimens used in this study are illustrated in **Fig. 1bcde** and the details of each specimen are listed up as follows:

- RC-W: RC slab with its lateral surfaces sealed and, upper and bottom surface open to drying-swelling (**Fig 1b**).
- RC-S: RC slab with its upper and lateral surfaces sealed, and bottom surface non-sealed (**Fig 1c**).
- PC-W: PC slab with its lateral surfaces sealed and, upper and bottom surface open to drying-swelling (**Fig 1d**).
- PC-S: PC slab with its upper and lateral surfaces sealed, and bottom surface non-sealed (**Fig 1e**).

The purpose of these specimens is to observe the difference of time-dependent deflection behavior through variation of superficial drying-swelling conditions, at two categories of concrete structures. Furthermore, 4 prismatic specimen with dimensions of 100 mm (height) × 300 mm (width) × 100 mm(length) were built, where 2 of these were sealed as specimens RC-W and PC-W, and other 2 as RC-S and PC-S, representing a volumetric portion of each slab with same sealing conditions, to observe the difference of drying-swelling behavior by measuring its weight change.

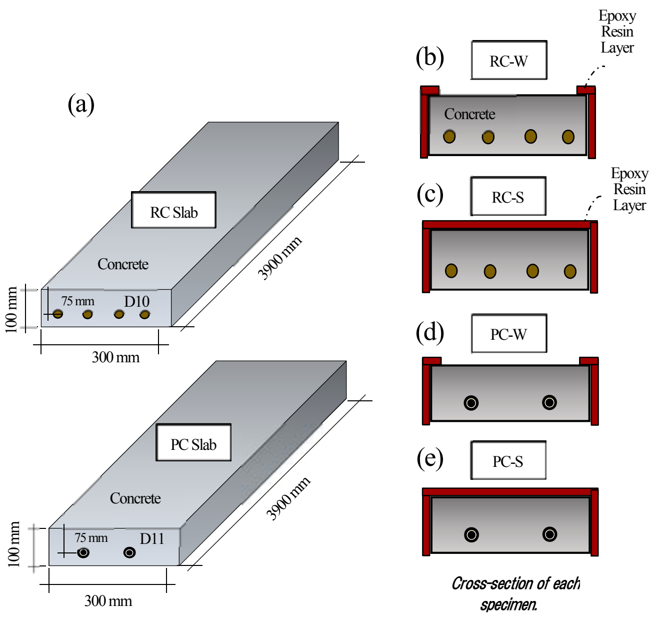

Fig. 1: Specimen dimensions and seal conditions details.

Table 1: Concrete mix proportion used.

W/C (%)	S/A (%)	Air (%)	Unit Weight (kg/m^3)				
			W	C	S	G	Ad
50	50	5	170	340	888	891	C×0.5%

Symbol	Details
W	City water
C	Ordinary Portland Cement, density of 3.16g/cm^3
S	Sand from Tokamachi-Nagaoka city, density of 2.64g/cm^3
G	Gravel from Tokamachi-Nagaoka city, density of 2.65g/cm^3
Ad	High performance AE water reducing agent - SP8HU

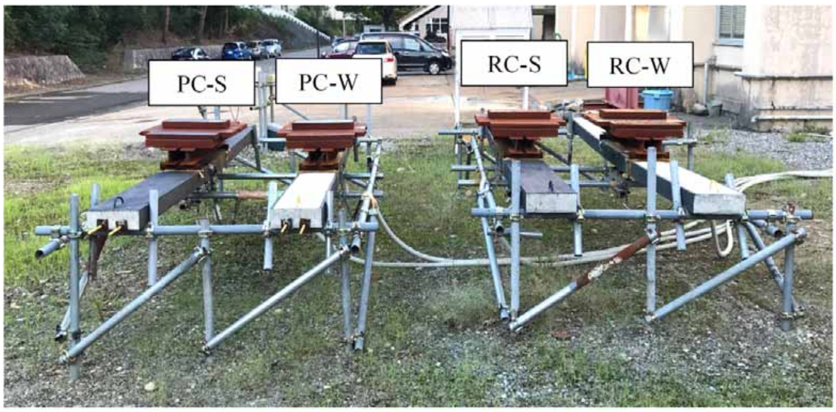

Fig. 2: Exposure test installed at campus of Nagaoka University of Technology

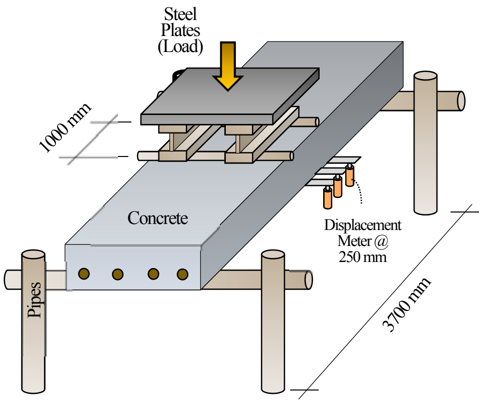

Fig. 3: Exposure-load test layout.

