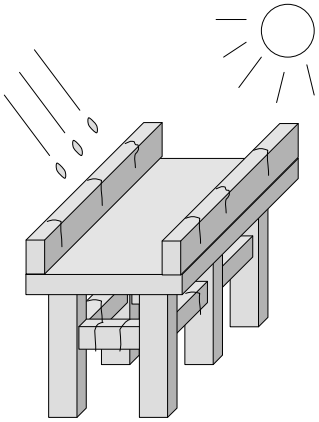
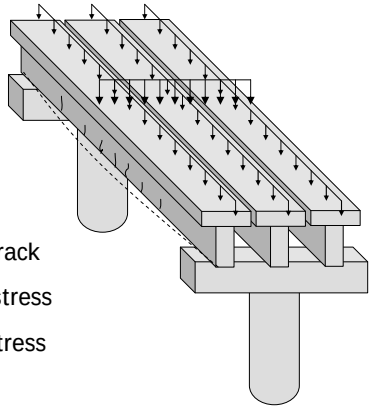
Mechanism and mathematical model of drying shrinkage of concrete

Takumi Shimomura

Time-dependent deformation, stress and crack in concrete structures





shrinkage crack

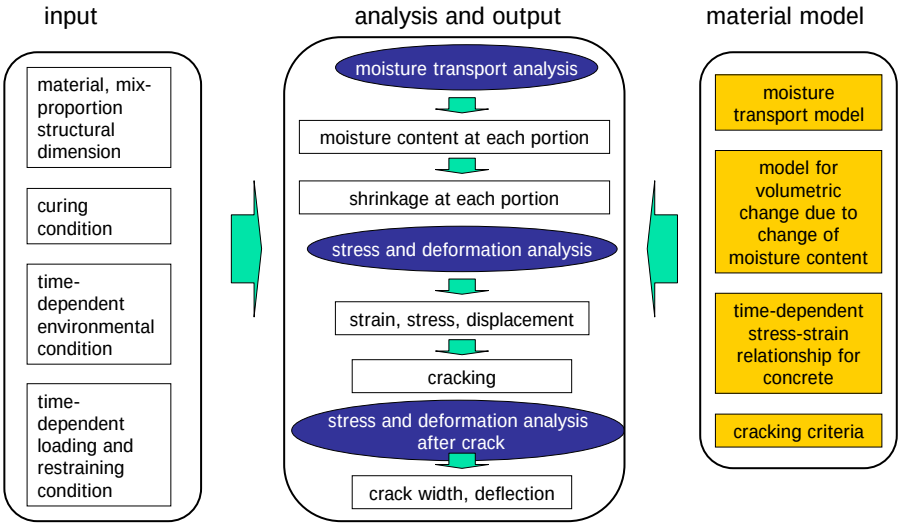
redundant stress

loss of prestress

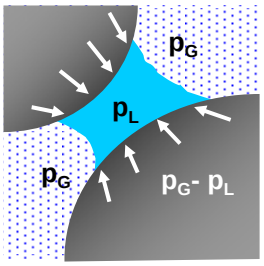
crack width

long term deflection

Scheme of analysis of time-dependent deformation, stress and crack in concrete structures



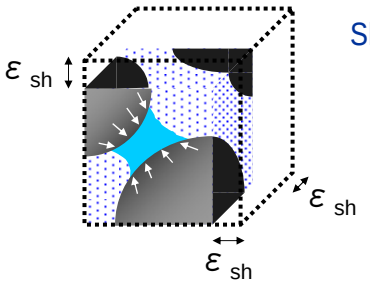
Shrinkage of pore structure due to moisture loss



