Geotechnical Symposium in Roma
16 & 17 March 2006

Special lecture

At the University of Rome "La Sapienza"

INELASTIC DEFORMATION CHARACTERISTICS OF GEOMATERIAL

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Tokyo University of Science

Introduction: in-elastic strain by plasticity, viscosity and cyclic loading, all affected by ageing effect

Elasto-plasticity: yielding characteristics

Viscosity: three types (*Isotach*, *TESRA* and *P&N*); and viscosity of other materials

Cyclic loading effect: interactions and particle shape effect

Ageing effect

1D consolidation of clay

Summary

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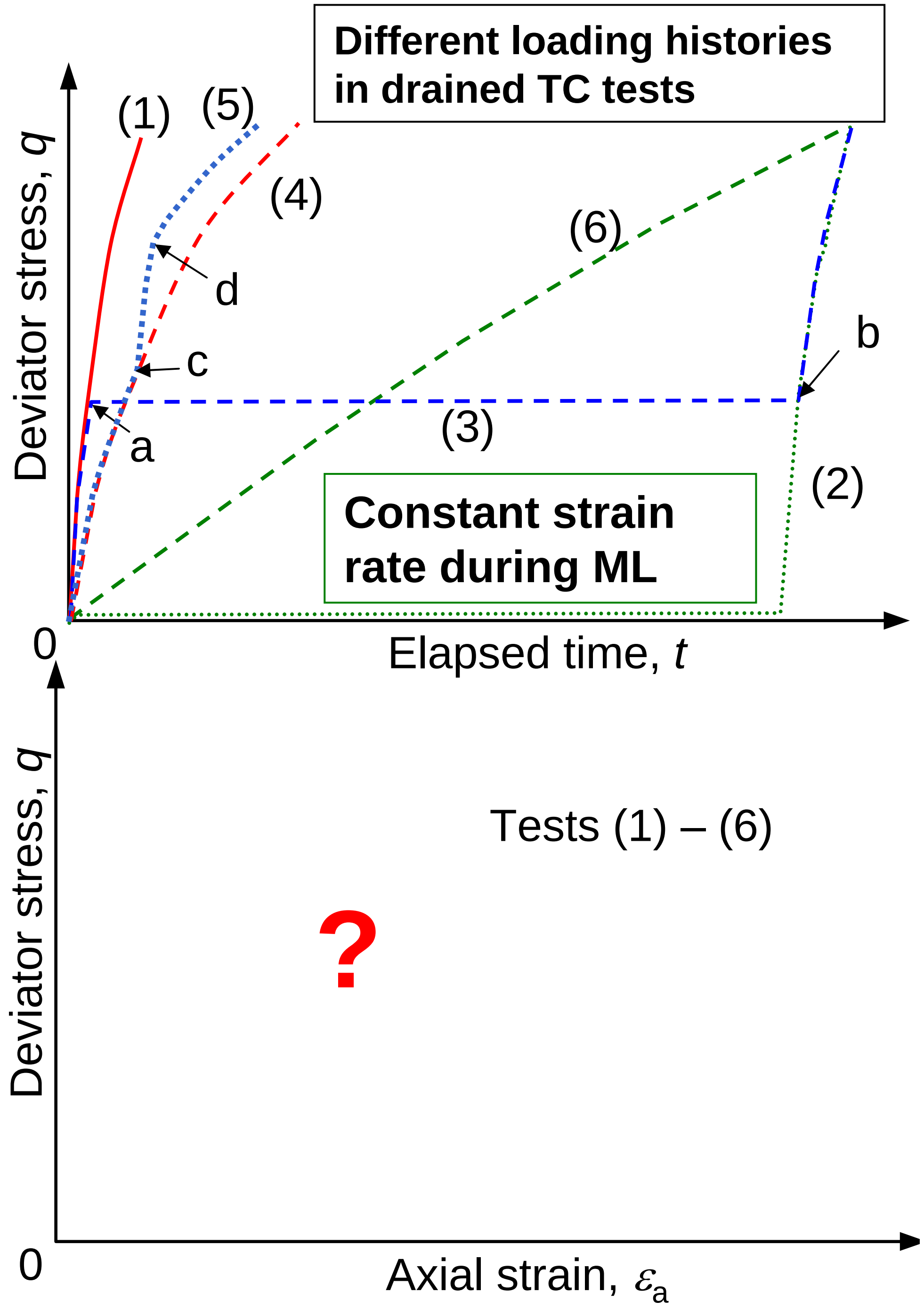
Summary

What is the response of geomaterial ?



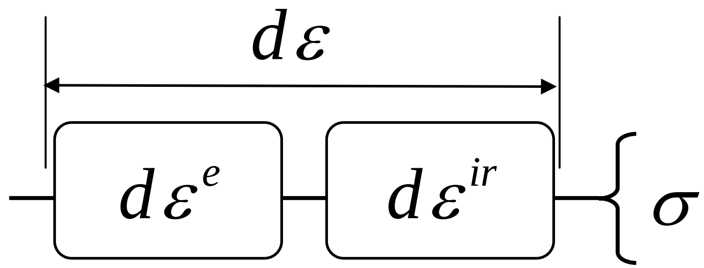
How to predict a strain increment, $d\varepsilon$?

Generally accepted concept:

$d\varepsilon$ = elastic component, $d\varepsilon^{e}$,

+

in-elastic (or irreversible) component, $d\varepsilon^{ir}$



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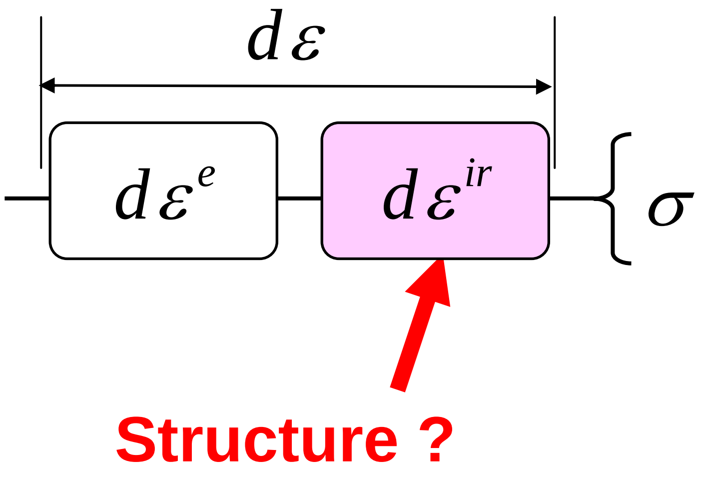
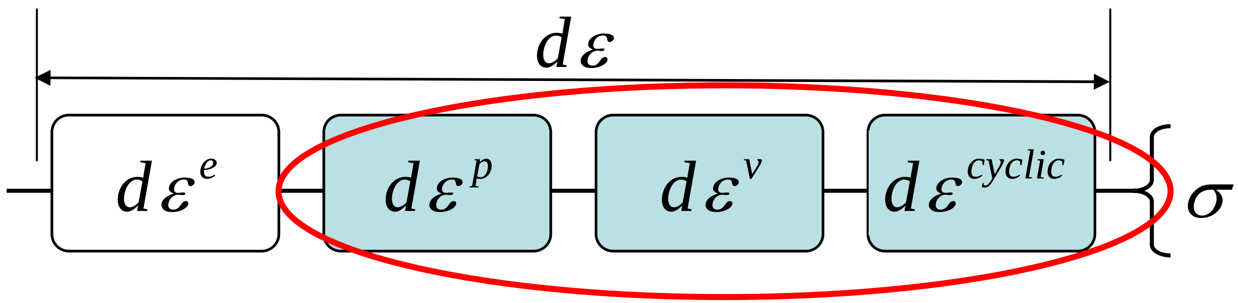


Three major causes for $d\varepsilon^{ir}$:

- **plastic (i.e., rate-independent) yielding;**
- **viscous (i.e., rate-dependent) deformation; &**
- **cyclic loading effect,**

all affected by ageing effect.

Can $d\varepsilon^{ir}$ be separated into three independent components ?



Extended Maxwell model (strain-additive model)

No ! they cannot be separated.

