IMPORTANCE OF AUTOGENOUS SHRINKAGE TO SERVICEABILITY PERFORMANCE OF RC FLEXURAL MEMBERS AND IMPROVEMENT BY USING LOW-SHRINKAGE HSC

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Necessity of low-shrinkage HSC

✧Additional performance

- ✓Significant autogenous shrinkage

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- ✓Restrained-shrinkage stress even before loading

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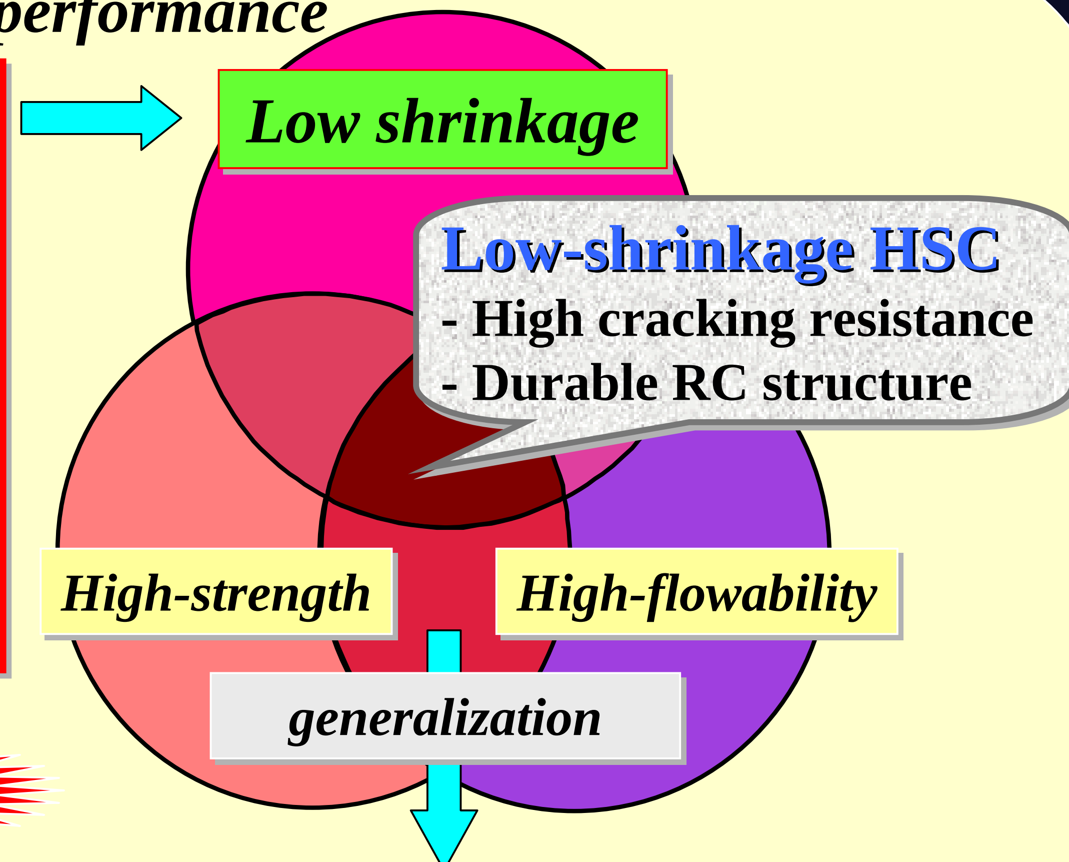
- ✓Deterioration of serviceability performance of RC members



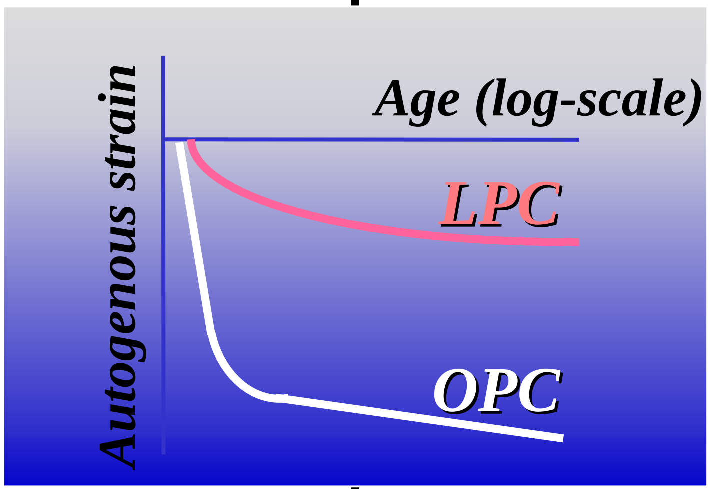
Assignment

High-structural performance, high-durability

Measure for reducing AS

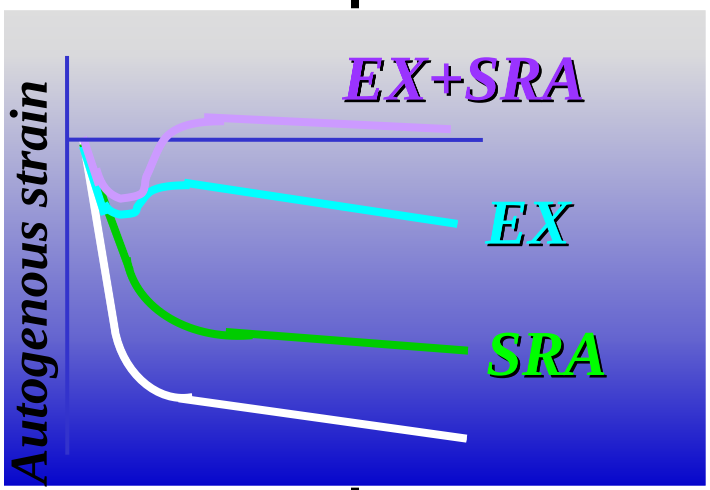
Low-shrinkage cement

- Belite-rich Portland cement
- Low-heat Portland cement



Special admixtures

- Expansive additive
- Shrinkage reducing agent



Control of autogenous shrinkage → Combination → Expansion rather than shrinkage

Objectives

However,

- ✓ *Insufficient investigations on the effect of AS and*
- ✓ *Effectiveness of low-shrinkage HSC (LS-HSC) from the viewpoint of structural performance of RC members*

Therefore

- ➢ *Evaluation of flexural serviceability performances of RC beams made with high-AS and LS-HSC*
- ➢ *A general method for calculating crack width and deformation of RC flexural beams, considering the effect of shrinkage/expansion before loading*

Mixture investigated

✧**Reference HSC** ✧**Low-shrinakge HSCs**

Con	NC	NE	NS	NES	LC	LE	LS	LES
Cem	Ordinary Portland				Belite-rich low heat Portland			
EX	-	Add.	-	Add.	-	Add.	-	Add.
SRA	-	-	Add.	Add.	-	-	Add.	Add.

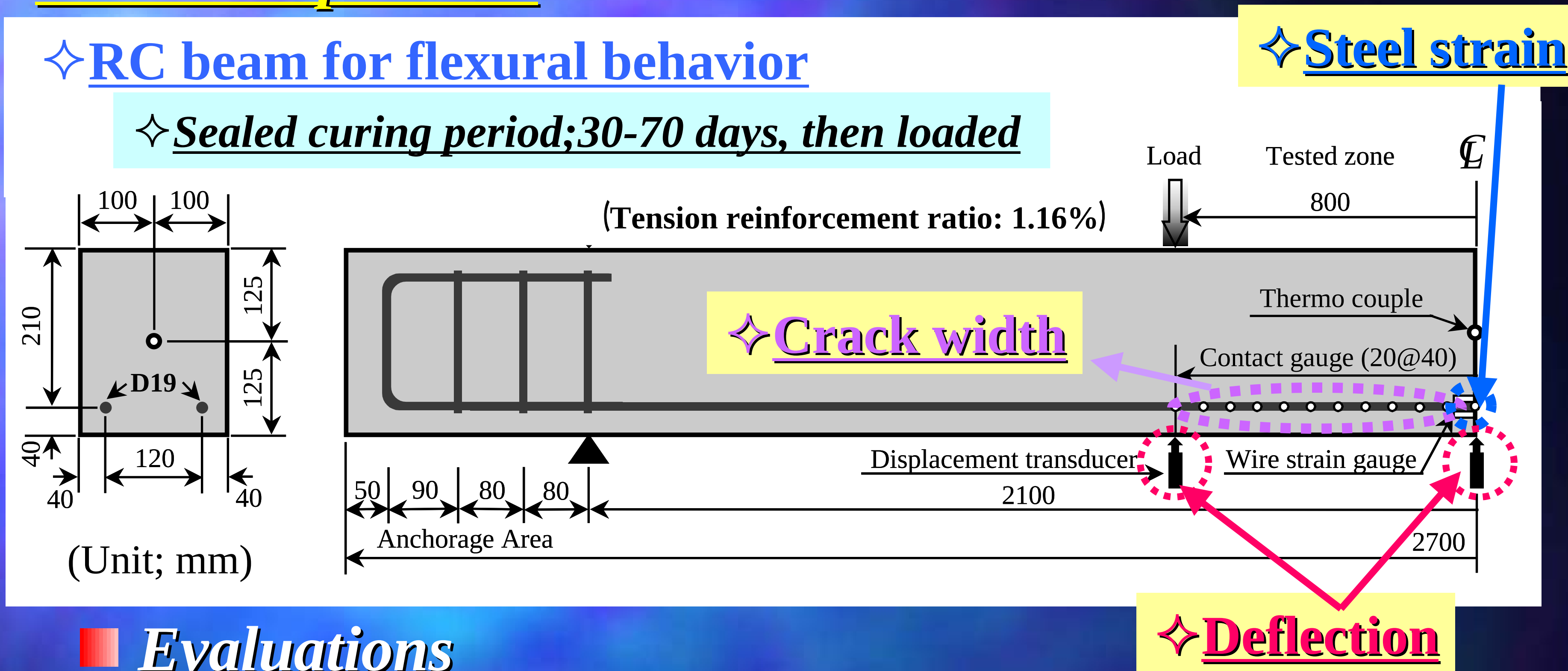
- *W/(C+EX); 0.3, W; 175 kg/m*^{3}
- *EX content; 40 kg/m*^{3}
- *SRA content; 6 kg/m*^{3}