Thermodynamic pressure gap

Laplace equation

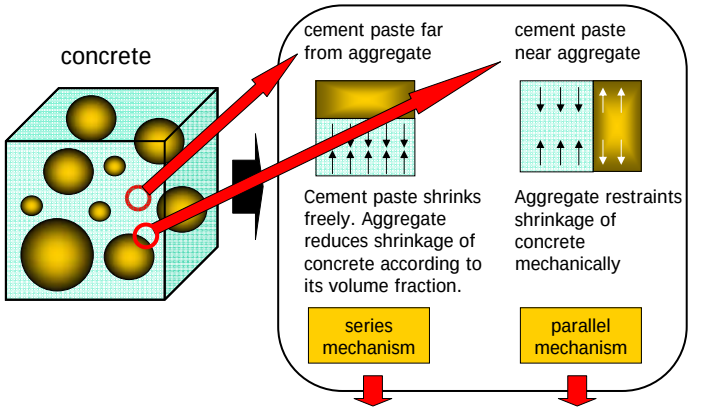
$$p_g - p_l = \frac{2\gamma}{r_S}$$



Shrinkage of pore structure

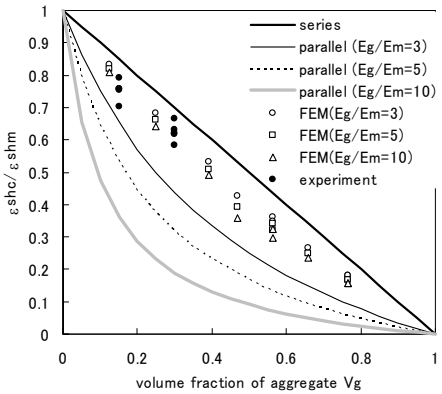
$$\varepsilon_{sh} = \frac{1}{E_S}\left(-\frac{2\gamma}{r_S}\int_0^{r_S}\frac{dV_{(r)}}{dr}dr\right)$$

Hypothesis on two interactions between aggregate and cement paste in volumetric change phenomena



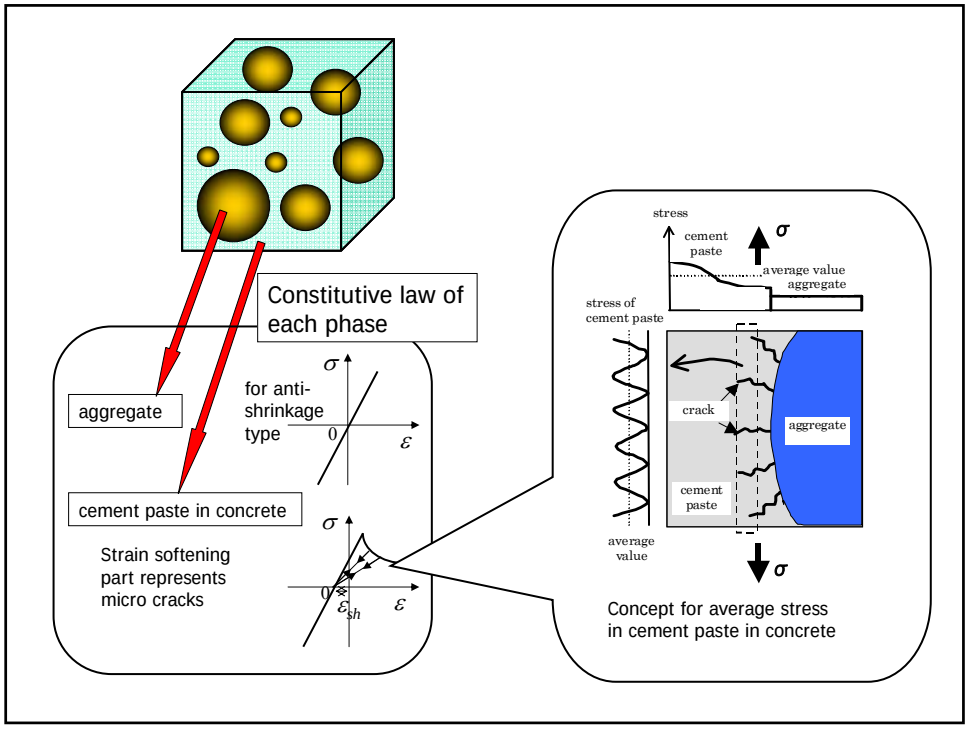
Both mechanisms are coexisting in actual concrete?