Fig. 4: Weather station located at exposure test site.

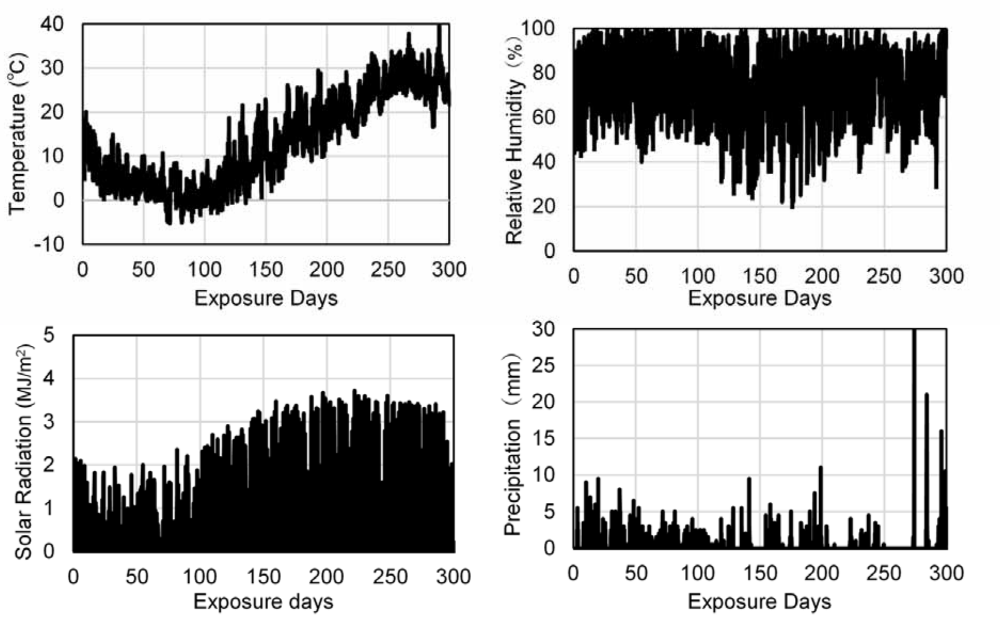

Fig. 5: Measurement results of temperature, relative humidity, global solar radiation and precipitation.

2.2 Exposure-loading test procedure.

RC & PC slabs and prismatic specimens were installed during winter, at campus of Nagaoka University of Technology, as it is shown in **Fig. 2**. The exposure began with no load by November 4th, 2017 and loading was applied 36 days later, by December 10th of same year.

The exposure-load test setting was carried out following the diagram of **Fig. 3.** The carrier frame was created using steel pipes to create simple supports with span of 3700 mm. Loading of 4.1 kN was applied at 2 points symmetrically centered on slab with interval of 1000mm, causing flexural cracks in RC slabs. The deflection was measured by displacement meters, located in 3 positions at bottom surface of the slab; one centered at the mid span position and the rest separated from this, at intervals of 250 mm.

The prismatic specimens were exposed next to the slabs, with no loading and its weight was measured at intervals of 1 week.

The environmental conditions of temperature, relative humidity, global solar radiation and precipitation were measured, utilizing a weather station (**Fig. 4**) located near of specimen set, at intervals of one hour.

Currently, the present exposure-loading test is still going on, gathering measurements.

3. Results & discussion.

Measurements results were summarized for 300 days of exposure. The results of environmental conditions are illustrated in **Fig. 5.**

The results of weight change of prismatic specimens with sealing conditions of RC-W and PC-W (series WLW), and specimens with sealing conditions of RC-S and PC-S (series WLS) were averaged, converted in volumetric units of concrete and plotted in Fig **6**. These results shown for all specimens, a weight increments due to swelling on the first 80 days and weight loss due to drying on rest of exposure time. Observing these, it was confirmed that rate of weight change is greater in series WLW than WLS. Hence, the increase of rate of concrete drying-swelling with the increasing of non-sealed surfaces, was confirmed. Additionally, the specimens sealed as WLW can be estimated to be more dried in nearest layers to bottom and upper surfaces, than layers located at center of cross section due to drying-swelling is allowed in bottom surface and upper surface and restrained on its lateral surfaces. Moreover, the specimens sealed as WLS can be estimated to be more dried in layers near to the bottom surface than layers near to upper surface due to drying-swelling process is allowed in bottom surface and restrained on rest of its surfaces. From these observations and given that drying-swelling process promotes shrinkage [2][7], it can be inferred that rate of drying shrinkage on concrete increases with the increasing of non-sealed surfaces. Subsequently, drying shrinkage is expected to be greater in nearest layers to bottom-upper surfaces than layers located at center of cross section of specimens sealed as WLW, and greater in nearest layers to bottom than upper surfaces of specimens sealed as WLS.