Targeted concrete strength; 70 N/mm^2 *at 28 days*

RC beam specimen

✧RC beam for flexural behavior

✧Sealed curing period;30-70 days, then loaded



- *Evaluations*

➢*Before loading*

Steel strain → Restrained stress on bottom fiber

➢*Under loading*

- Cracking load

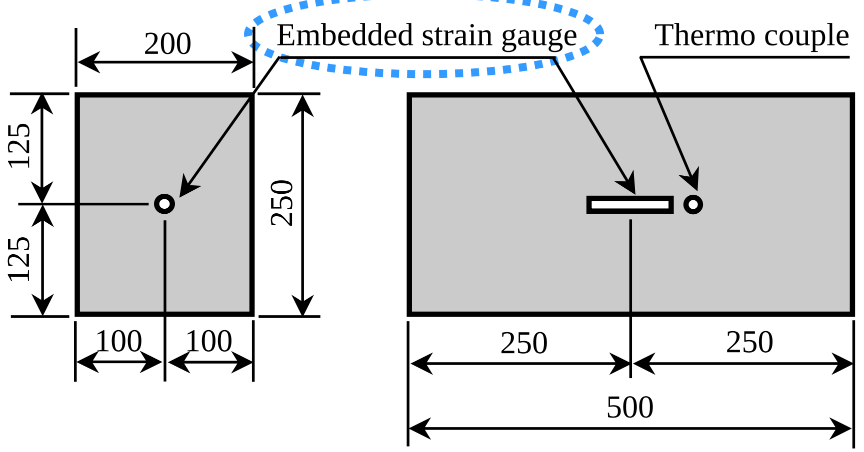
- Crack width; Contact-type strain gauge