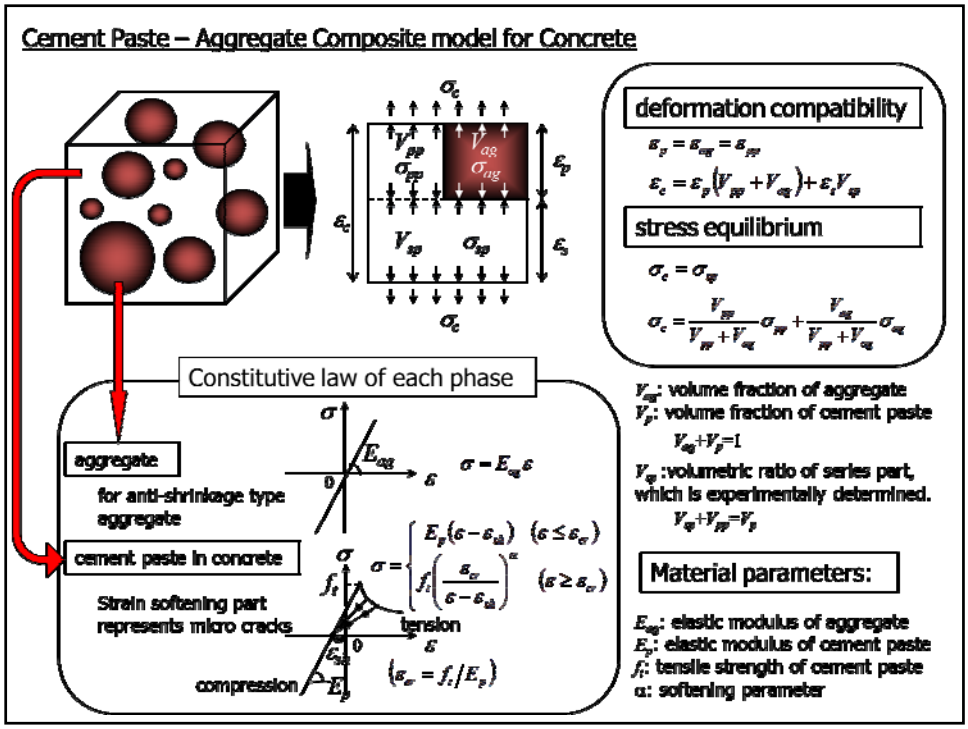
Relationship between “shrinkage of concrete / shrinkage of mortar” and volume fraction of aggregate in concrete: theoretical value, experimental value and FEM simulation



Series and parallel mechanisms are coexisting in actual concrete.

Series mechanism is dominant.

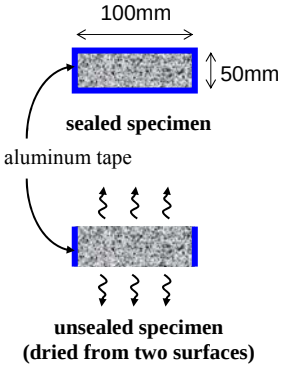

Constitutive law of each phase
aggregate
for anti-shrinkage type
cement paste in concrete
Strain softening part represents micro cracks
stress
cement paste
average value aggregate
stress of cement paste
crack
aggregate
cement paste
average value
Concept for average stress in cement paste in concrete


Cement Paste – Aggregate Composite model for Concrete
deformation compatibility
stress equilibrium
Constitutive law of each phase
aggregate
for anti-shrinkage type aggregate
cement paste in concrete
Strain softening part represents micro cracks
tension
compression
Material parameters:
V_{ag}: volume fraction of aggregate
V_p: volume fraction of cement paste
$V_{ag}+V_p=1$
V_{sp} :volumetric ratio of series part, which is experimentally determined.
$V_{sp}+V_{pp}=V_p$
E_{ag}: elastic modulus of aggregate
E_p: elastic modulus of cement paste
f_t: tensile strength of cement paste
α: softening parameter

Verification (1): Time-dependent deflection of concrete beam subjected to sustaining load and drying environment