On the other hand, the deflections at mid span of RC and PC slabs are plotted in **Fig. 7** and **Fig. 8**, respectively. These results exhibited a smaller change of deflection on the first 80 days, and greater increases of deflections on rest of exposure period, for all slabs. From results of **Fig. 7**, it was observed that deflection magnitudes of RC-W are greater than RC-S. Also, from results of **Fig. 8**, it was observed that magnitudes of PC-W are greater than PC-S. Based on this, the increase of time-dependent deflection with the increasing of non-sealed surfaces, on RC slabs as well as PC slabs, was confirmed. This difference of deflection magnitudes occurs due to the difference of each specimen rate of drying-swelling observed in results of **Fig. 6**, promoting shrinkage and drying creep in similar proportions, and due to these deformations on slab caused from shrinkage and creep are restrained by reinforcement steel and supports, excessive tensile stresses are developed, affecting curvature as well as deflections at each cross-section of the slab.

Also, through comparing **Fig. 7** and **Fig. 8**, the increase of time-dependent deflection was observed greater in PC slabs than RC slabs and this difference is expected to occur due to the creep effect being greater in PC slabs than RC slabs.

Therefore, following above experimental observations, it can be concluded that rate of long-term deformation is affected by the number of non-sealed surfaces.

4. Numerical approach.

4.1 Numerical algorithm

Numerical analysis of this study was performed according to the method of Toru Shiga [5] coupled it with next assumptions:

1) Drying-swelling allowed in non-sealed surfaces and its displacement in 2 normal directions to the cross sections.
2) Stress analysis of PC slabs based on the composite model of Obata [2], with a creep function assumed equal for aggregate and cement paste at all cross section.
3) Stress analysis of RC slabs after flexural cracks occurred, considering compression stress and creep as 1), and tensile stress with average stress between cracks, based on the tension stiffening model of Okamura [9], with creep effect neglected.

Basing above assumptions, the slabs were discretizing into portions where numerical simulation is schematized in **Fig. 9.** The applied models quantify the shrinkage distribution at each cross-section through calculation of moisture transport as well as volumetric change [7]. With shrinkage distribution, stress analysis [2][9] is carried out computing the curvature and deflections at each cross section of the slab. Computations were performed in time steps of 1 hour, where measurements from whether station of temperature, relative humidity, global solar

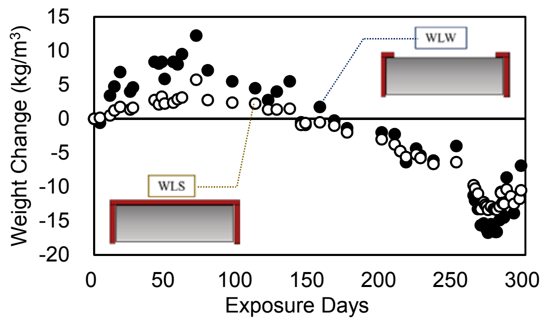

Fig. 6: Comparison of weight change measured of series WLW and WLS.

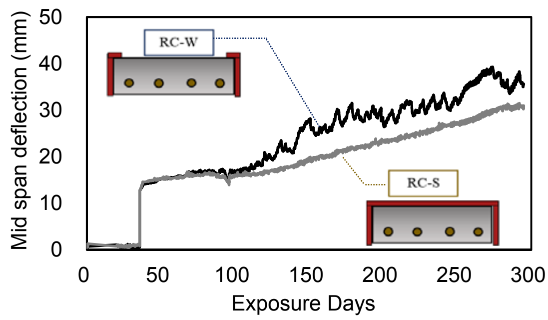

Fig. 7: Comparison of RC slabs deflections measured.

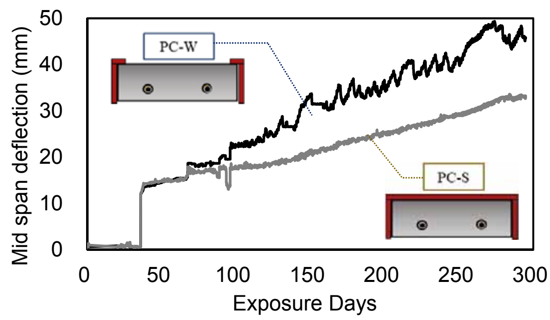

Fig. 8: Comparison PC slabs deflections measured.