- Deflection; Displacement transducer

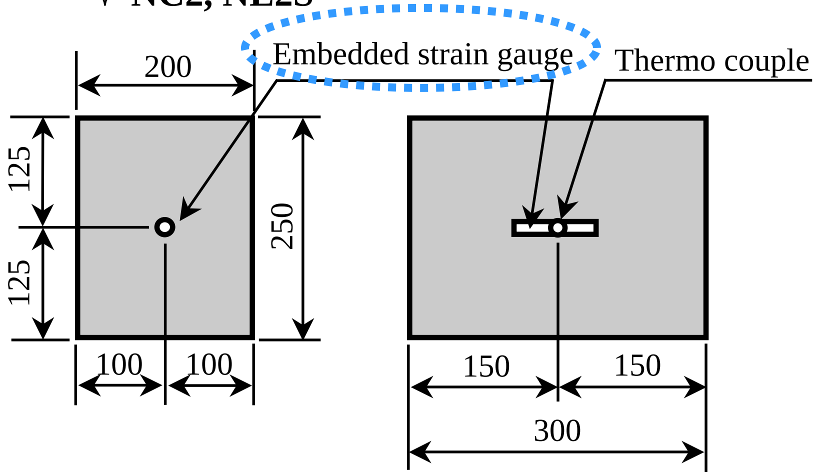
Beam specimens

✧Beam for free deformation and creep tests

✧ **NC1, NE1, NS, NE1S, LC, LE1, LS, LE1S**

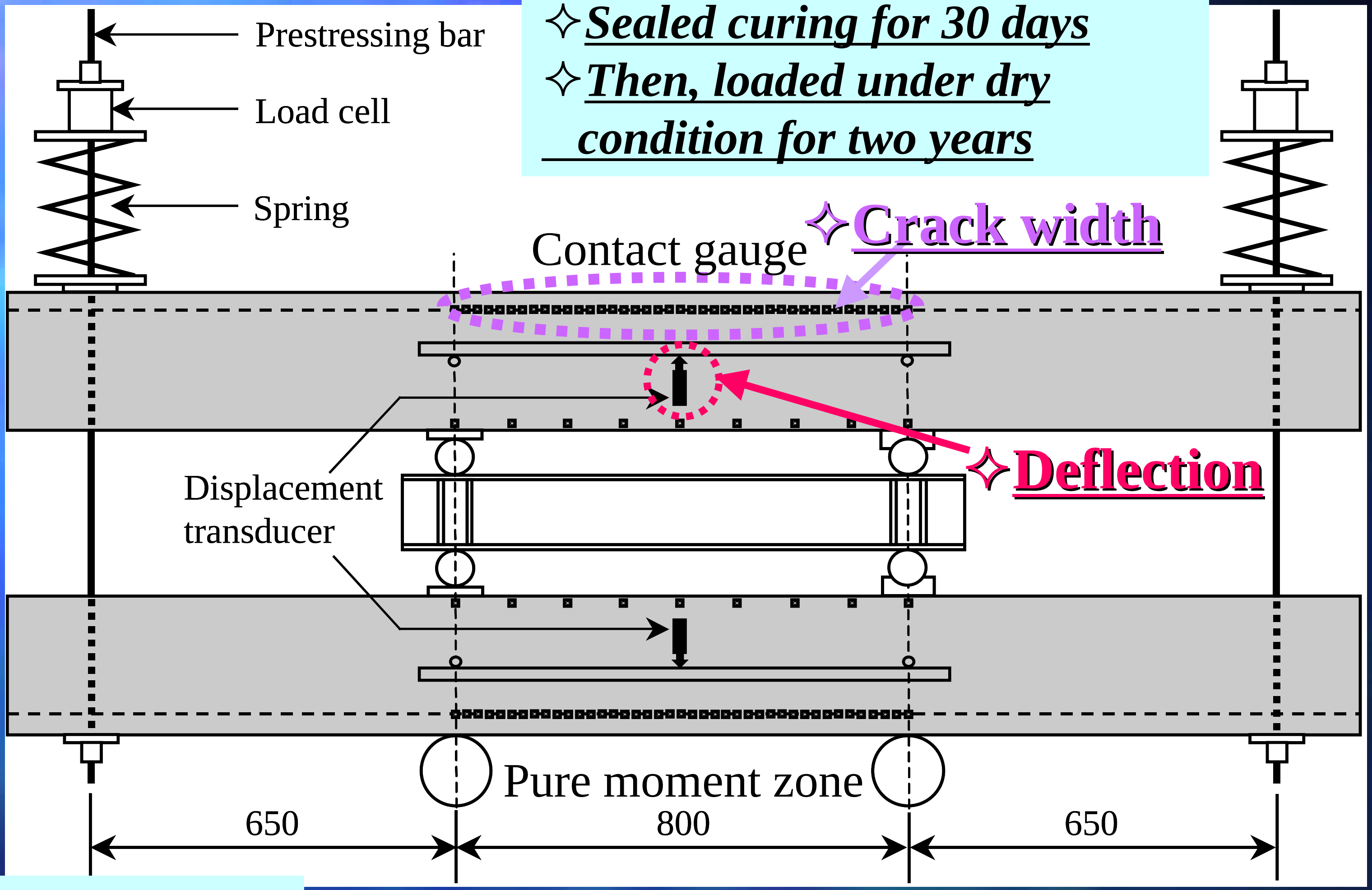


✧ **NC2, NE2S**



Test setup for sustaining load

✧ *Sealed curing for 30 days*
✧ *Then, loaded under dry condition for two years*

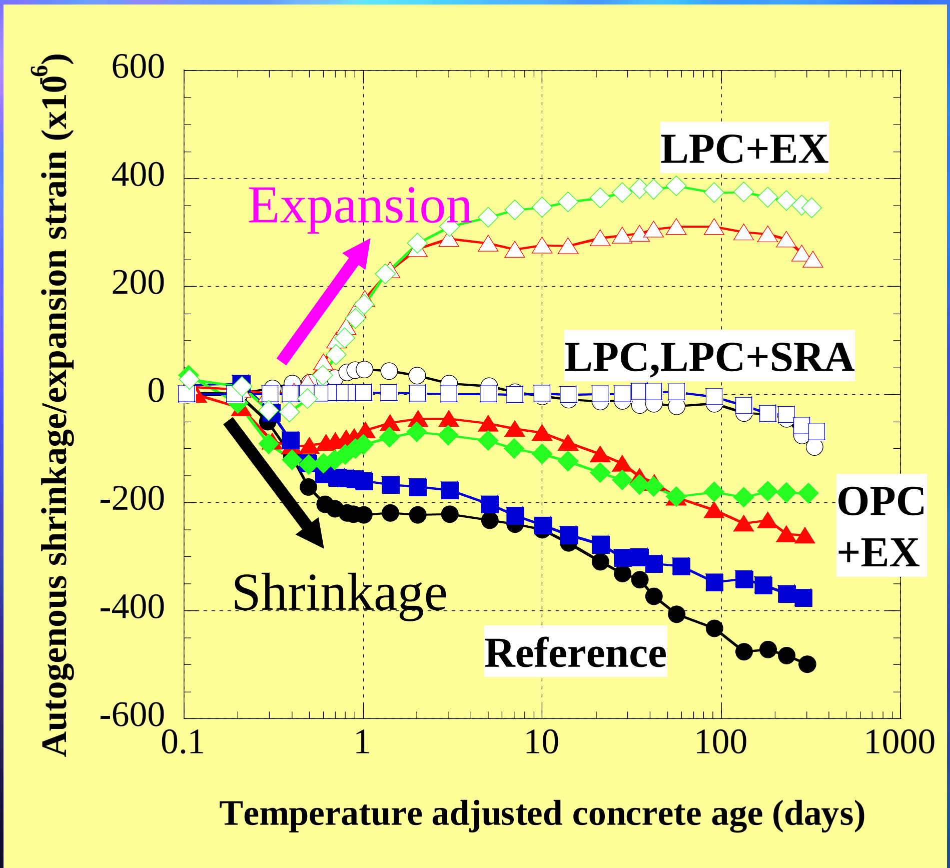


✧Load levels

150 N/mm² and 300 N/mm² of reinforcement stress at fully cracked section.

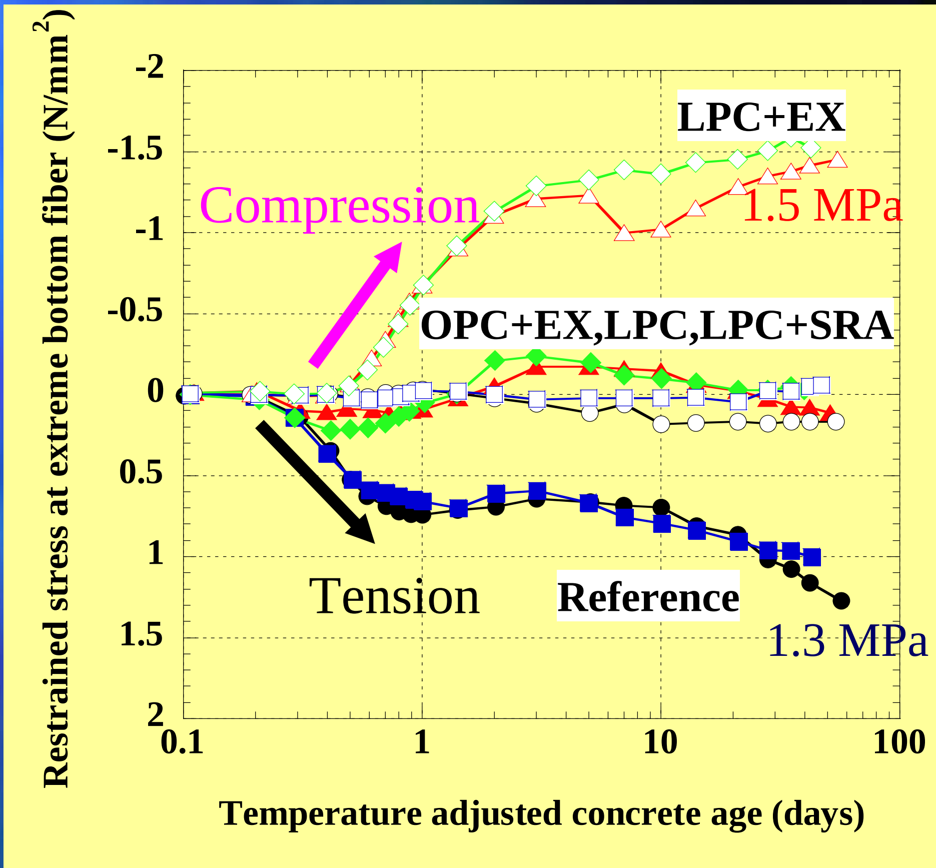
Strain properties

Thermal expansion of concrete; assumed to be $10 \times 10^{-6}/^{o}C$



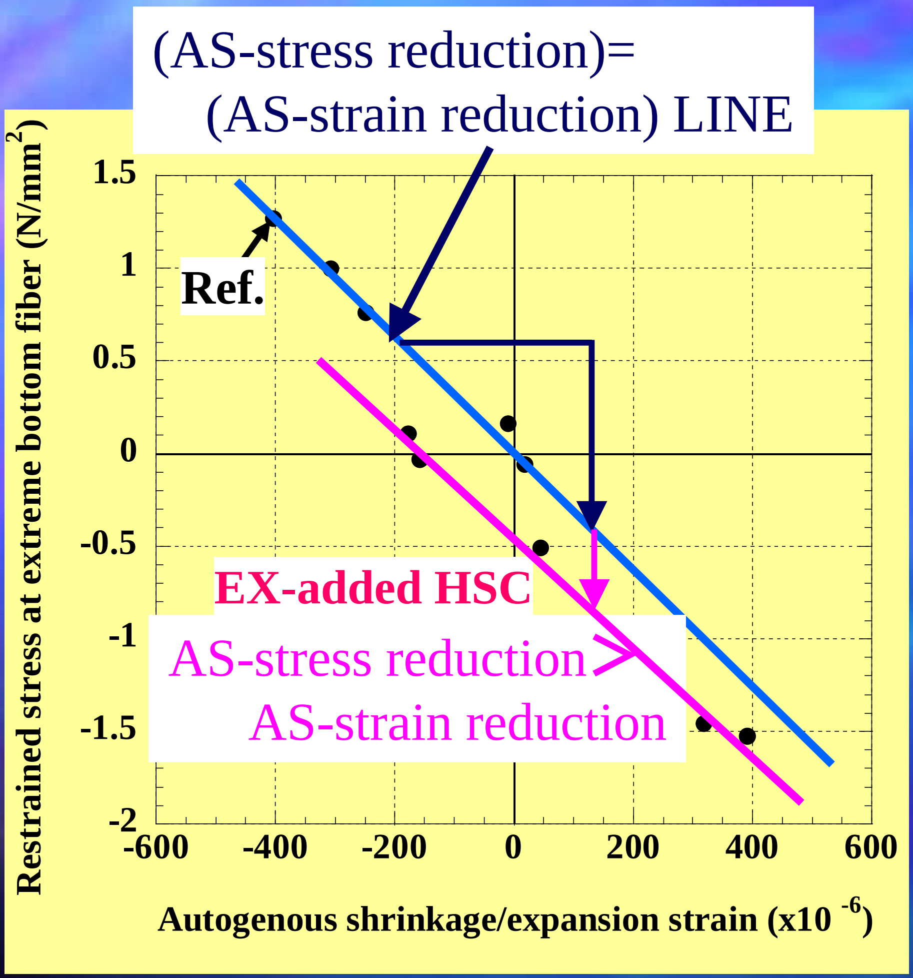
Restrained stress

$$\sigma_{cb} = -\frac{P_s}{A_c}\left[1 + \frac{(d - C_g)(h - C_g)}{I_c / A_c}\right]$$

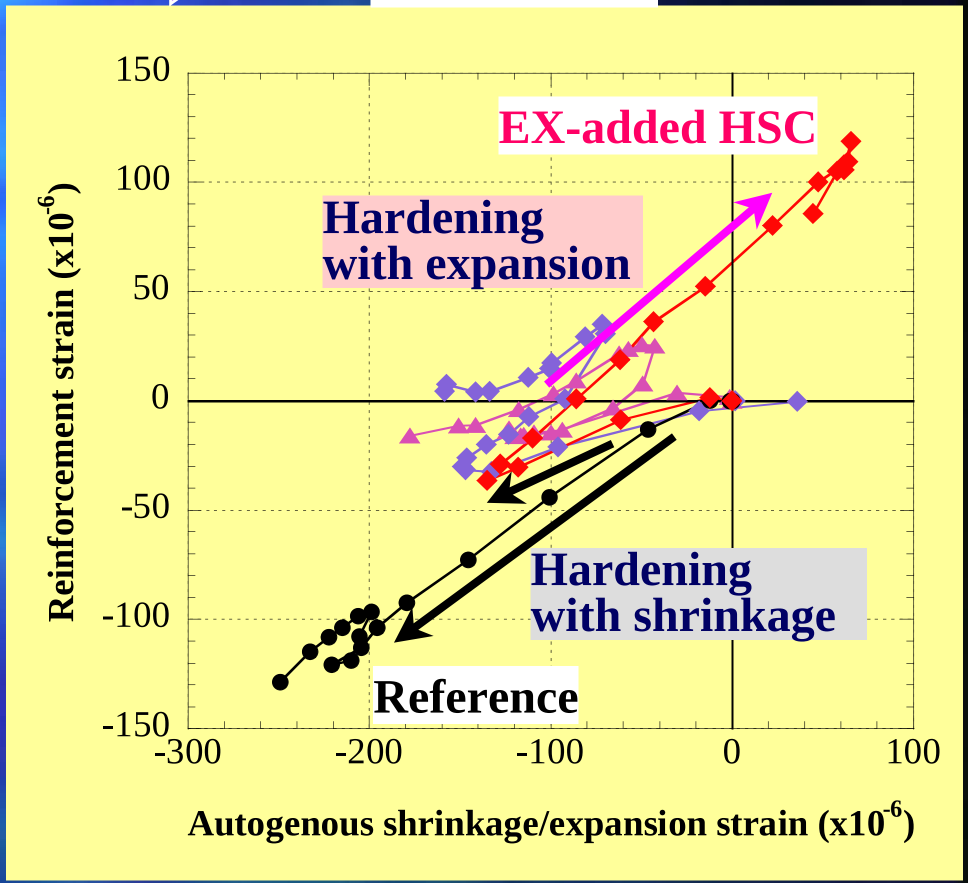


➢ ***Using LPC, EX, SRA, or their combinations is effective for controlling not only AS but also restrained-AS stress.***

Effectiveness of EX on eliminating restrained-AS stress

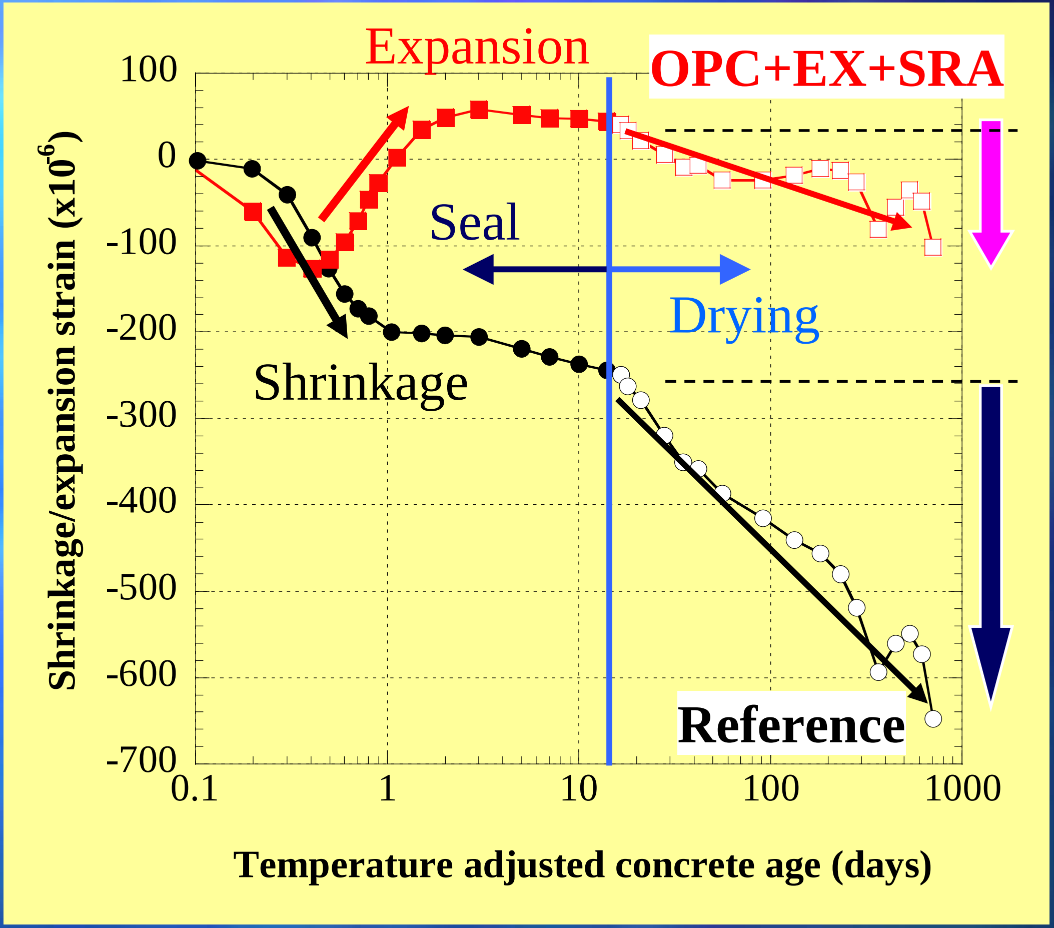


Mechanism



➢ ***Using expansive additives achieve a significant efficiency for eliminating restrained-AS stress at early ages.***