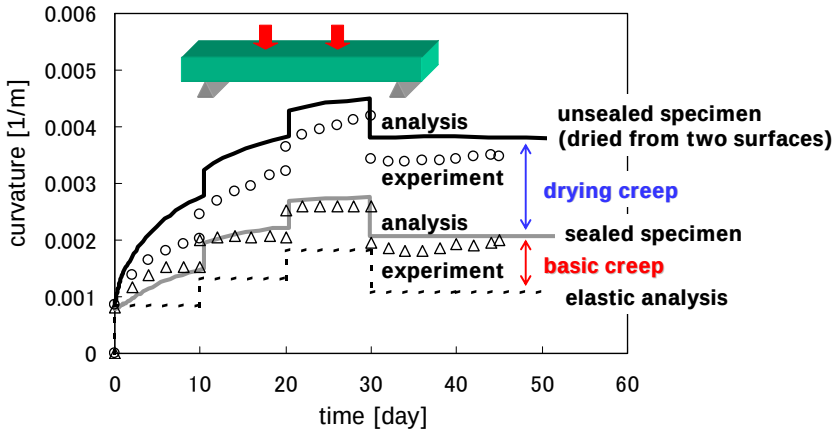
Analysis of time-dependent deflection of mortar beam subjected to sustaining load under drying environment

Sustaining loading test



curvature of cross section was measured

Experimental and analytical results

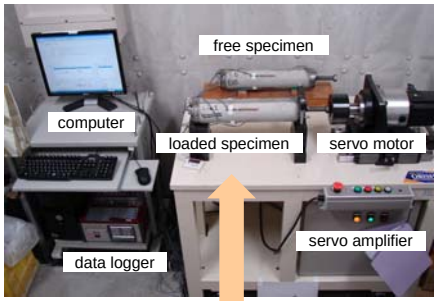


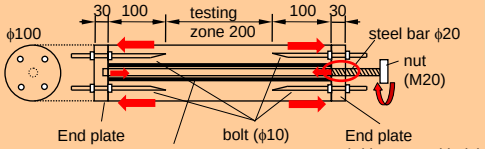
time-dependent curvature at the midspan of specim

basic creep is considered at concrete level

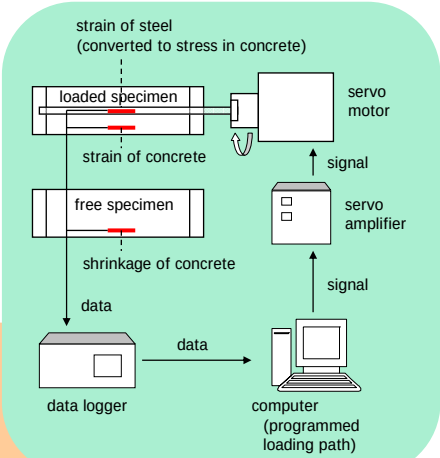
Verification (2): Experiment and analysis of time-dependent stress and strain of cylindrical concrete under various loading and drying path

Testing system for sustaining tensile loading test





Cylindrical concrete specimen with center hole



Control system

Nagaoka University of Technology

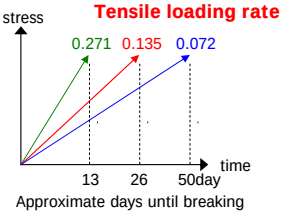
Experimental series

Series	Specimen	Drying condition	Tensile loading rate (N/mm²/day)
A	A-0	Unsealed (dried)	0 (free shrinkage)
	A-1		0.072
	A-2		0.135
	A-3		0.271
B	B-0	Sealed (not dried)	0 (free shrinkage)
	B-1		0.072
	B-2		0.135
	B-3		0.271

- W/C of concrete: 0.50
- Curing: 28 days being wrapped with plastic bag
- Testing condition: 20deg, 60%RH

Unsealed (dried)

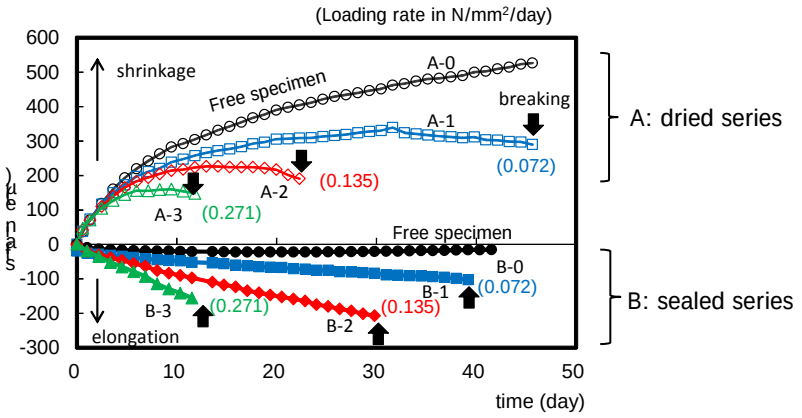
Sealed (not dried)