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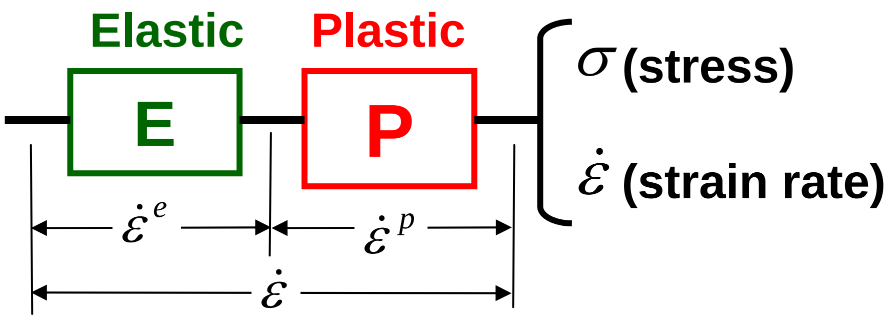
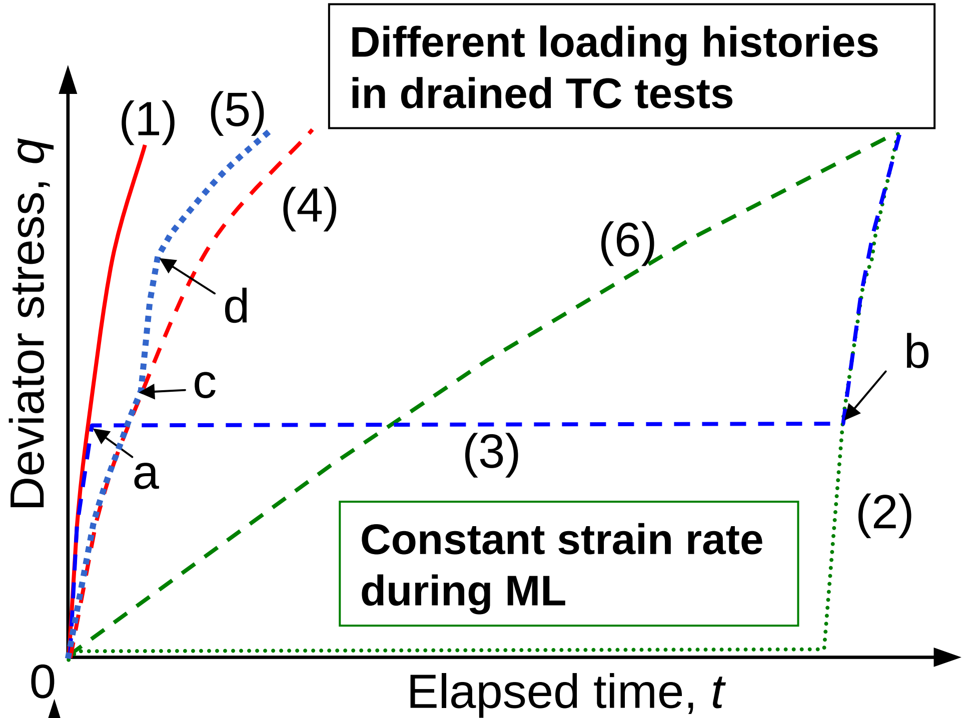
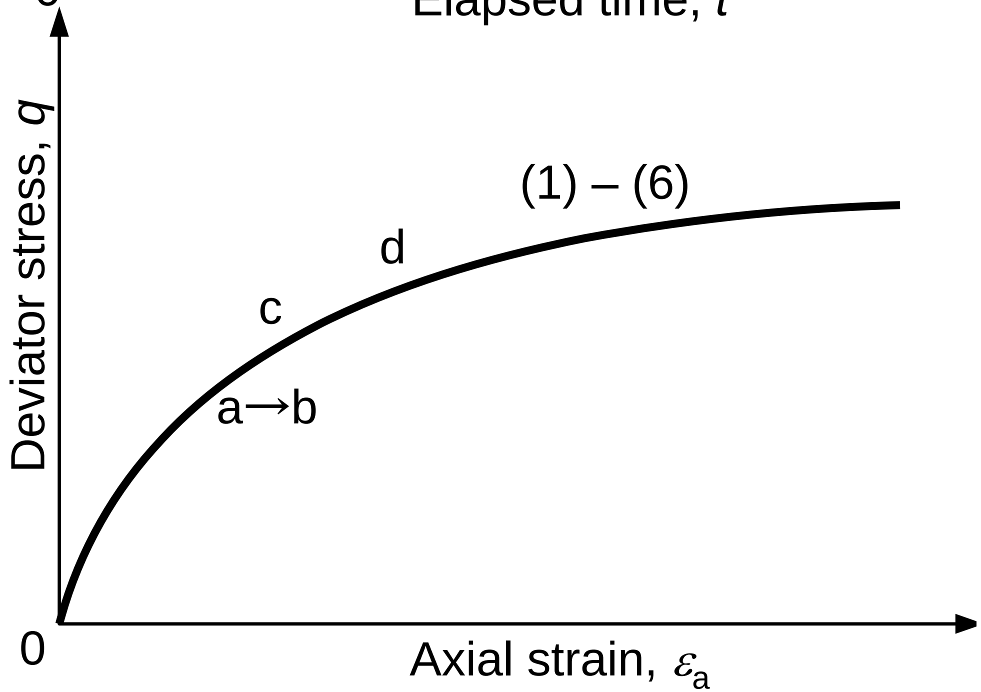
- **Elasto-plasticity: yielding characteristics**
- **Viscosity: three types (*Isotach*, *TESRA* and *P&N*); and viscosity of other materials**
- **Cyclic loading effect: interactions and particle shape effect**
- **Ageing effect**
- **1D consolidation of clay**
- **Summary**