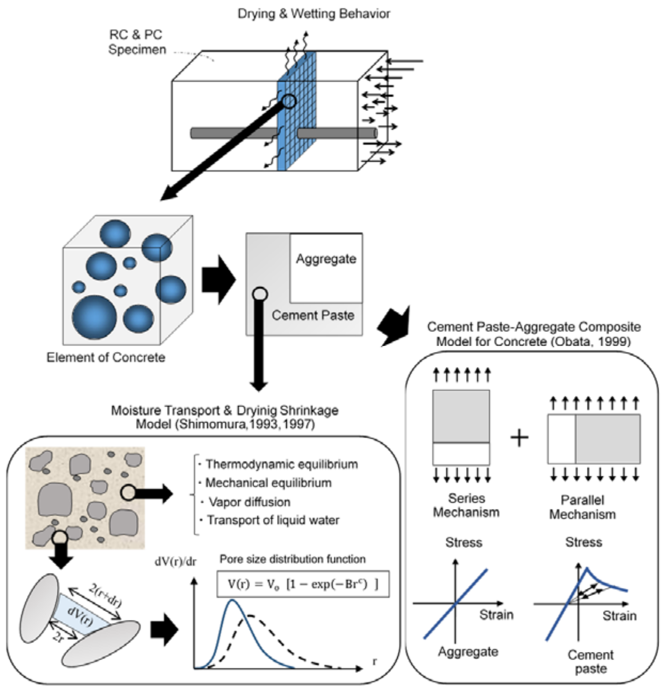

Fig. 9: Outline of computational model employed for hygrothermal and stress analysis.

radiation and precipitation were inputted in hygrothermal analysis to consider the change of environmental conditions.

4.2 Comparison of analytical & experimental results.

Numerical computations of time dependent deflections of RC and PC slab, at each sealing conditions, were plotted against the experimental data, in **Fig. 10** and **Fig. 11**, respectively. Observing these results, it was confirmed that computation models can describe the tendency of time-dependent deflection of each specimen, considering shrinkage distribution at cross section, creep, its sealing conditions as well as environment conditions.

Overestimation from computation models of time-dependent deflection can be observed in results of RC slab in **Fig. 10**, due to creep is considered for compression stress but neglected in tensile stress calculations. On the other hand, it was observed from results of **Fig. 11** that computational models can simulate the time-dependent deflection of PC slabs. Furthermore, the computational models presented a greater fluctuation of time dependent deflection, on results of RCW and PCW, than those of RCS and PCS due to the fact that sealed surfaces affect drying-swelling rate of hygrothermal analysis, estimating greater magnitudes of differential shrinkage and creep at cross section, as the non-sealed surfaces increase.

5. Conclusions.

A long-term exposure-loading test performed for RC and PC slabs having surfaces with different drying-swelling conditions, summarized for 300 days. The conclusions earned from this work are summarized as:

1) The effects of superficial hygrothermal conditions on long-term deformation for RC and PC slabs was experimentally confirmed, and it was concluded that time-dependent deflection increases with the increasing of non-sealed surfaces due to surfaces being opened to drying-swelling increases the rate of drying shrinkage and creep.
2) A numerical approach to predict long-term deflections through considering the superficial hygrothermability of concrete member, was verified.

Acknowlegments.

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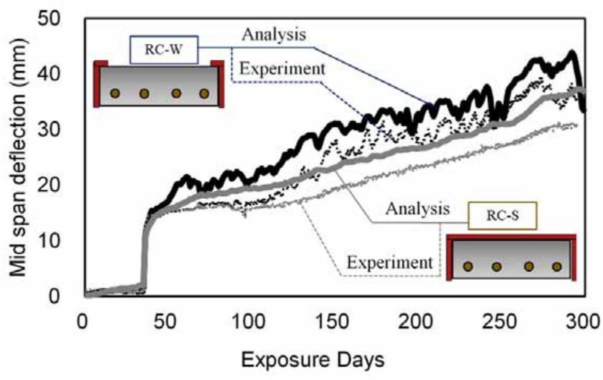

Fig. 10: Comparison of analytical results and experimental data of RC slabs deflections.

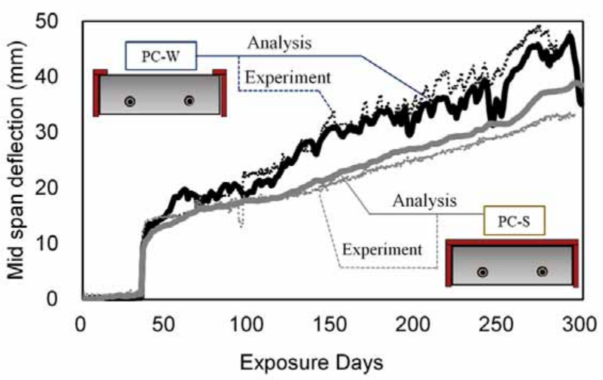

Fig. 11: Comparison of analytical result and experimental data of PC slabs deflections.

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