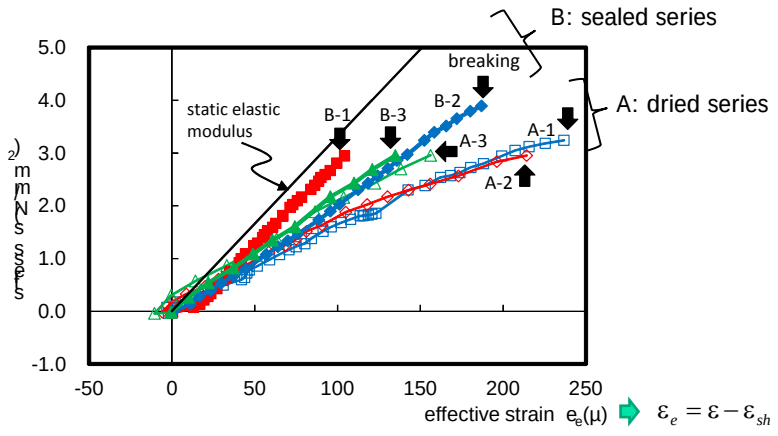
Approximate days until breaking

Nagaoka University of Technology

Test results: time-dependent strain of concrete specimen



Test results: Relationship between stress and effective strain of concrete specimen



$\varepsilon_e = \varepsilon - \varepsilon_{sh}$

(strain of loaded specimen) – (strain of free specimen)