Elasto-plastic

- **no viscosity**
- **no cyclic loading effect**
- **no ageing effect**

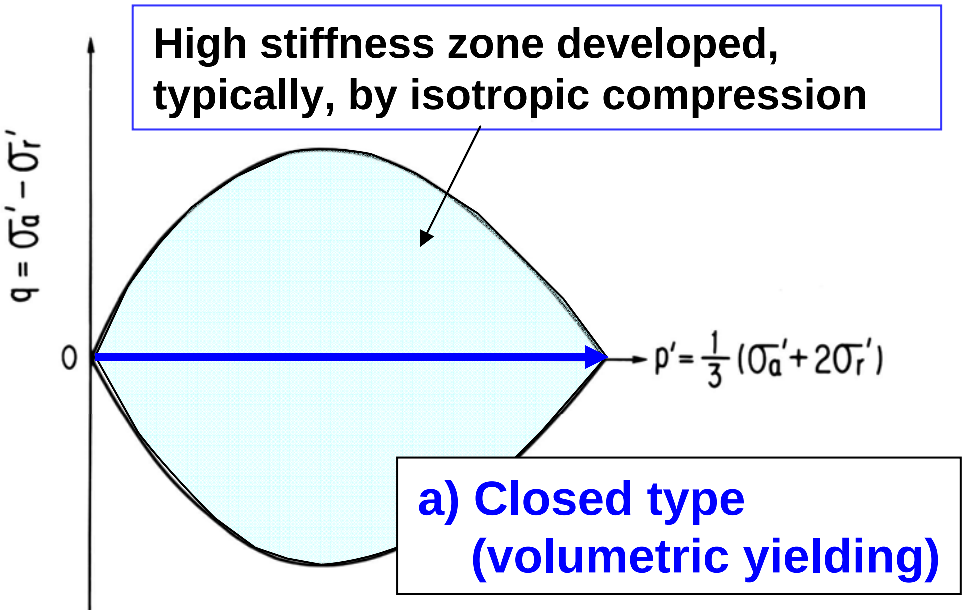


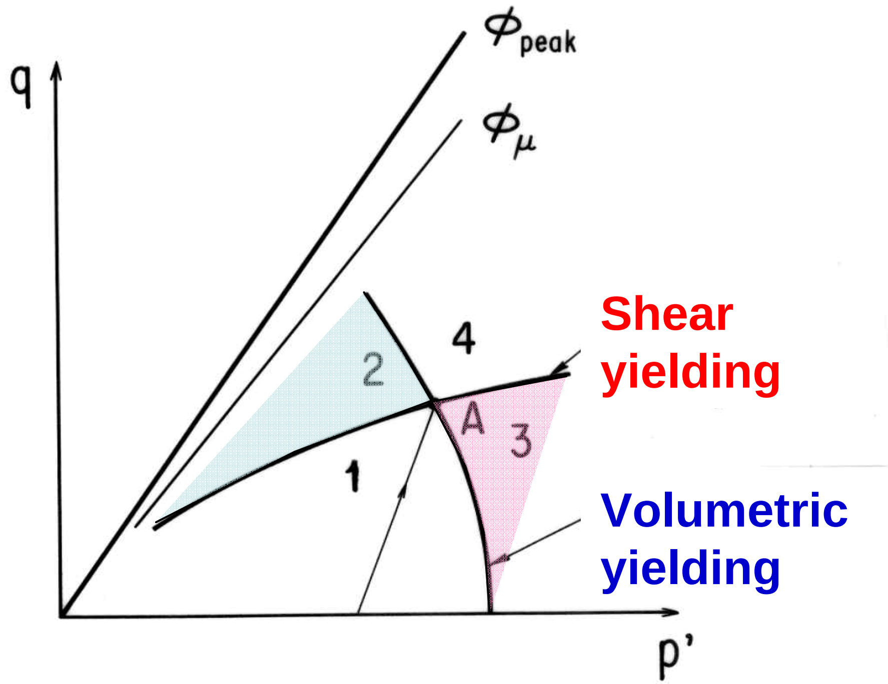


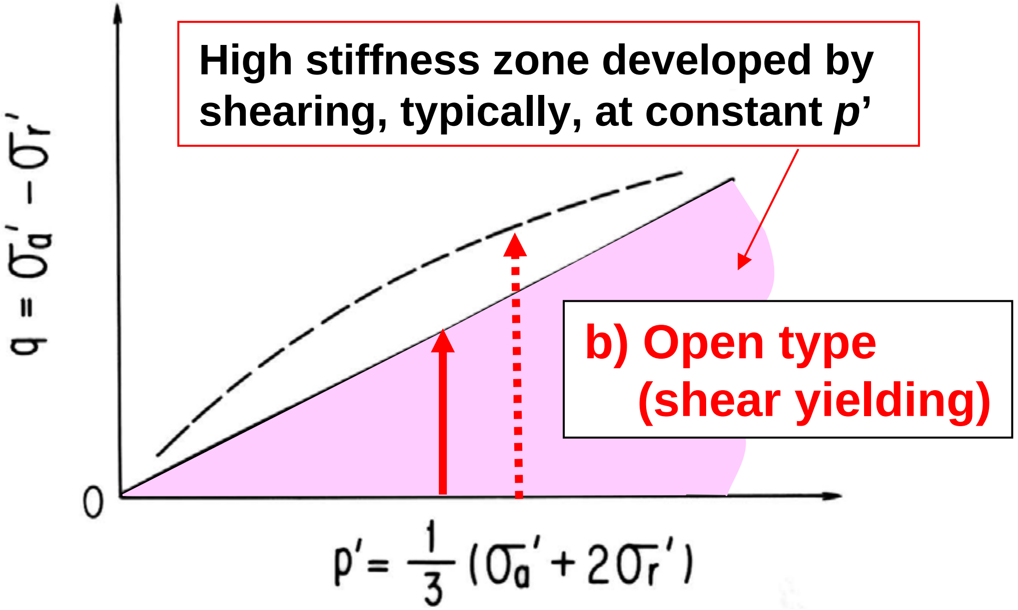


A unique stress-strain curve for all tests 1 – 6

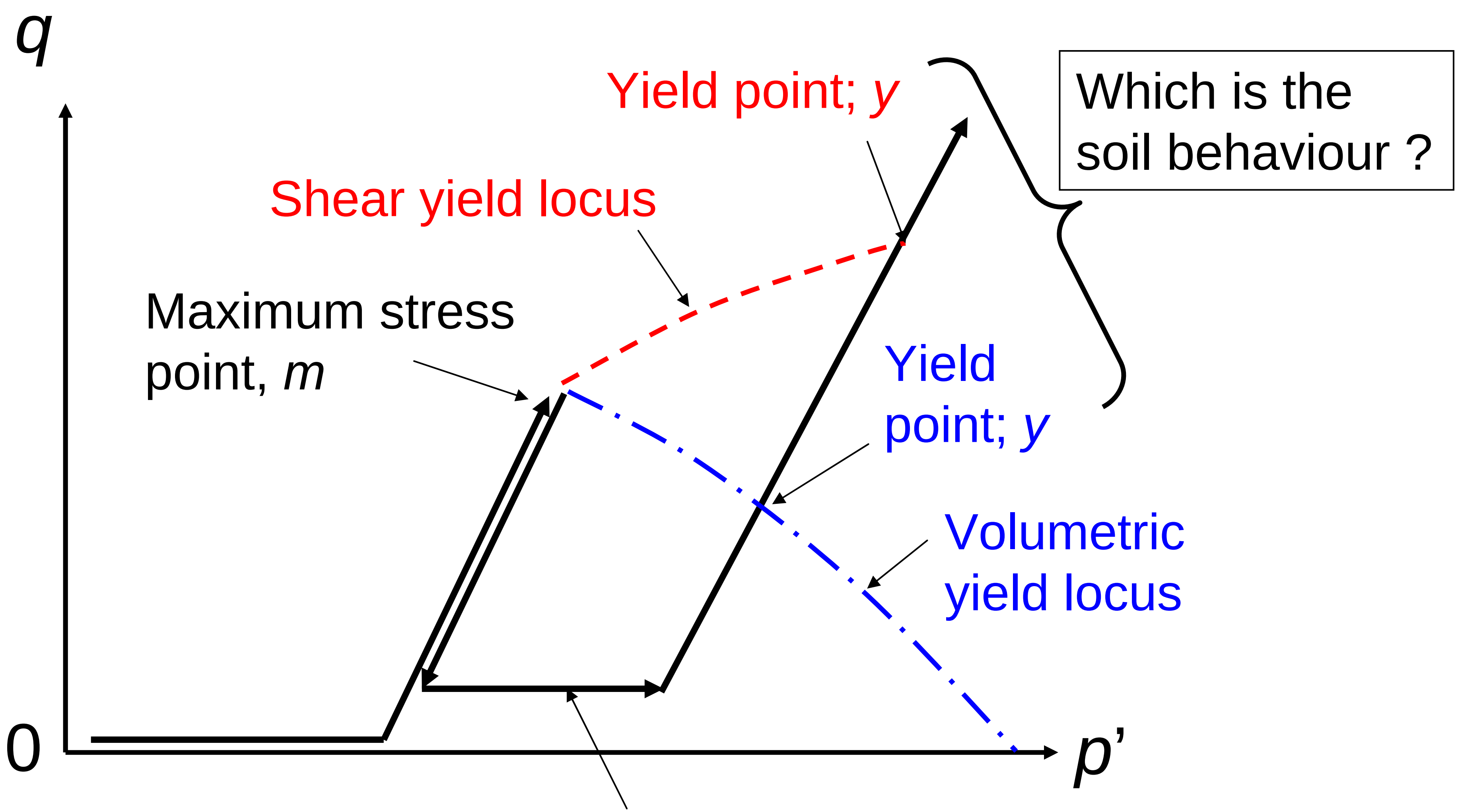
Two major yield locus types





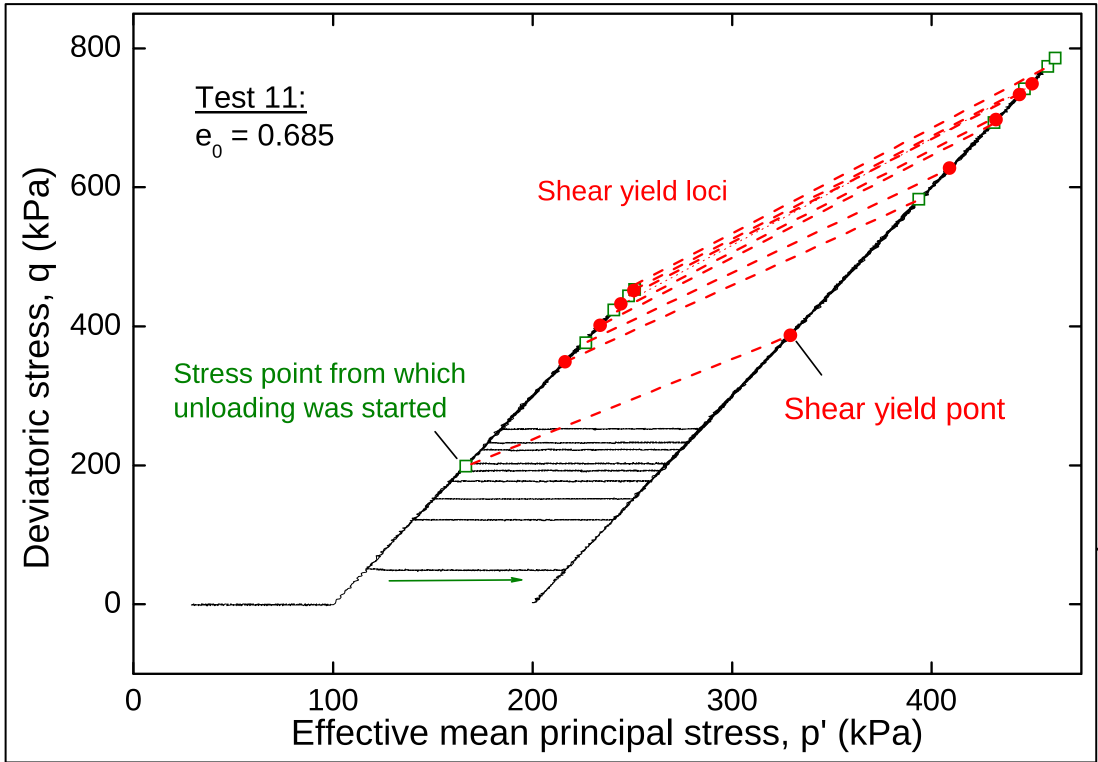


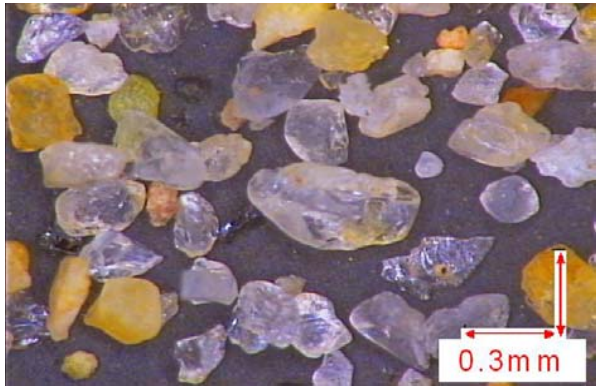
Zone	Shear	Volumetric
1	unloading	unloading
2	loading	unloading
3	unloading	loading
4	loading	loading