Shrinkage properties under drying condition



- *Combined use of EX and SRA; very effective for reducing shrinkage/resultant induced stress from early-ages to long-term ages*

Properties of RC beams just before loading

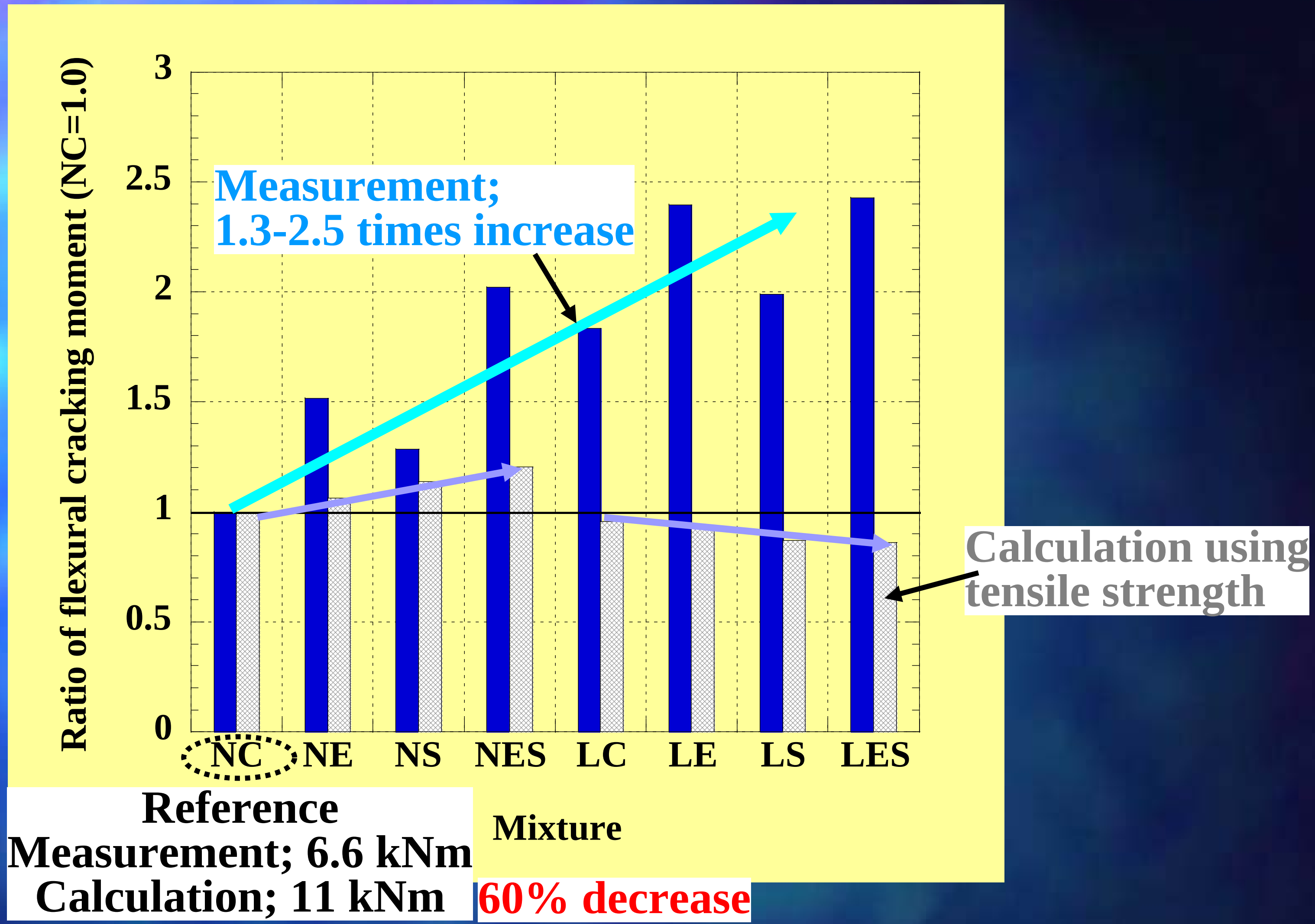
Type	Age at loaded	Strain of tension bar	Stress of bottom fiber	Free strain of concrete
NC1	63	-187	1.27	-397
NCE2	65	-16	0.11	-174
NCS	57	-147	1.00	-313
NCE2S	70	4	-0.03	-175
NC2-150	31	-138	0.82	-255
NC2-300	33	-130	0.77	-262
NCE1S-150	31	81	-0.48	30
NCE1S-300	33	83	-0.49	28
LC	70	-24	0.16	-12
LCE2	64	214	-1.45	311
LCS	64	8	-0.06	5
LCE2S	61	224	-1.52	383

Strain of tension reinforcing-bar: -190 ~ +220 x10^{-6}

Restrained stress at extreme bottom fiber: -1.5 ~ 1.3 N/mm^2

Autogenous shrinkage/ expansion strain :-400 ~ +400 x10^{-6}

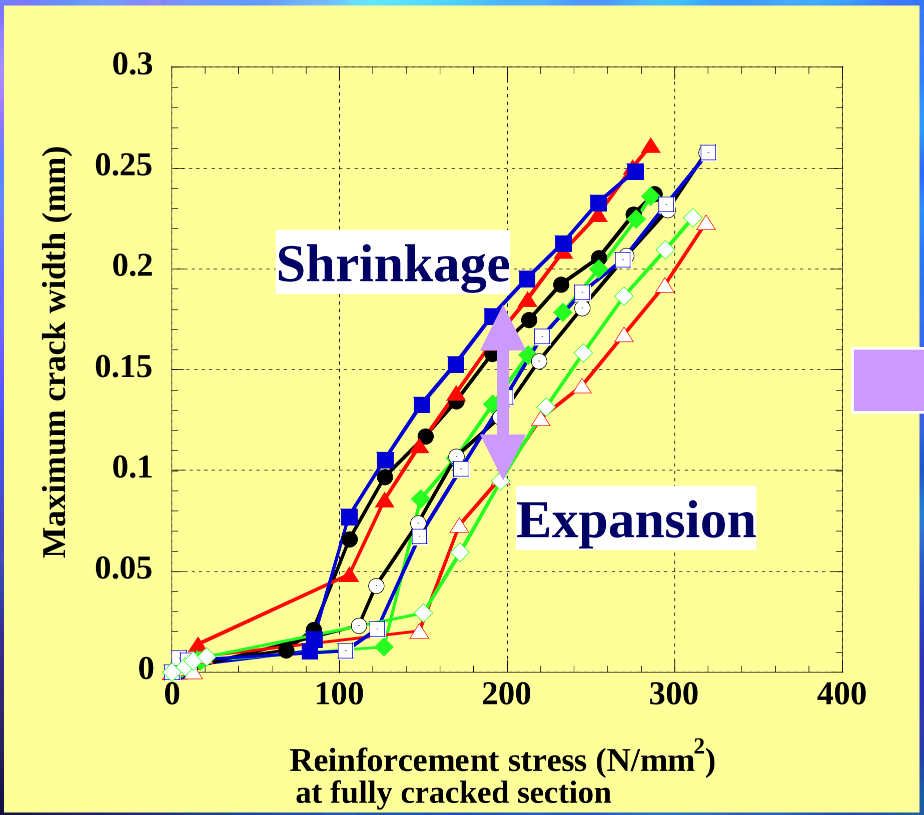
Flexural cracking moment

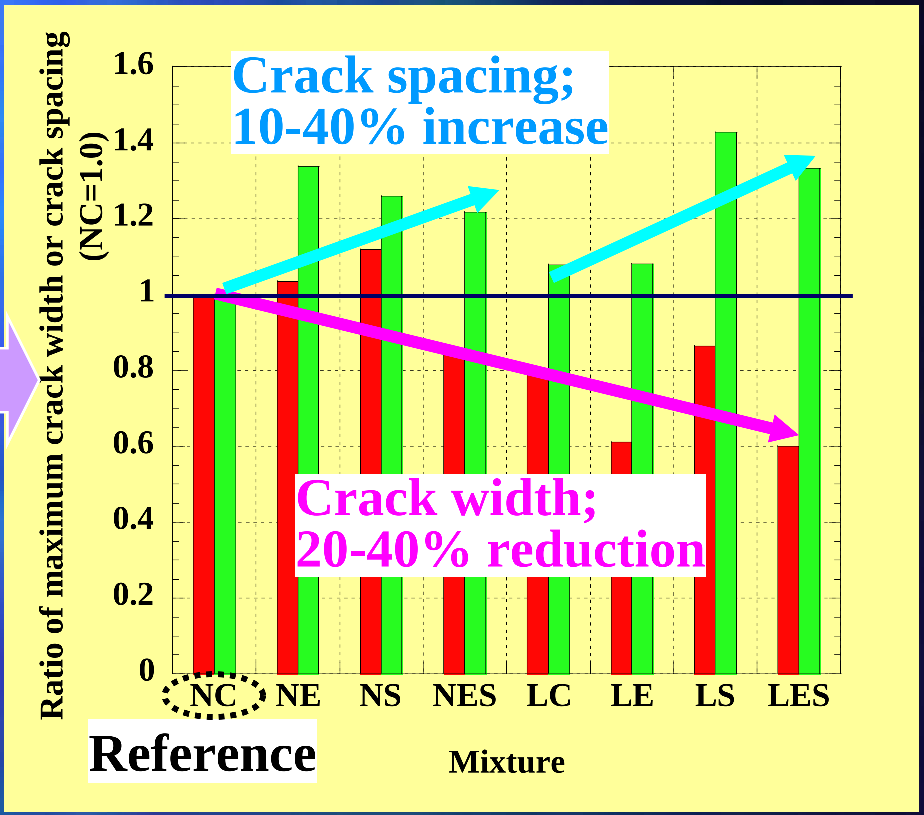


- *AS of HSC affects the decrease in Mcr significantly.*
- *LS-HSCs markedly improve Mcr, even though the difference in calculated Mcr among mixtures is considered.*