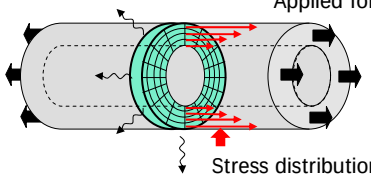
NUMERICAL SIMULATION

Analytical procedure

Concrete specimen

Evaporation of water

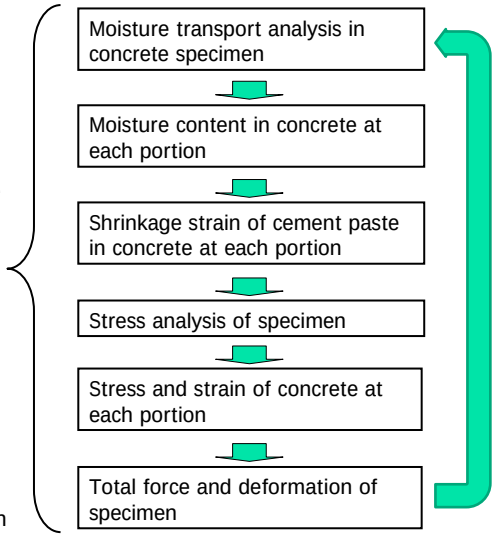
Applied force



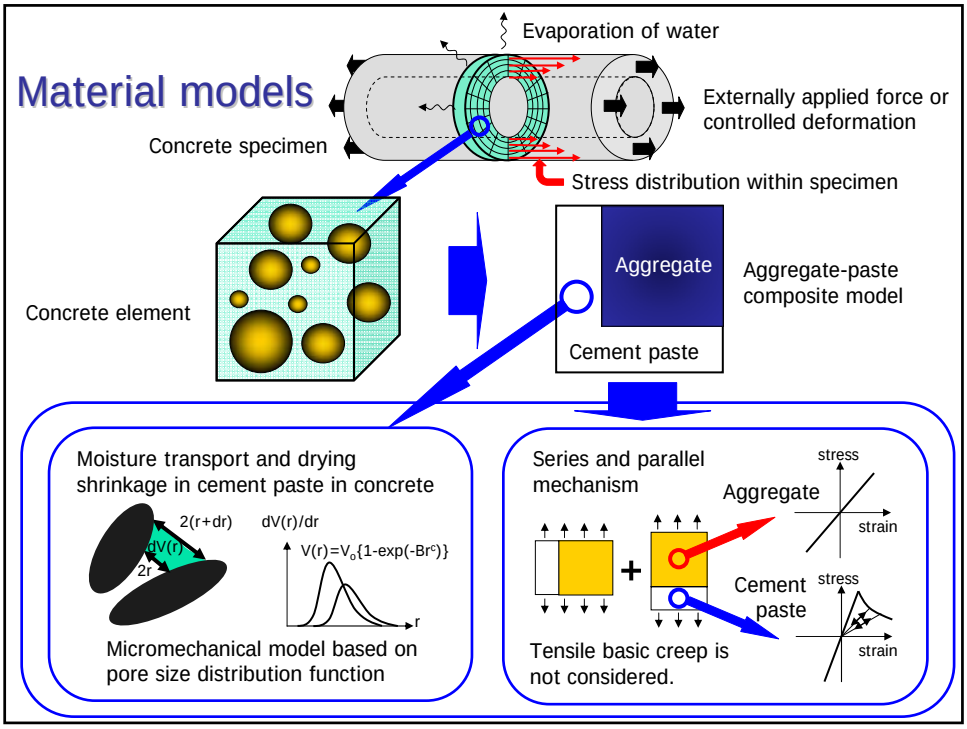
Stress distribution within specimen

- Moisture transport in the specimen is regarded as axial symmetry.
- Stress and strain in the specimen are assumed uniform with respect to longitudinal direction. Their distribution in cross section is considered.

Calculation at each time step

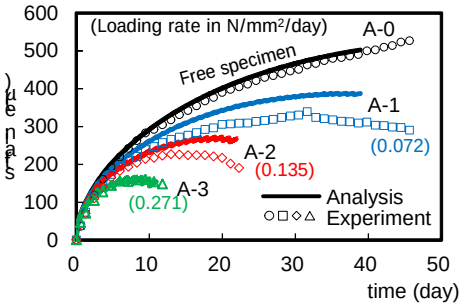


Material models

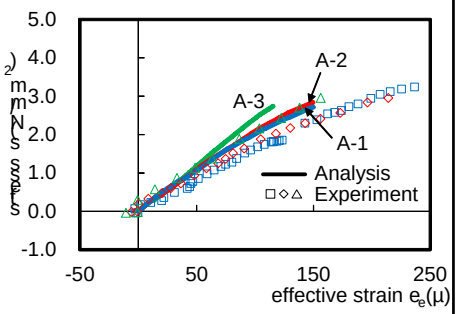


Analytical results: A series (dried series)

Unsealed (dried)



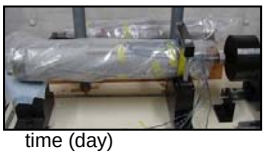
Time-dependent strain of concrete specimen

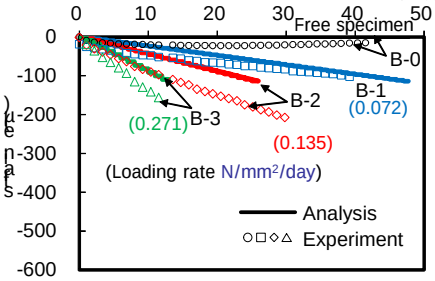


Relationship between stress and effective strain of concrete specimen

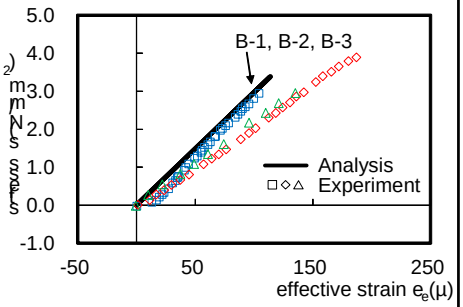
Analytical results: B series (sealed series)

Sealed (not dried)