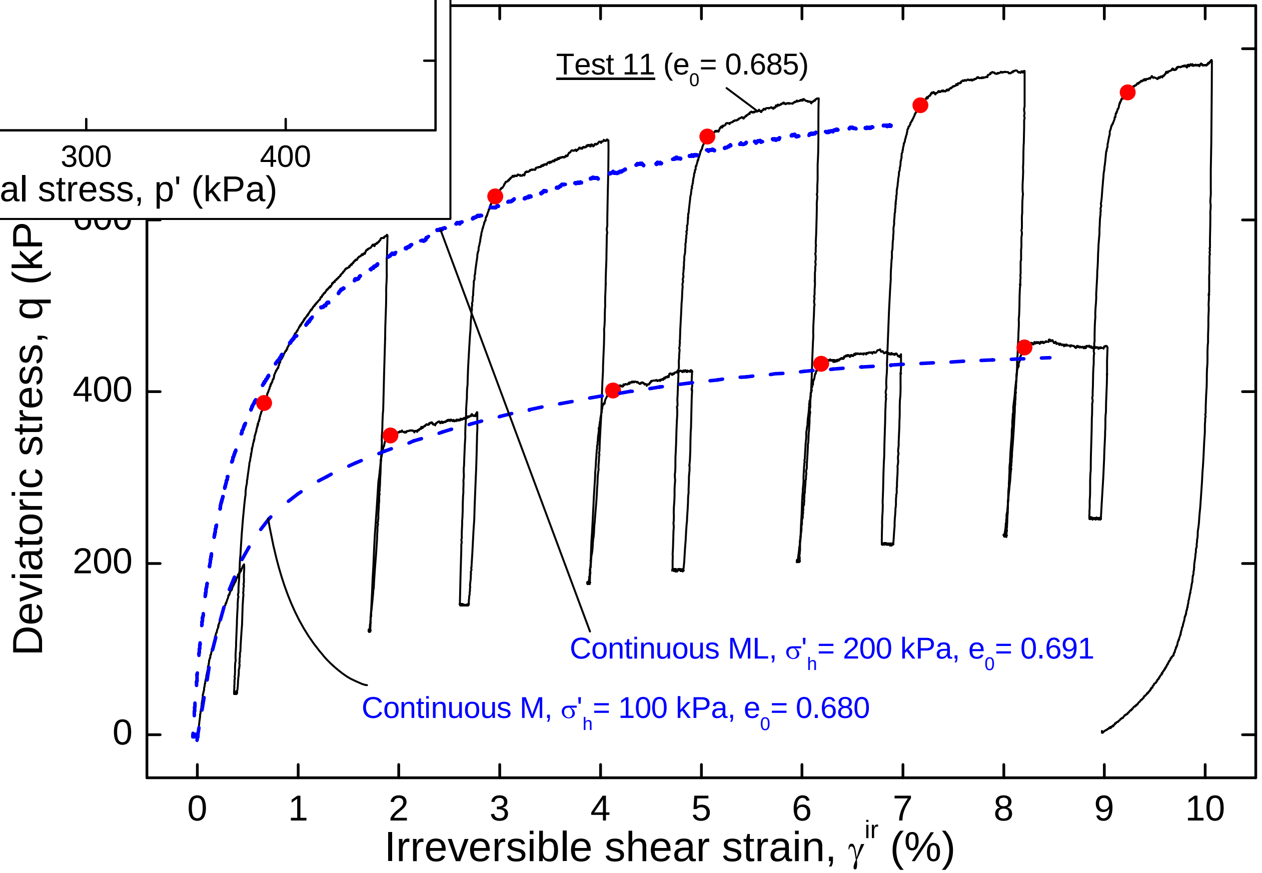


Stress path to evaluate the yielding property of sand, first employed by Poorooshasb et al. (1967) & Poorooshasb (1971)

Dense Toyoura sand, Drained TC



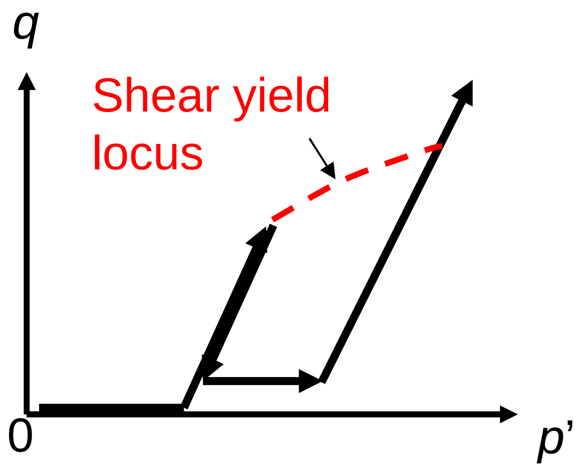


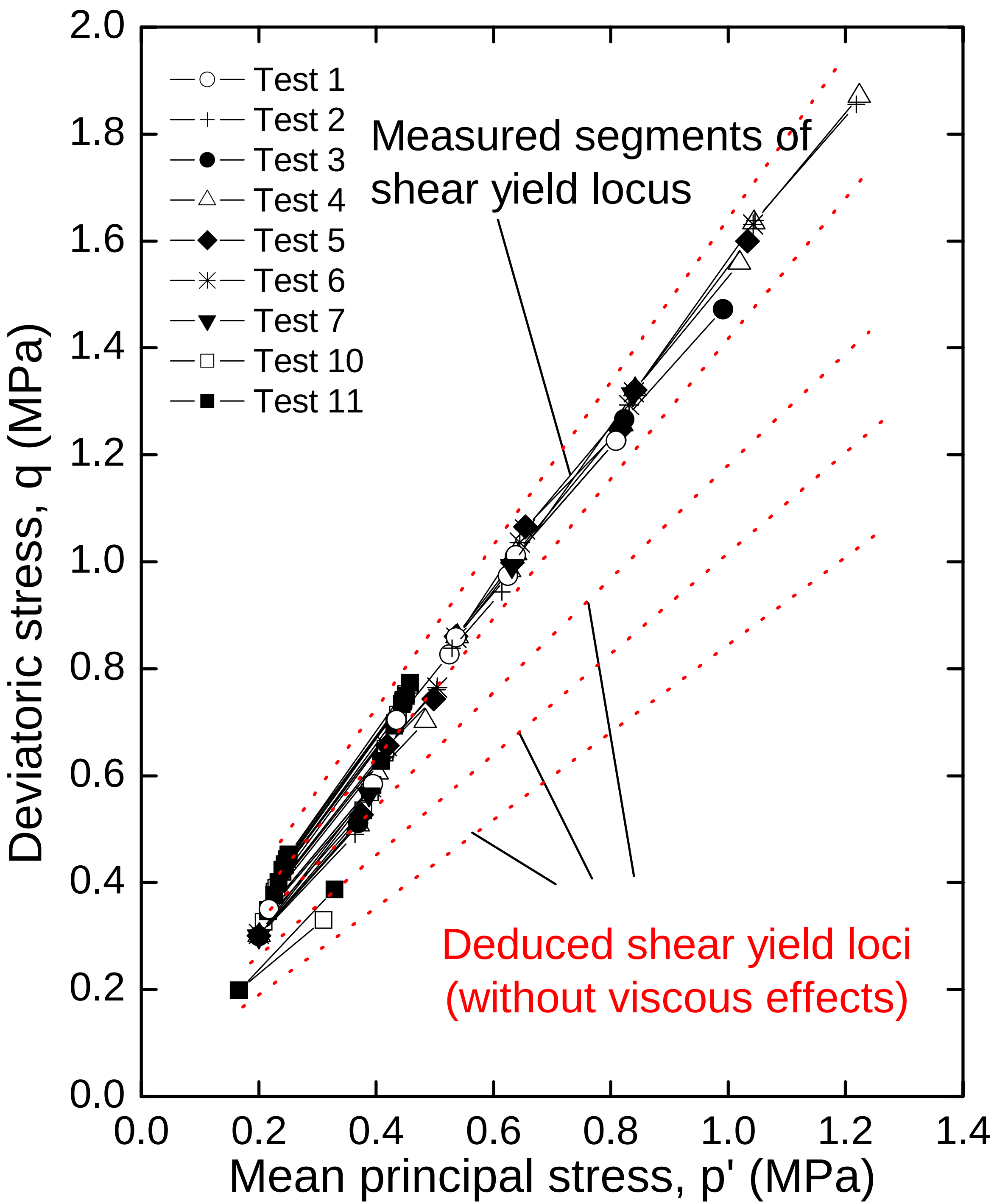


The strain rate (absolute value) was always kept constant to maintain the viscous effect constant.

Nawir et al. (2003b) *S & F*

Summary:



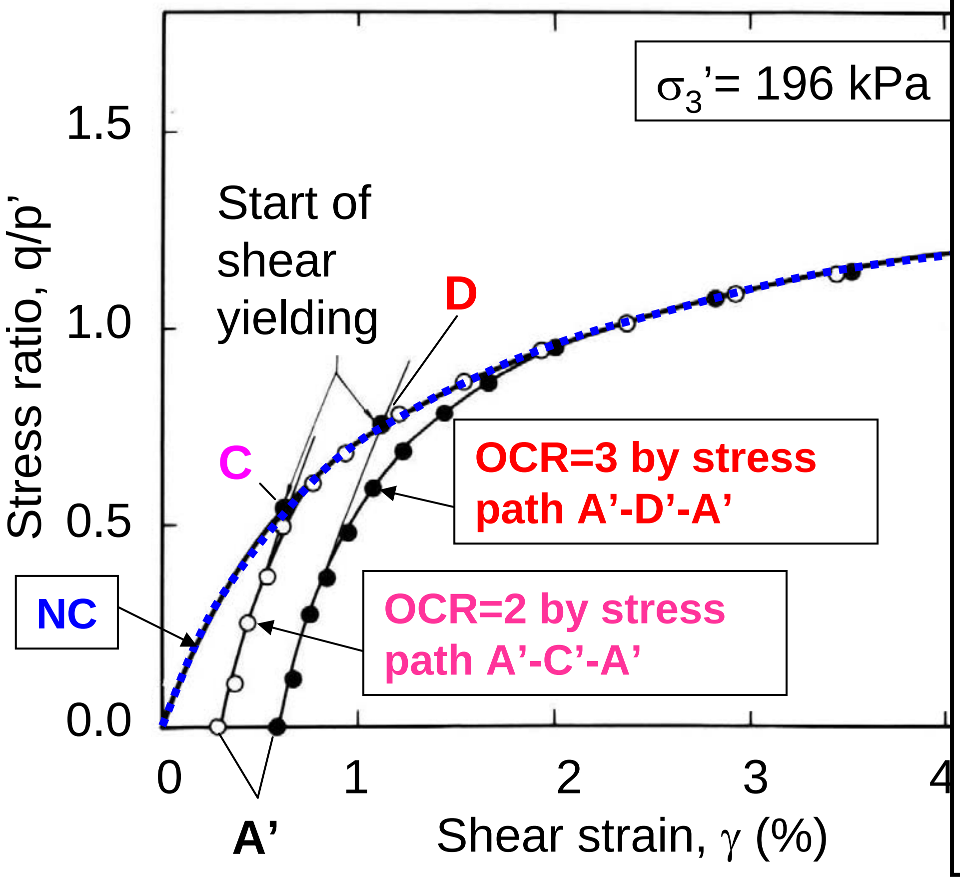


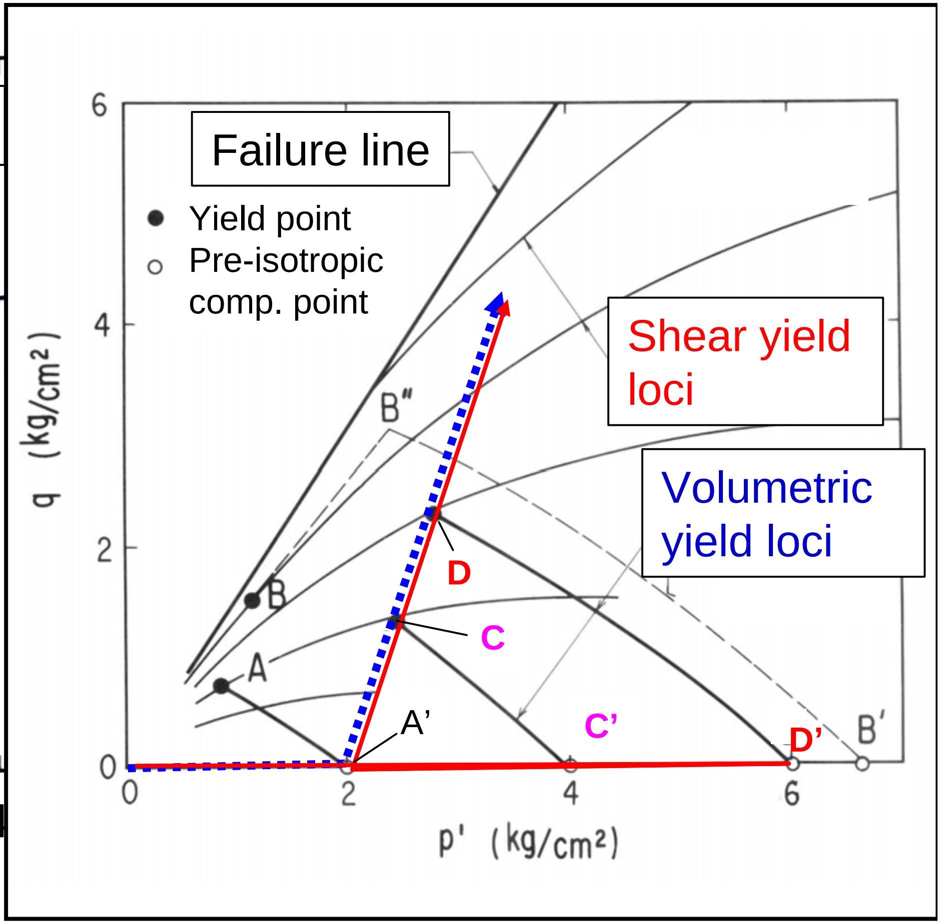
Some variance is due to viscous effects

Nawir et al. (2003b) *S & F*

Loose Fuji river sand, drained TC

Shear yielding cannot explain effects of isotropic OC.





The horizontal coordinates of points A' have been shifted so that all the stress-strain curves overlap after the start of yielding.

Tatsuoka & Molenkamp (1983)

Loose Fuji river sand, drained TC

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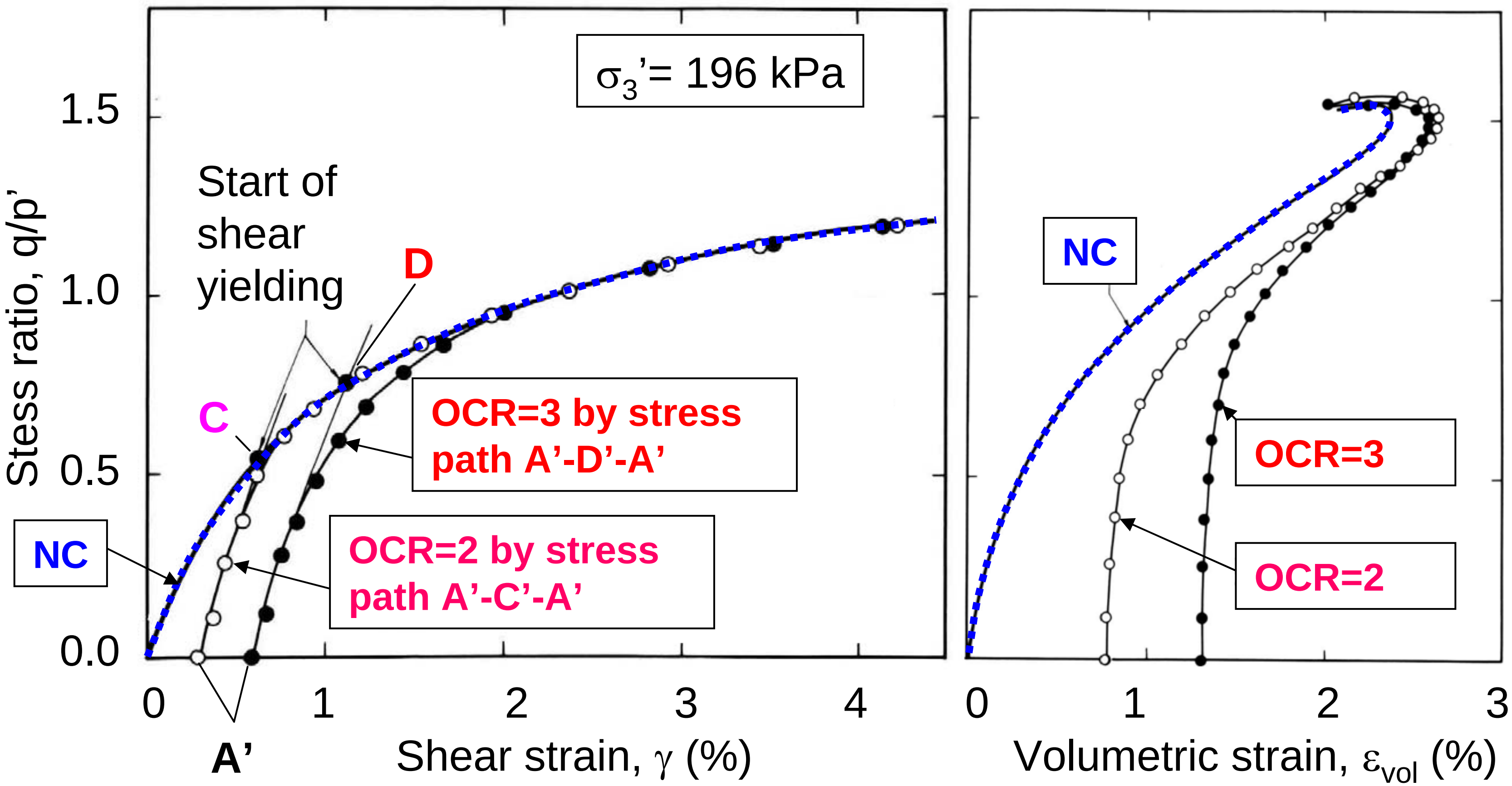