Maximum crack width and crack spacing

Reinforcement stress at fully cracked section =200 N/mm^2

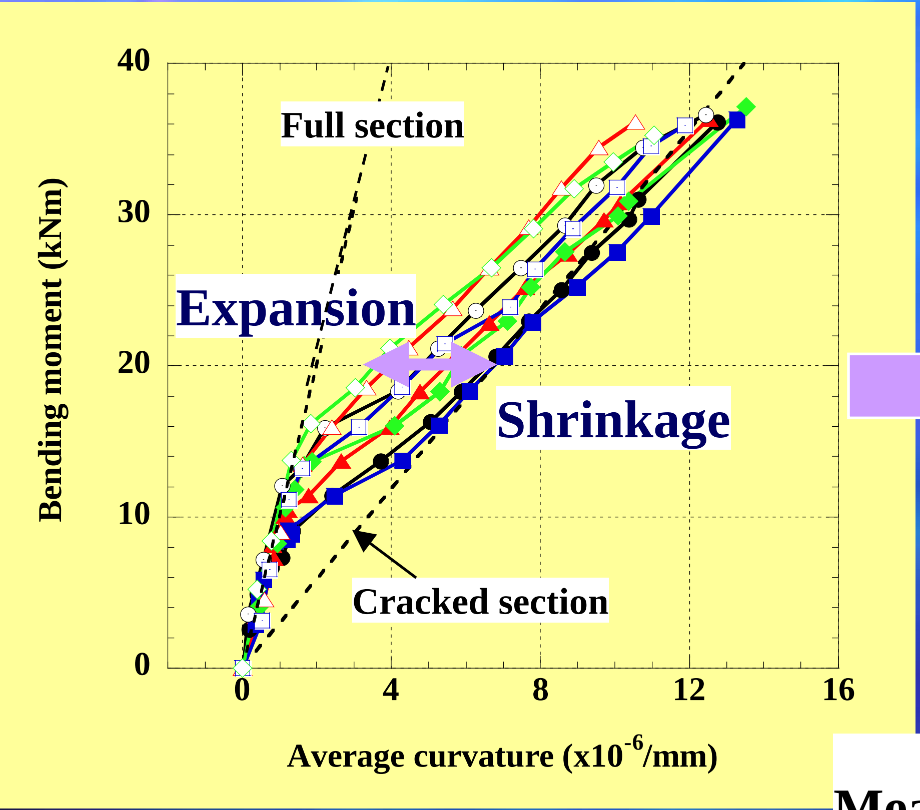


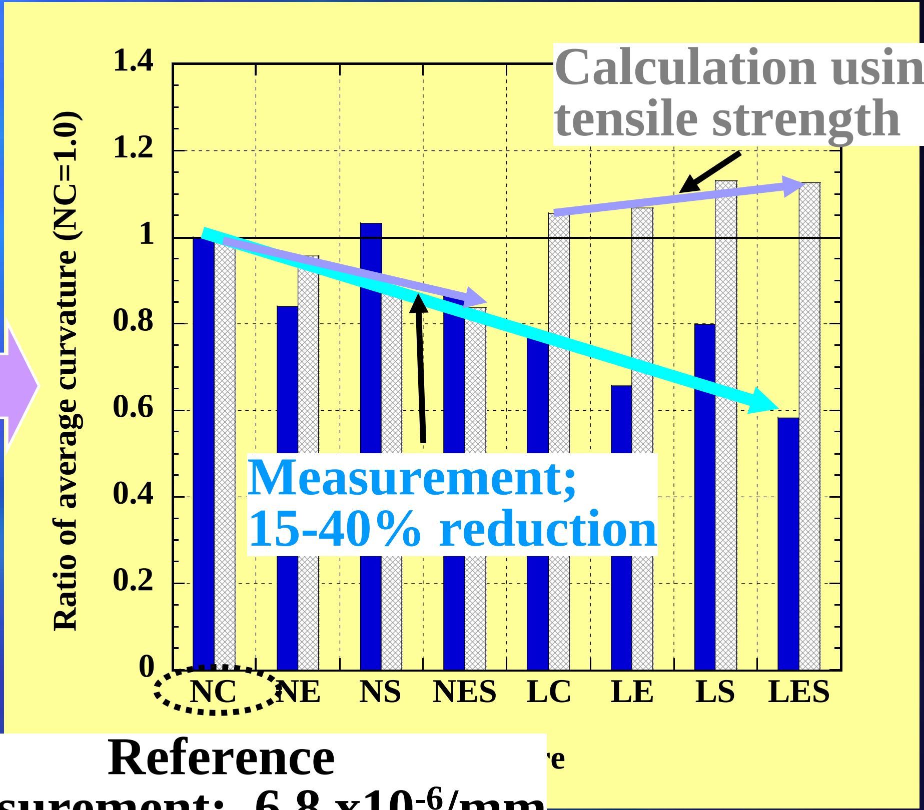


➢ *LS-HSCs improve cracking performance significantly.*
--Decrease in crack width, while increase in crack spacing!!

Average curvature

Reinforcement stress at fully cracked section =200 N/mm^2





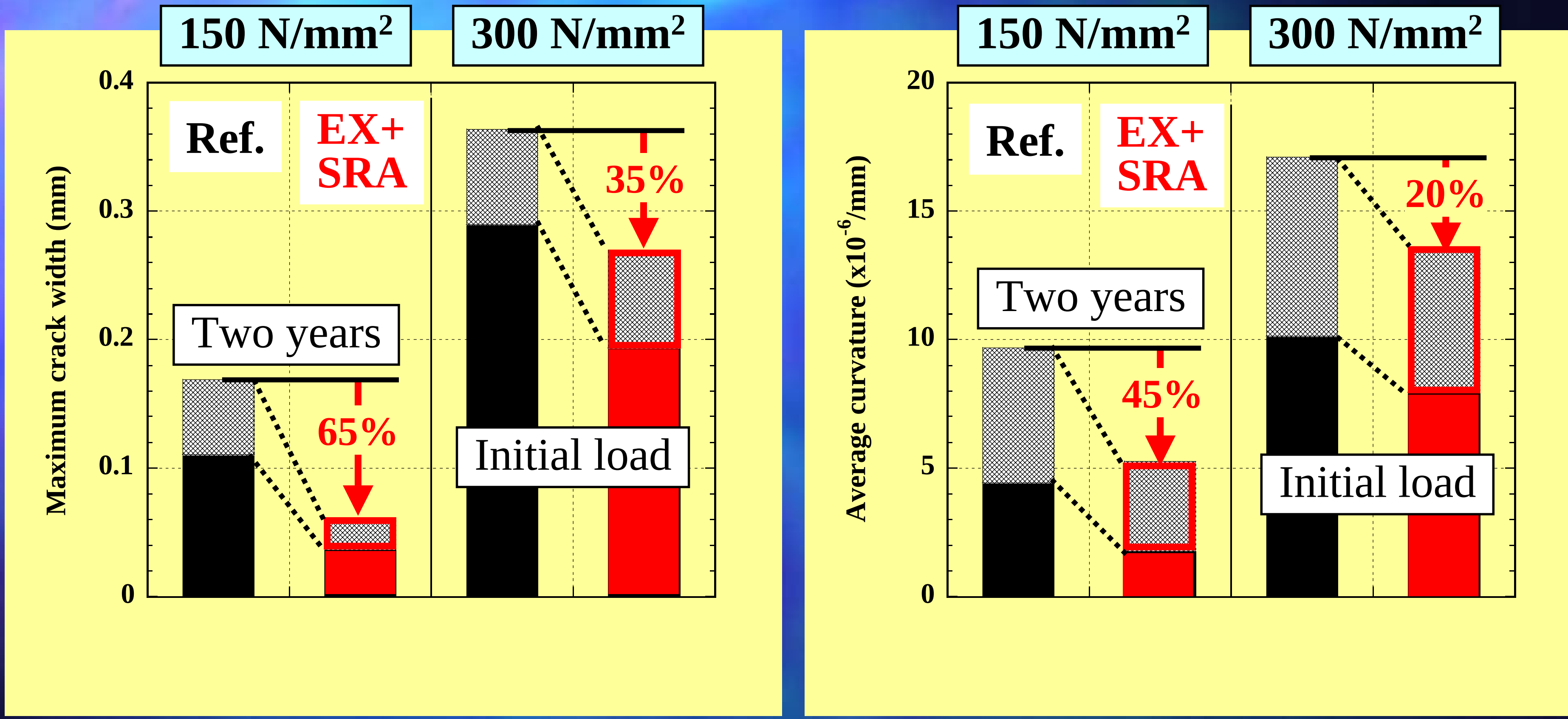
Reference
Measurement; .6.8 $x10^{-6}$/mm
Calculation; 5.8 $x10^{-6}$/mm
20% increase

➢ ***AS affect the increase in deformation, while LS-HSCs improve deformation behavior!!***

Time-dependent serviceability performance

Maximum Crack width / Average curvature

Reinforcement stress at fully cracked section



- ➢ *Time-dependent crack width/curvature; marked improvement by LS-HSC*
- ➢ *Effectiveness of LS-HSC; significant when common load level*