Time-dependent strain of concrete specimen

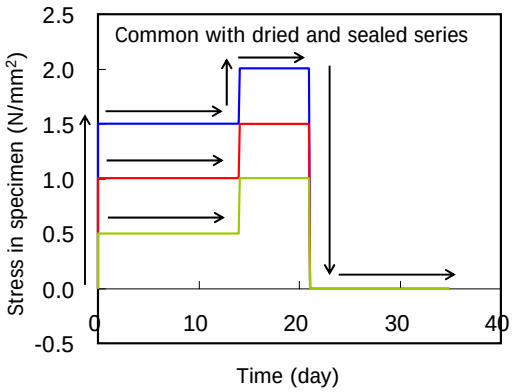


Relationship between stress and effective strain of concrete specimen

DEMONSTRATION OF EXPERIMENT AND ANALYSIS UNDER VARIOUS LOADING PATH

Example of sustaining loading test under arbitral loading path

Loading path



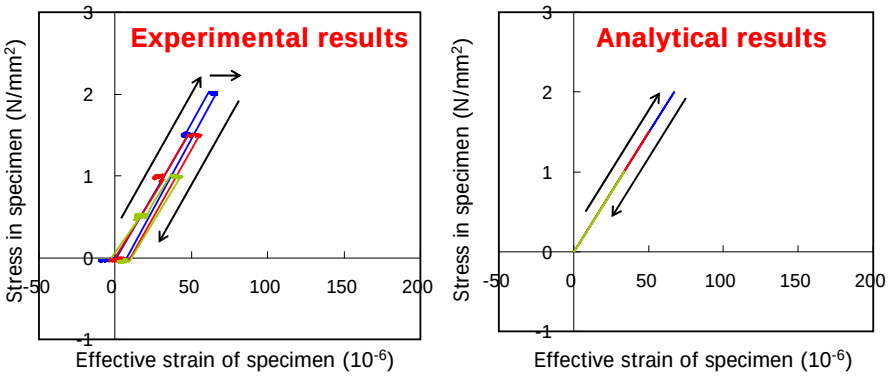
Drying condition

Unsealed (dried)

Sealed (not dried)

Experimental and analytical results in sealed series

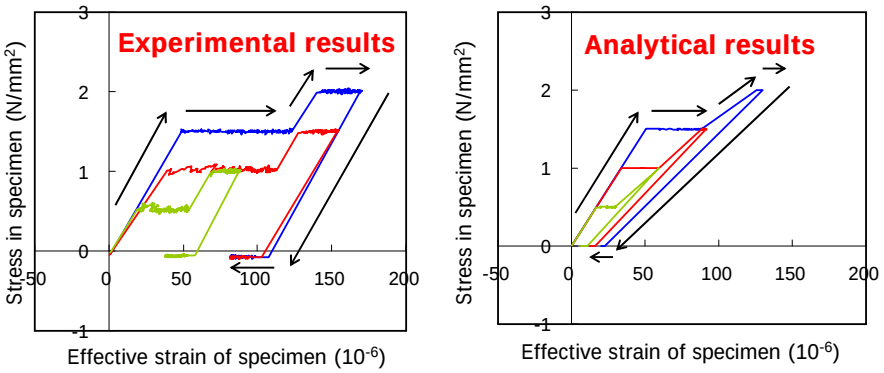
Sealed (not dried)



Relationship between stress and effective strain of concrete specimen

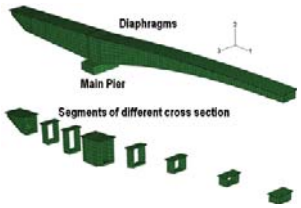
Experimental and analytical results in dried series

Unsealed (dried)

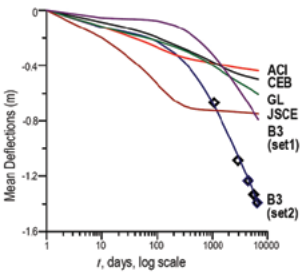


Relationship between stress and effective strain of concrete specimen

Long-term deflection of PC bridge



Bazant et.al, Concrete International, 2010 June



Predicted long-term deflections using various creep and shrinkage model in design codes