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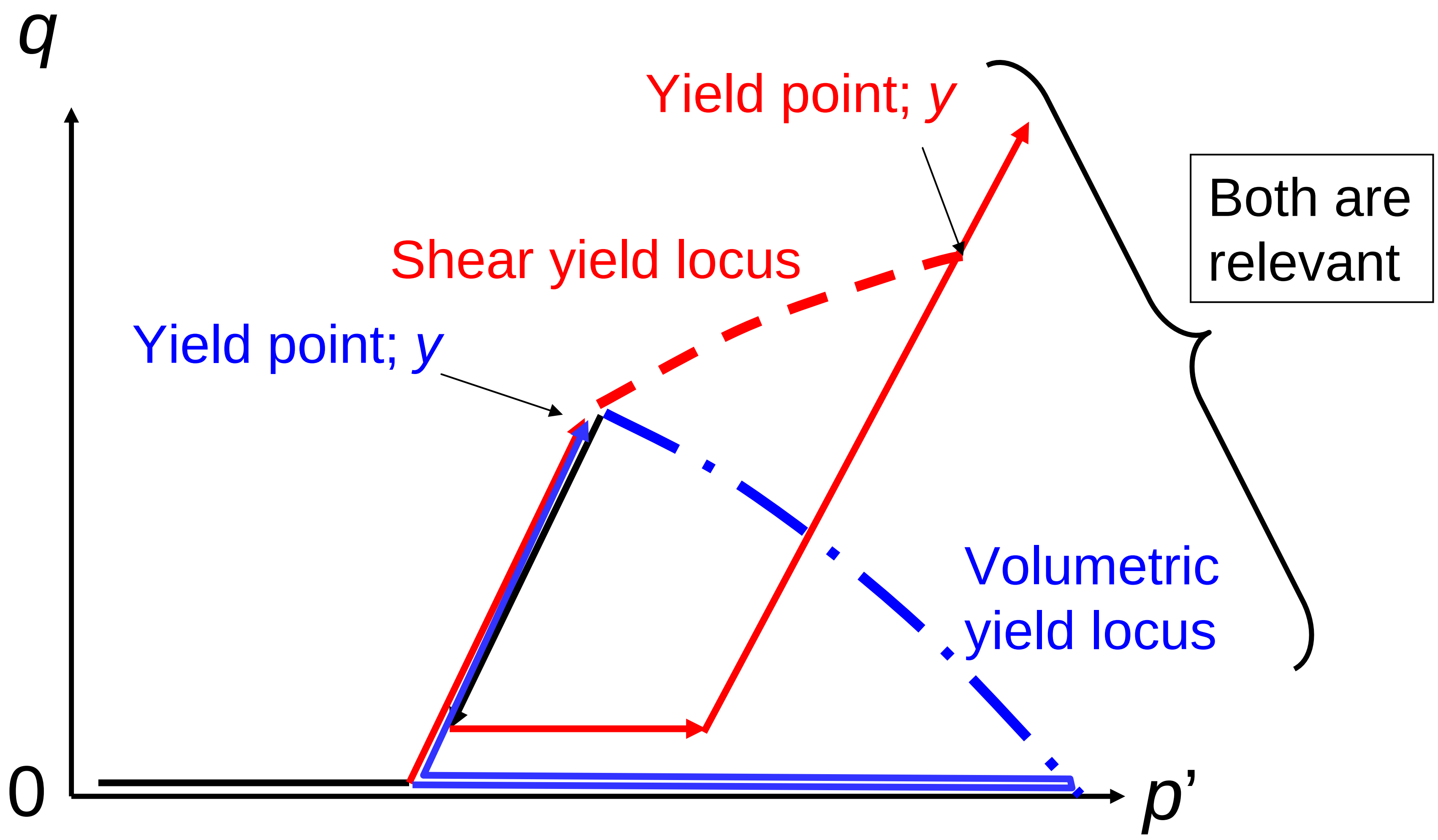

- Volumetric yielding: ***dominant with soft clay***

- Shear yielding: ***dominant with dense sand & gravel***

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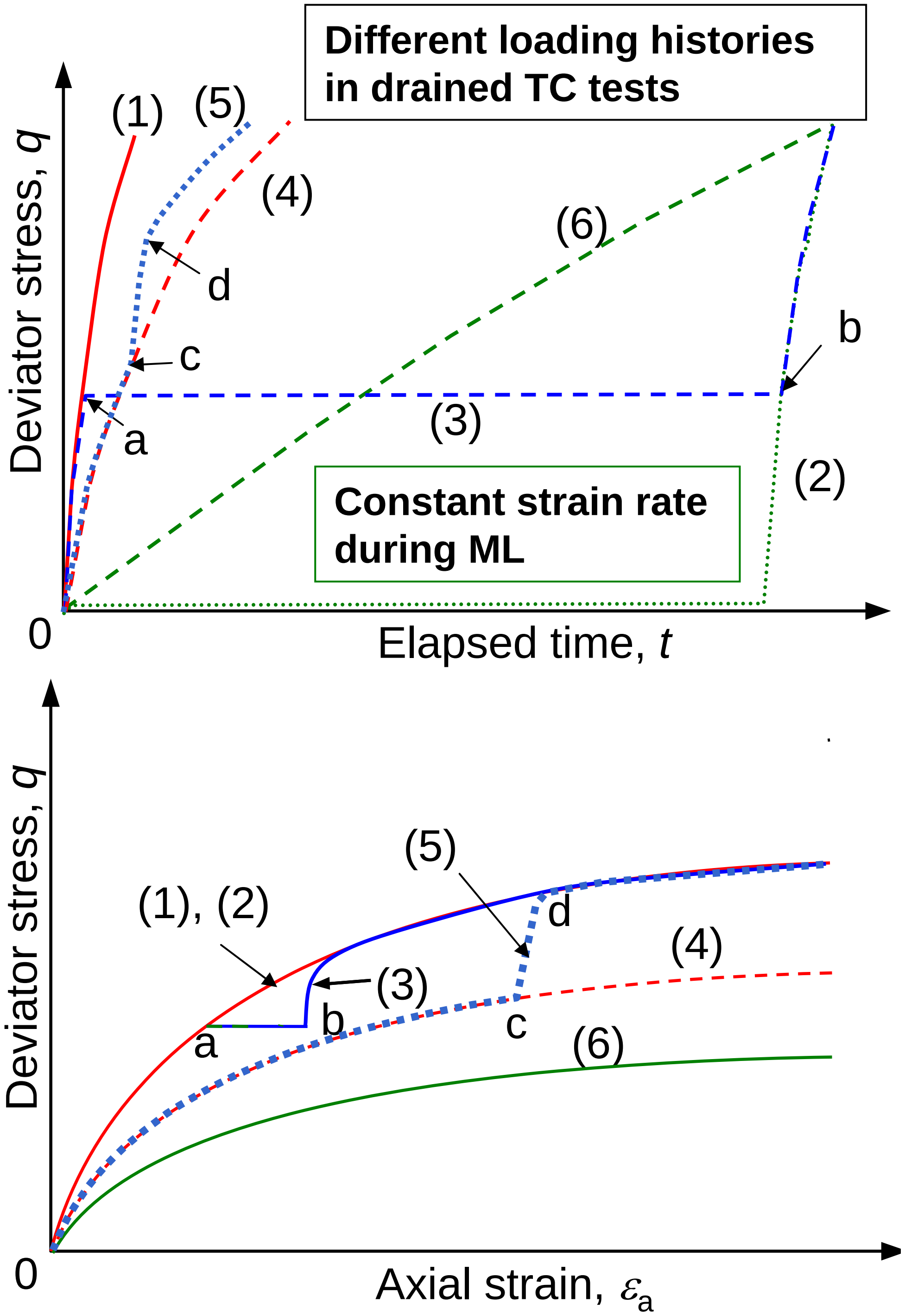
Summary

Elasto-viscoplastic
(shear yielding only & Isotach viscosity)
- no ageing effects

Different stress-strain curves by viscosity, controlled by $\dot{\varepsilon}_a^{ir}$

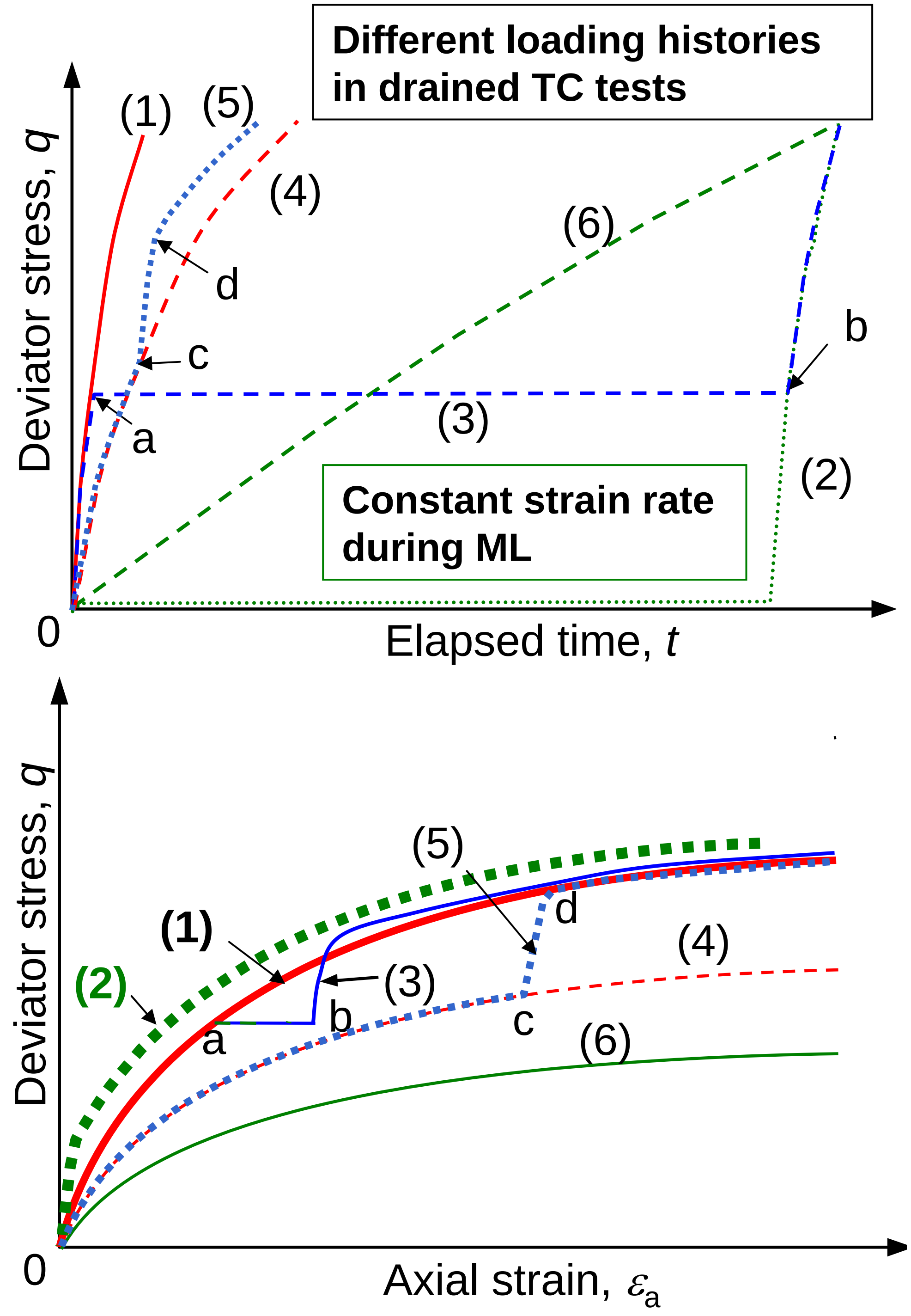
The same stress-strain curves for tests 1 & 2 because of no ageing effect & no volumetric yielding