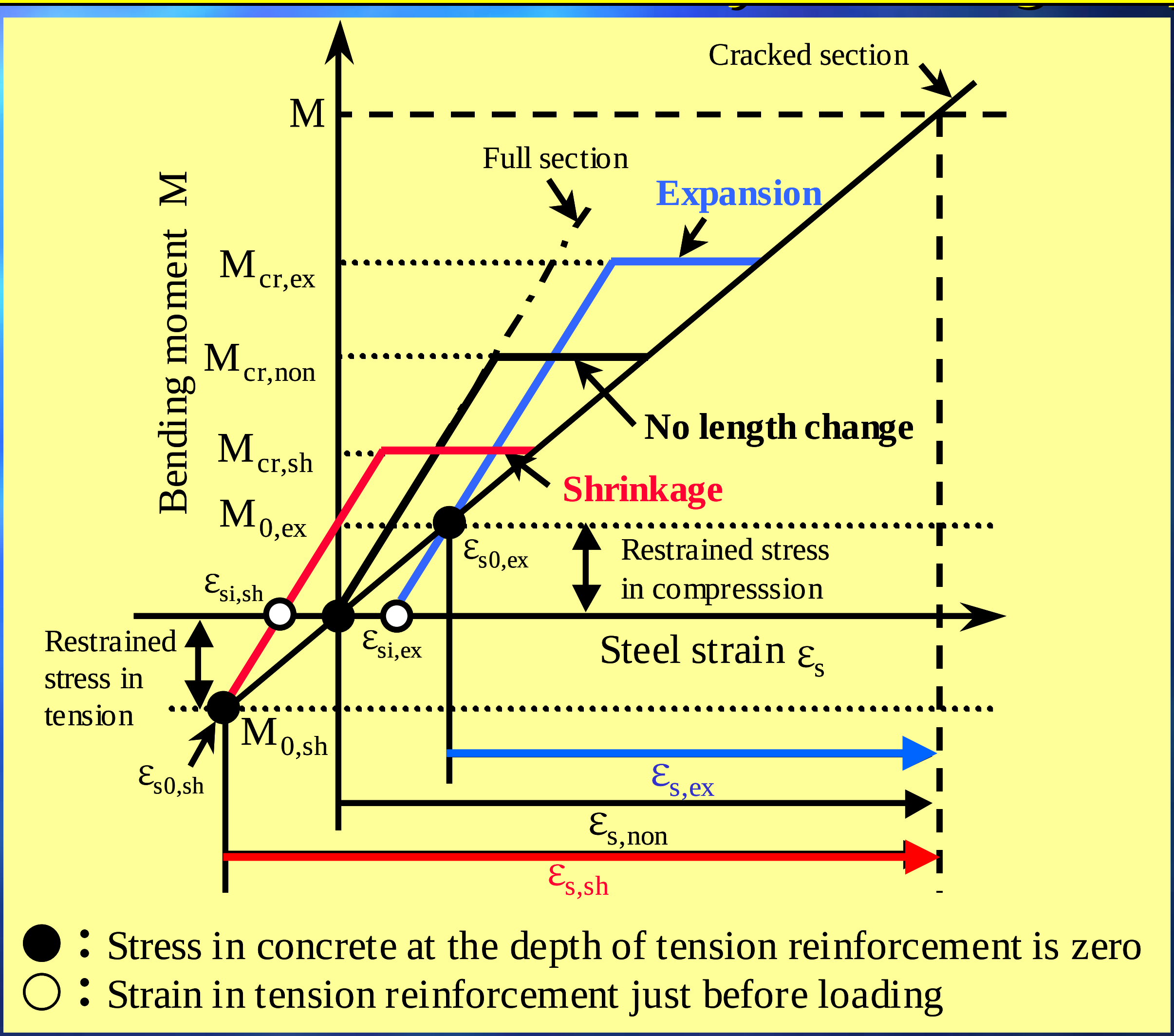
Summary of experimental results

- Using LPC, EX, SRA, or their combinations is effective for reducing AS and resultant induced stress; achievement of HSCs have a less AS and also a potential of expansion.

- Autogenous shrinkage surely affect the deterioration of serviceability performances of RC flexural beams.

- LS-HSCs markedly improve its serviceability performances; the combined use of Belite-rich low heat Portland cement and expansive additive is particularly effective.

Basic concept of strain change in tension reinforcement on crack width by shrinkage/expansion



This concept was incorporated into JSCE DESIGN CODE-2002

Validity of the proposed concept for evaluating instantaneous crack width

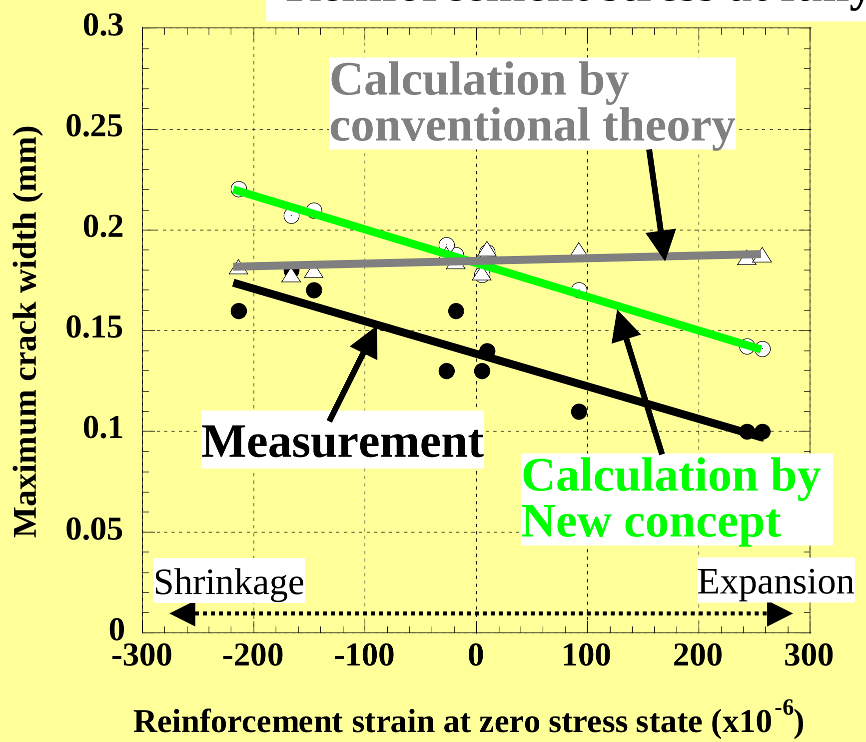
New concept

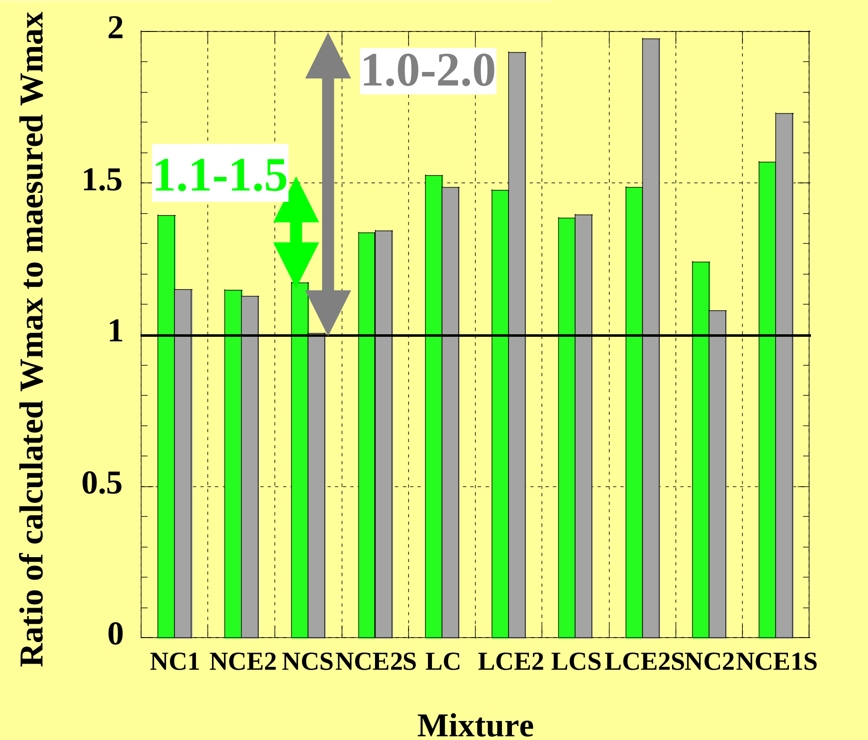
✧JSCE Design Code

$$w = 1.1 k_1 k_2 k_3 \{4c + 0.7(c_s - \phi)\} \left[\frac{\sigma_{se}}{E_s} + \varepsilon'_{csd} \right]$$

0×10^{-6} for short term loading

Reinforcement stress at fully cracked section 200





➢*Improved prediction accuracy*

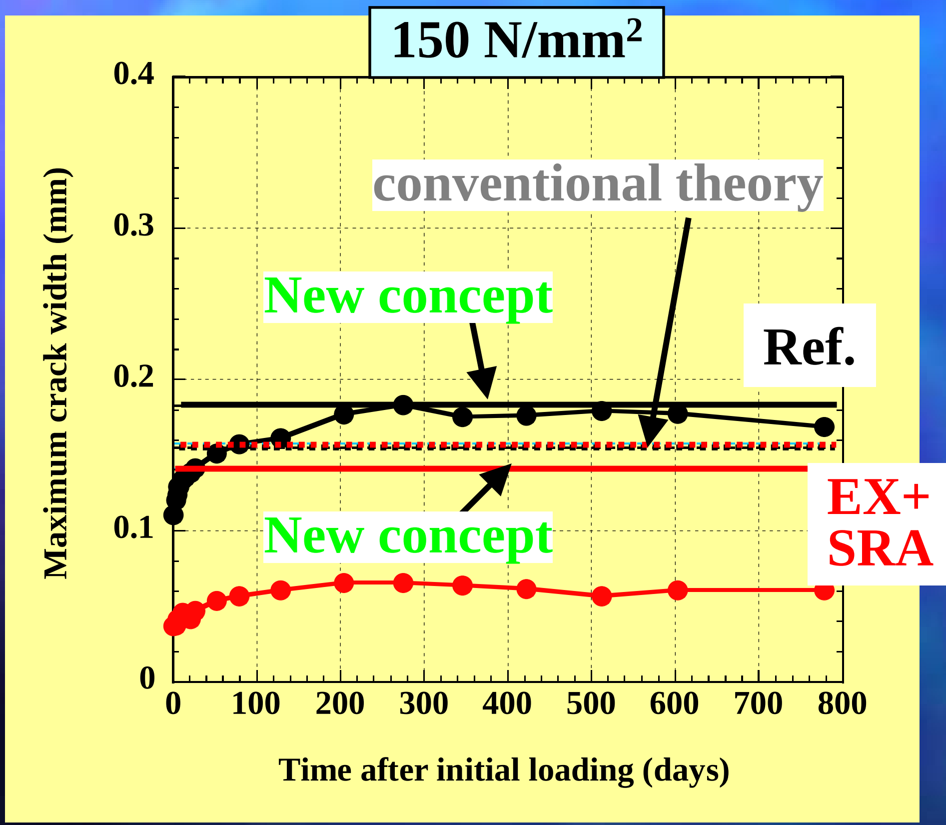
Validity of the proposed concept for evaluating time-dependent crack width