Long-term deflection of PC bridge and its prediction

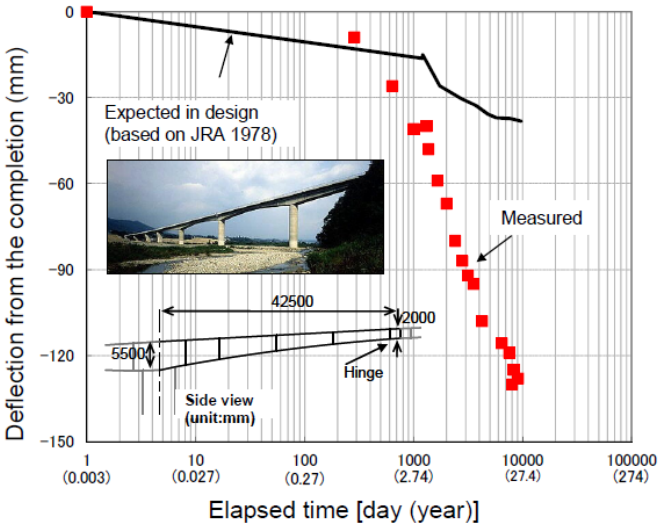
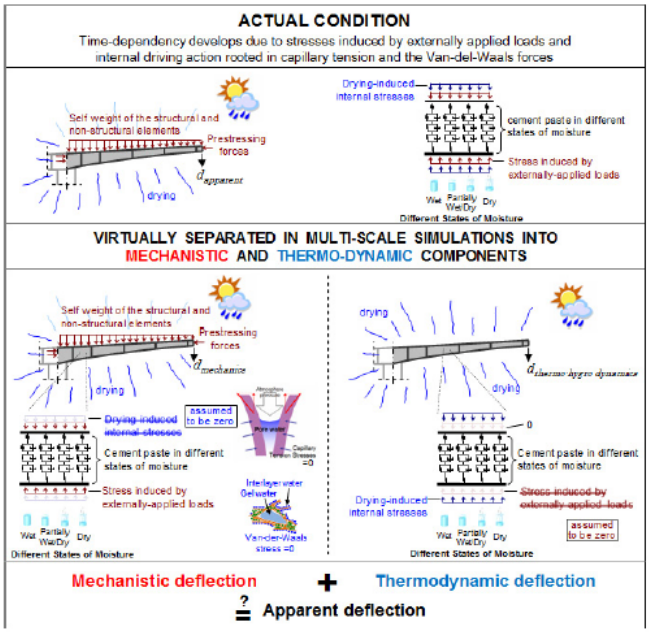
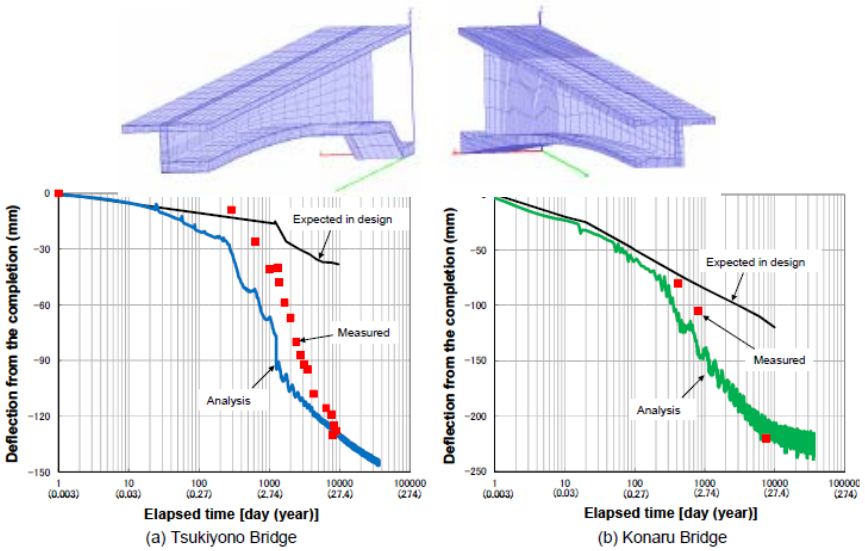


Fig. 1 Observed and predicted displacement of Tsukiyono Bridge.

Mechanism of excessive long-term deflection of PC bridge



Numerical simulation of long-term deflection of PC



(a) Tsukiyono Bridge (b) Konaru Bridge

Motohiro Ohno, Nobuhiro Chijiwa, Benny Suryanto and Koichi Maekawa, An Investigation into the Long-Term Excessive Deflection of PC Viaducts by Using 3D Multi-scale Integrated Analysis, Journal of Advanced Concrete Technology, Vol.10, pp.47-58, 2012.