Elasto-viscoplastic
(double yielding & isotach viscosity)
- no ageing effects

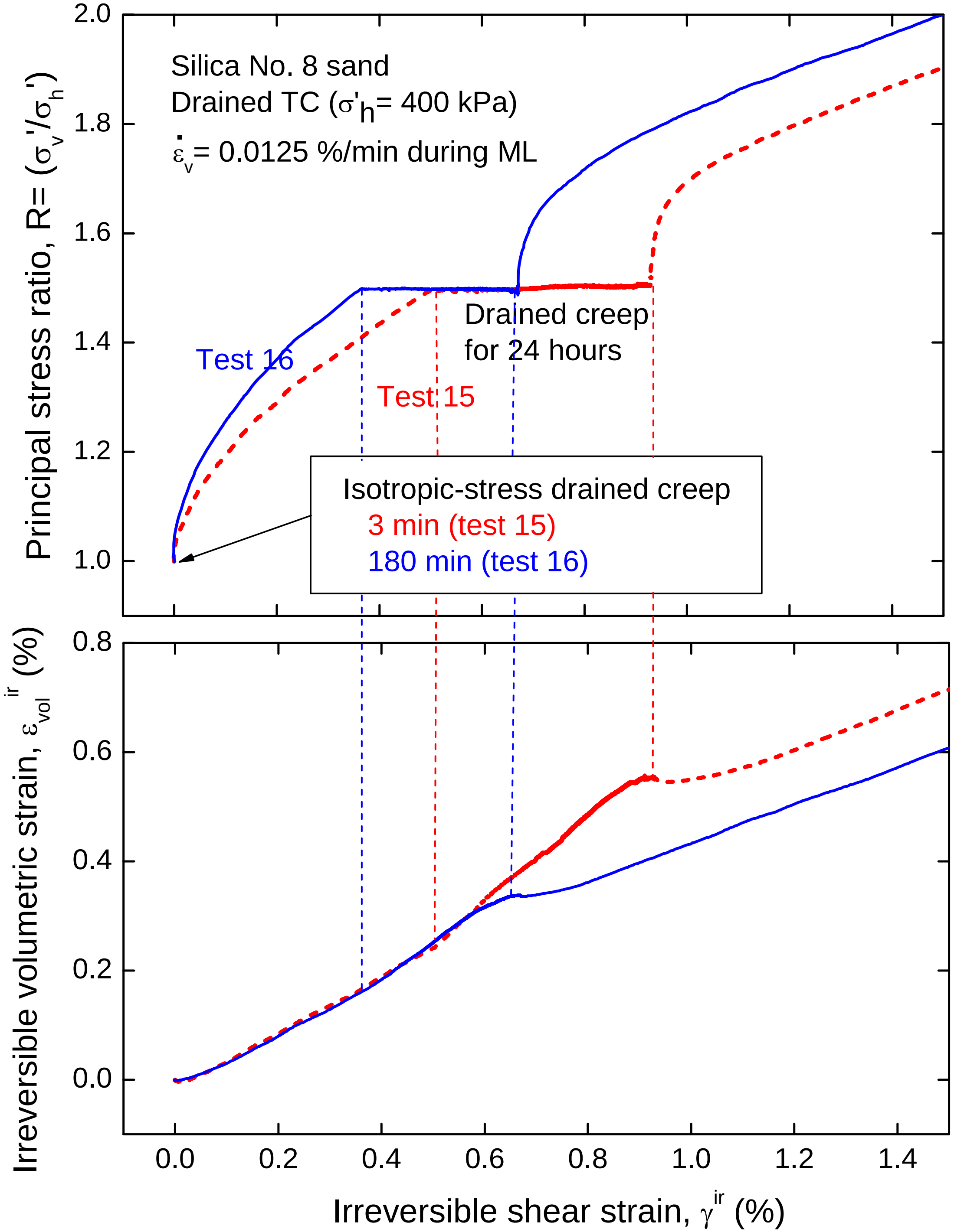
Different stress-strain curves by viscosity, controlled by $\dot{\varepsilon}_a^{ir}$

Different stress-strain curves in tests 1 & 2 due to volumetric creep at *q*= 0 in test 2



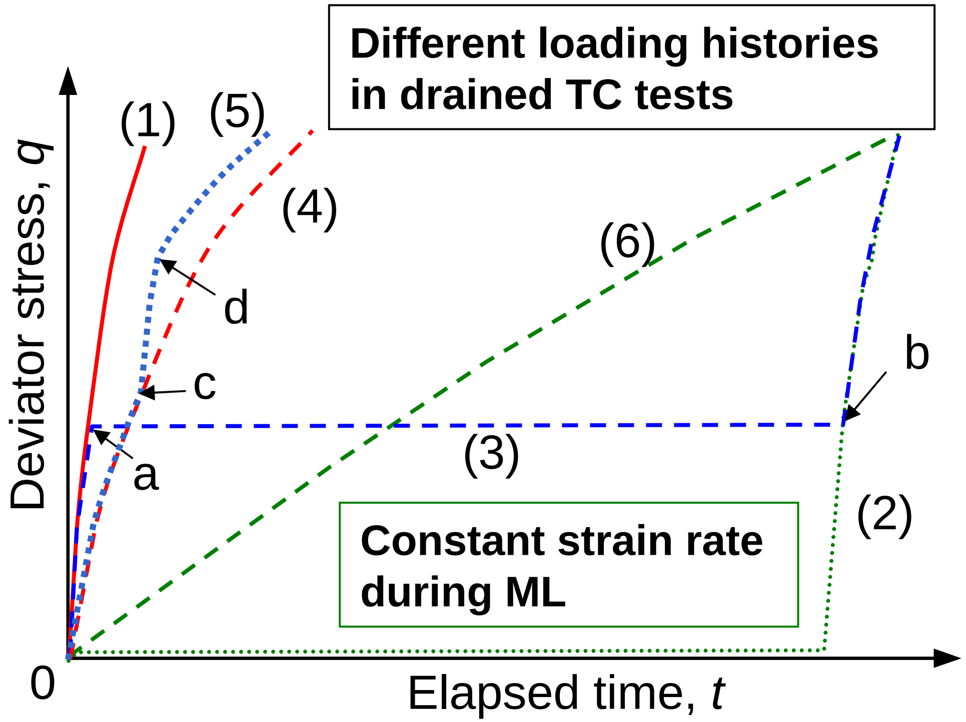
Loose Silica No. 8

Significant effects of volumetric creep at *q*= 0 on the subsequent stress-strain behaviour in drained TC