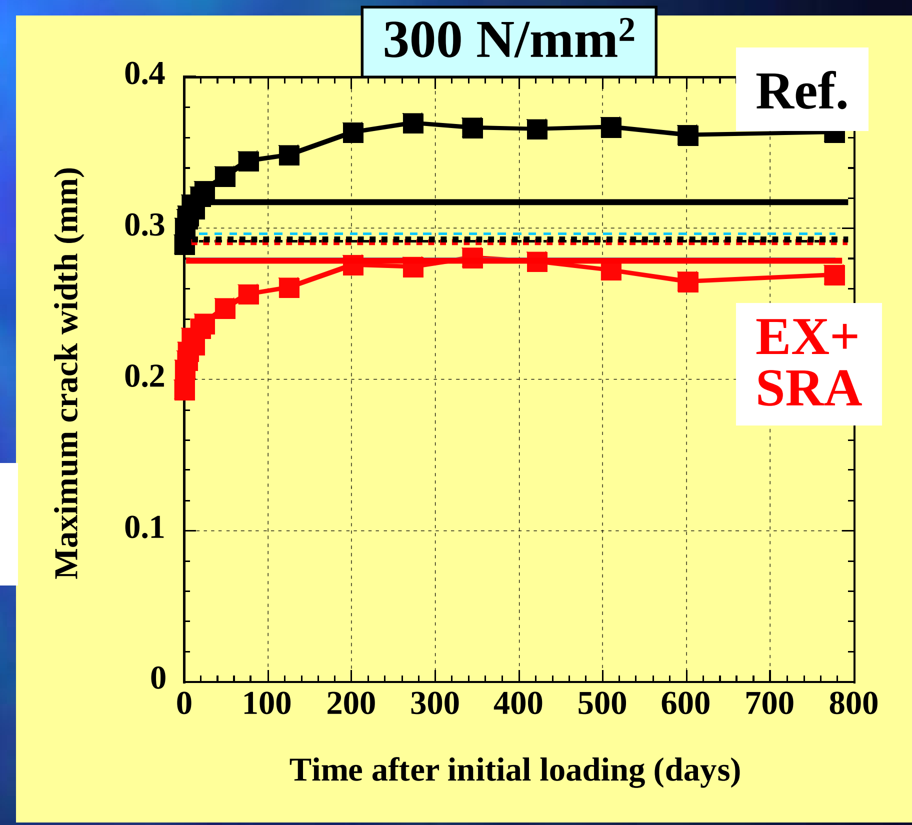
✧JSCE Design Code

$$w = 1.1k_1k_2k_3\{4c + 0.7(c_s - \phi)\}\left[\frac{\sigma_{se}}{E_s} + \varepsilon'_{csd}\right]$$

New concept ($\frac{\sigma_{se}}{E_s}$)

ε'_{csd} → $100\text{x}10^{-6}$ for HSC

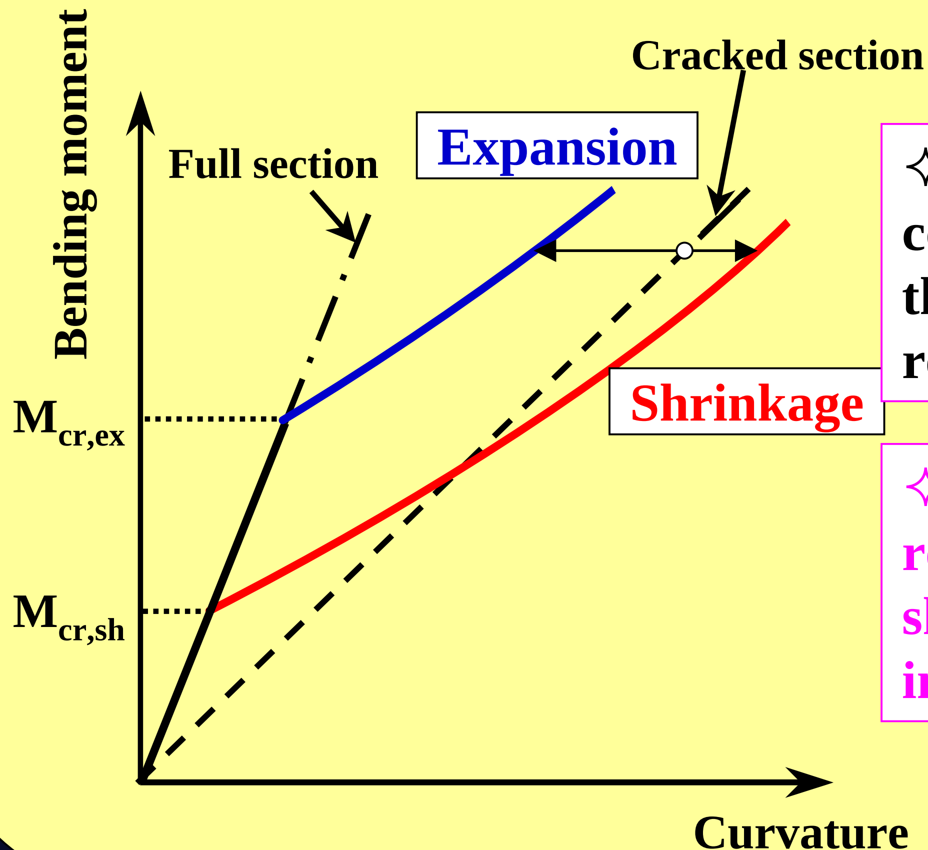




➢*Improved prediction accuracy*

Necessity of new concept for evaluating deformation of HSC with high-AS, less-AS and expansion

Schematic diagram of M-curvature relationship for the case where AS and Expansion is dominant!!

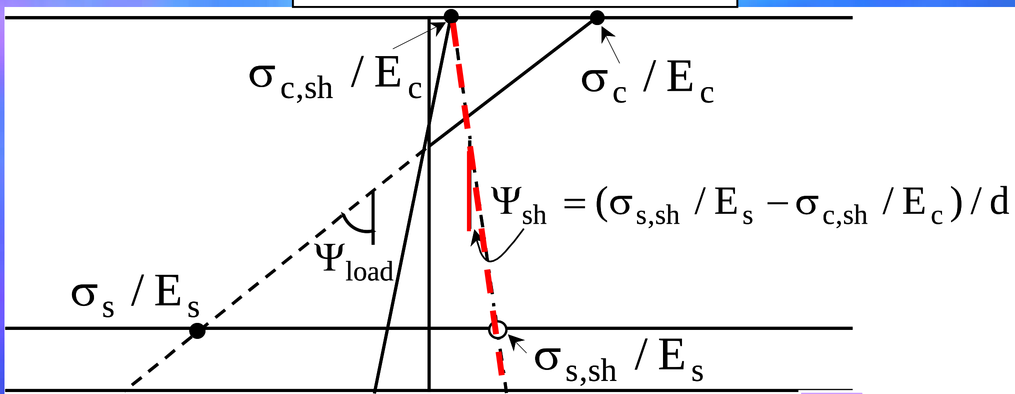


✧Difficult to explain by conventional theory, even though the change in Mcr due to restrained stress is considered.

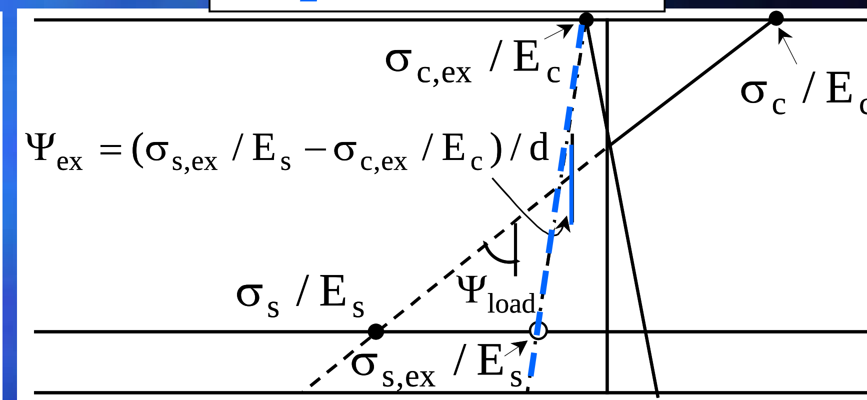
✧Curvature change by the release of restrained stress should be considered in order to improve prediction accuracy.

Basic concept of the effect of restrained-shrinkage/ expansion stress on curvature

Shrinkage case



Expansion case



$$\Psi_{sh} = \left(\frac{\sigma_{s,sh}}{E_s} - \frac{\sigma_{c,sh}}{E_c} \right) / d$$

Shrinkage/expansion -induced curvature

$$\Psi_a = -\Psi_{sh} + \left(\frac{\sigma_s}{E_s} - \frac{\sigma_c}{E_c} \right) / d$$

Shrinkage/expansion + load-induced curvature

- ***Restrained-shrinkage stress contribute to increasing curvature***
- ***Restrained-expansion stress contribute to decreasing curvature***

Modification of JSCE Code for effective flexural stiffness

✧New concept

$$E_e I_e = \left(\frac{M_{cr}}{M_d}\right)^4 \frac{E_e I_g}{1 - \frac{\Delta M_{csg}}{M_d}} + \left\{1 - \left(\frac{M_{cr}}{M_d}\right)^4\right\} \frac{E_e I_{cr}}{1 - \frac{\Delta M_{cscr}}{M_d}}$$

$$E_e I_{cr} = M_d / \Psi_a$$

$$\Psi_a = -\Psi_{sh} + \left(\frac{\sigma_s}{E_s} - \frac{\sigma_c}{E_e}\right) / d$$

$E_e I_g$: flexural stiffness at full section

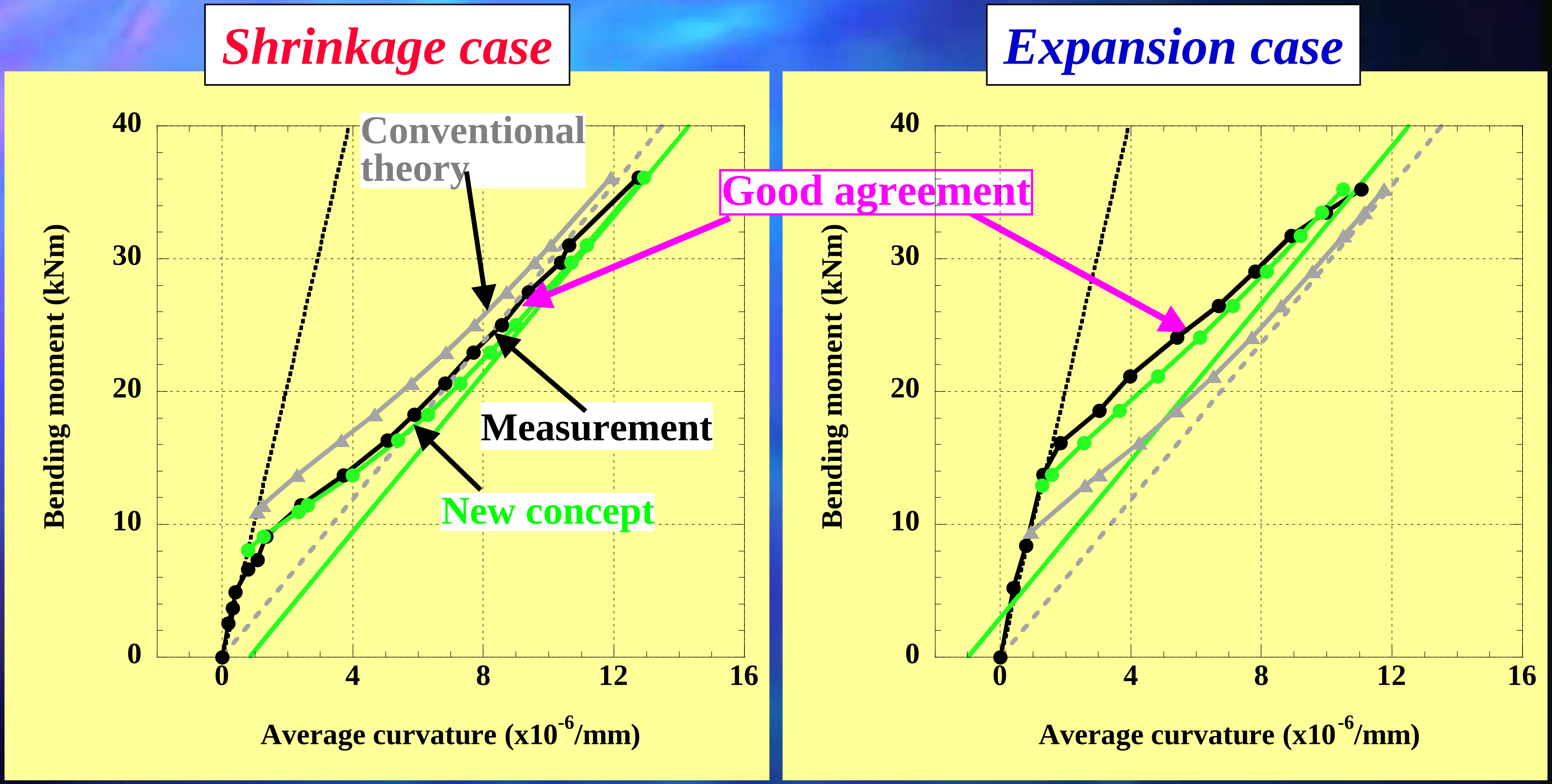
$E_e I_{cr}$: flexural stiffness at cracked section considering the restrained stress

E_e : effective Young's modulus, $E_e = E_{ct} / (1 + \varphi)$

ΔM_{csg}, ΔM_{cscr}: fictitious bending moment caused by shrinkage and restraint of the reinforcement bars at full/cracked section

➢ ***flexural stiffness at cracked section is modified by considering the increased/decreased curvature due to the release of shrinkage/ expansion-induced stress.***

Validity of the proposed equation

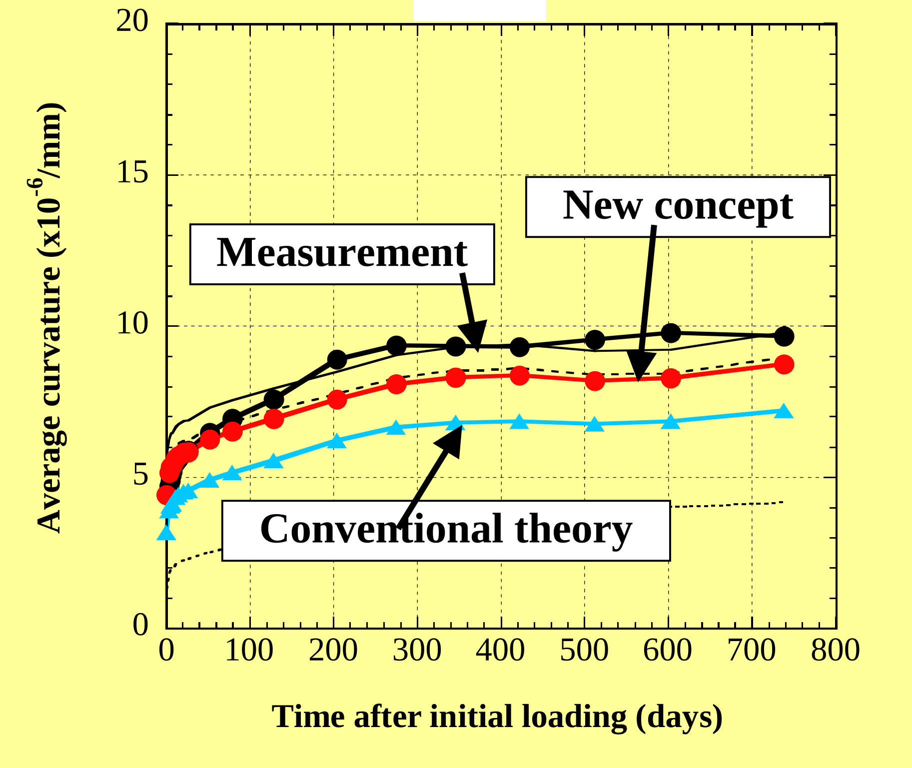


➢ ***Improved prediction accuracy by proposed concept***

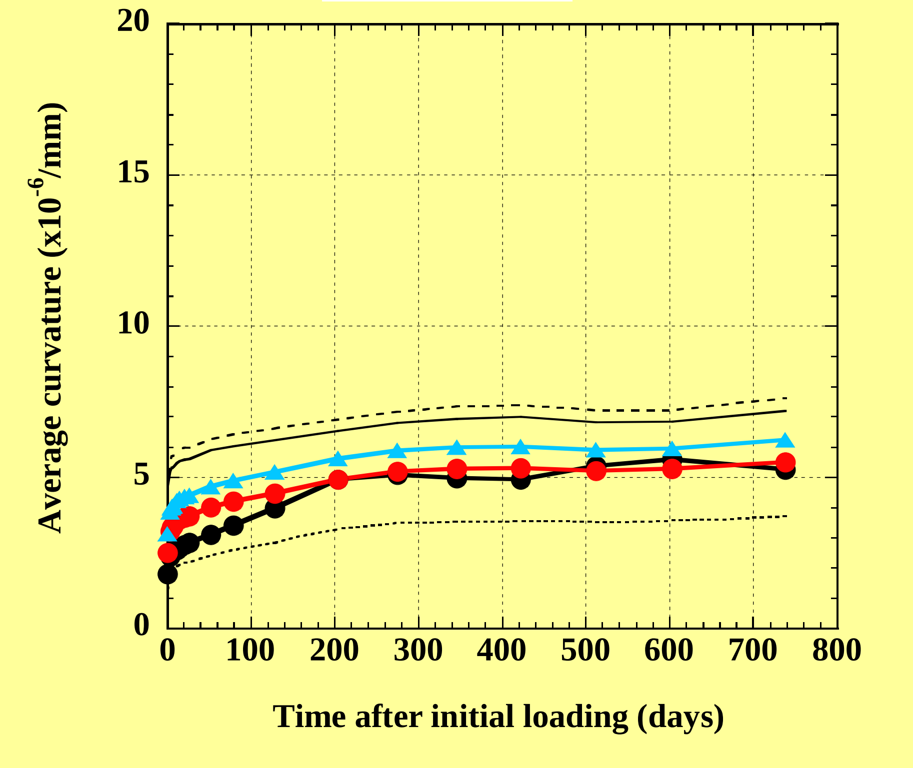
Validity of proposed equation for evaluating time-dependent curvature

Reinforcement stress at fully cracked section=150 N/mm²

Ref.



EX+SRA



➢ ***Improved prediction accuracy***

Summary of general evaluation method

- *Prediction of instantaneous/time-dependent flexural crack widths of high-shrinkage/low-shrinkage HSC;*
  improved accuracy by proposed concept.

- *Prediction of instantaneous/time-dependent deformation of high-shrinkage/low-shrinkage HSC;*
  improved accuracy by proposed equation.
  (in the future, it is expected to adopt in design code)

Thank you !!