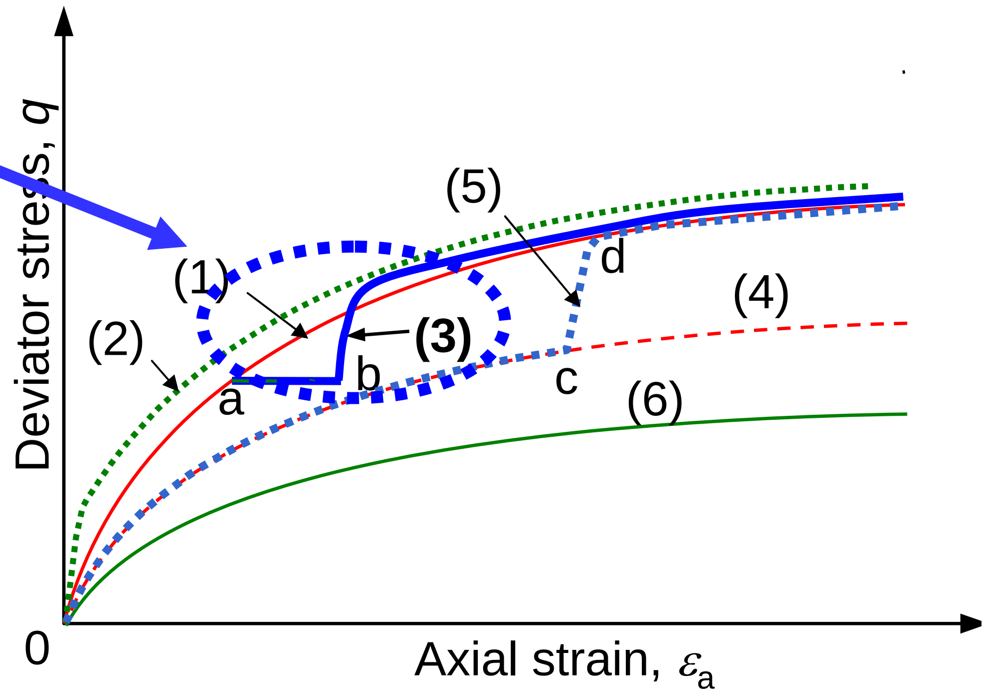


Kiyota et al. (2005);
Kiyota &Tatsuoka (2005), *S &*

Elasto-viscoplastic (double yielding & isotach viscosity) - no ageing effects



Apparent ageing effect due to viscous properties in test 3

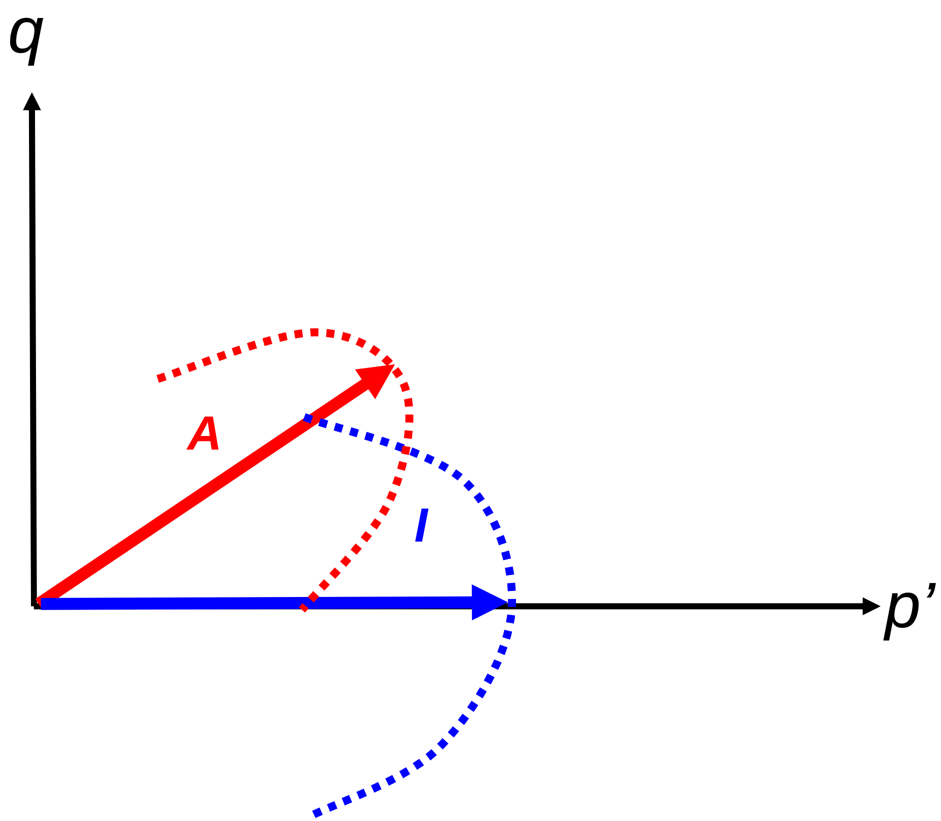


Some existing elasto-plastic models assume different yield loci for:

A. anisotropic (or K_0-) consolidation; &

I. isotropically consolidation,

not taking into account viscous effects.

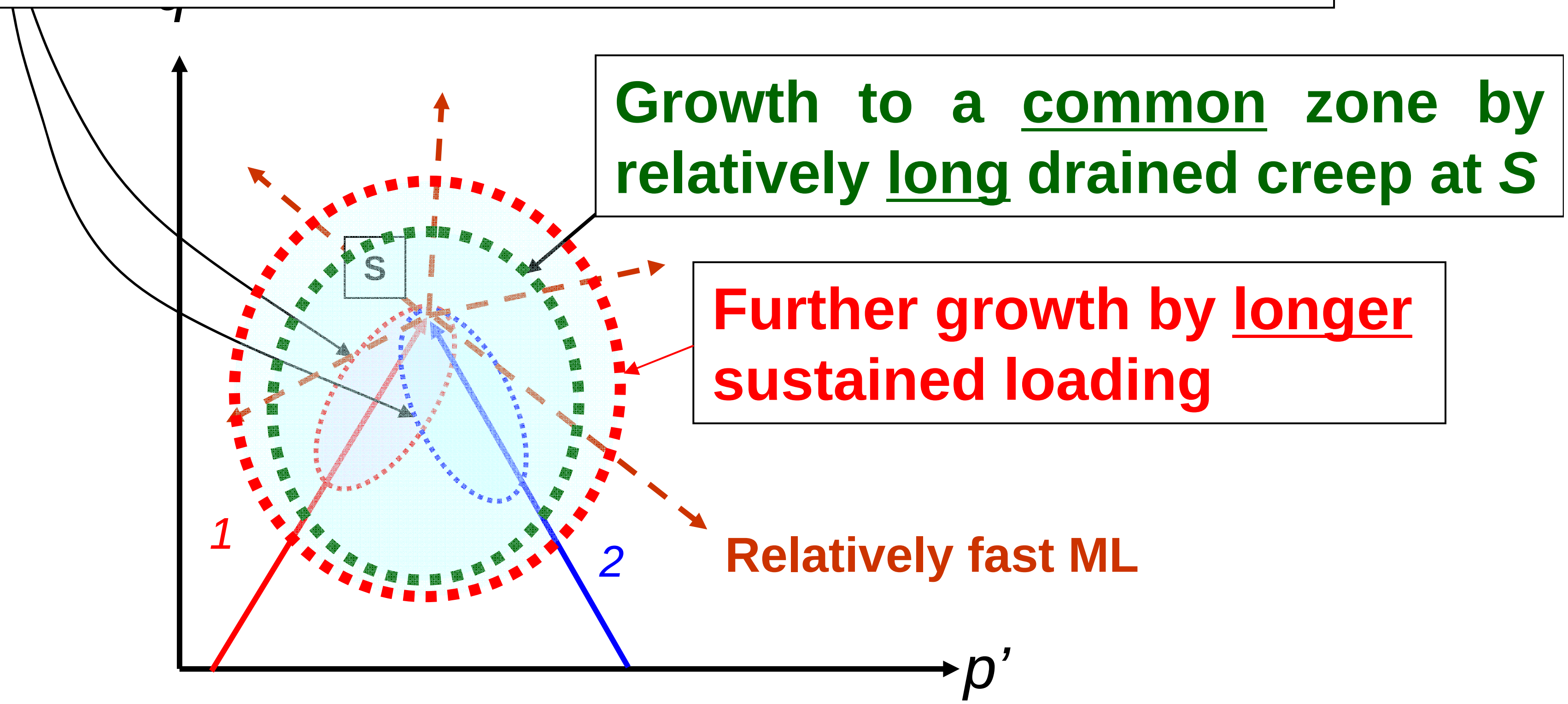


Tatsuoka et al. (1999a) *Hamburg*

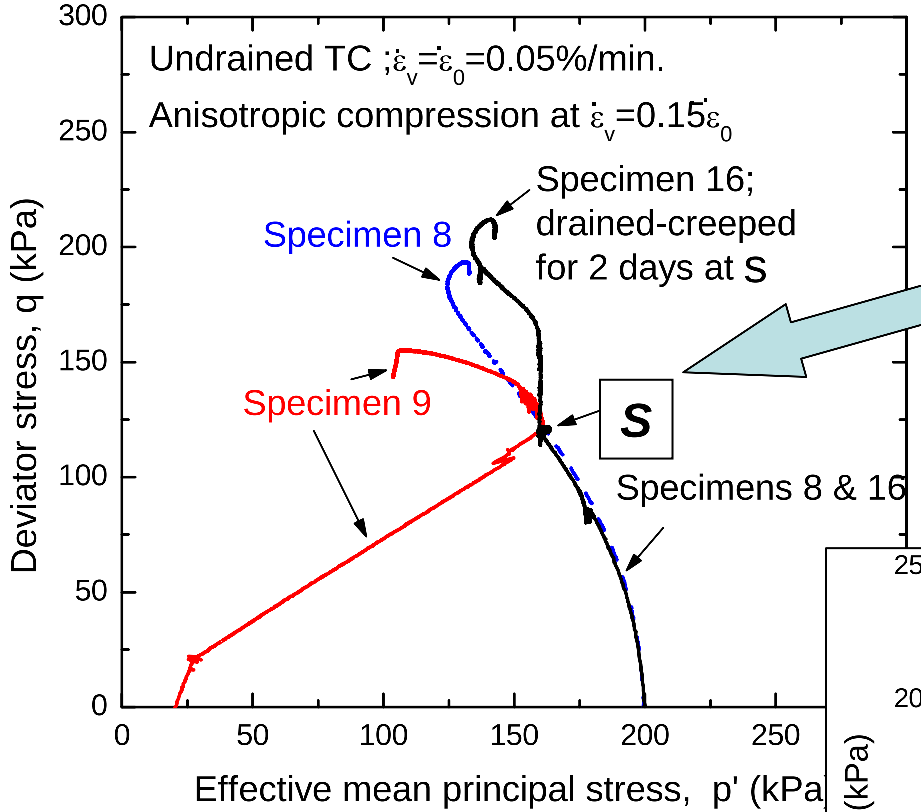
Even without ageing effect……

- **Relatively fast ML along stress paths *1* & *2***
- **Relatively <u>short</u> drained creep at stress point *S***
- **Relatively fast ML**

Then, different high stiffness zones

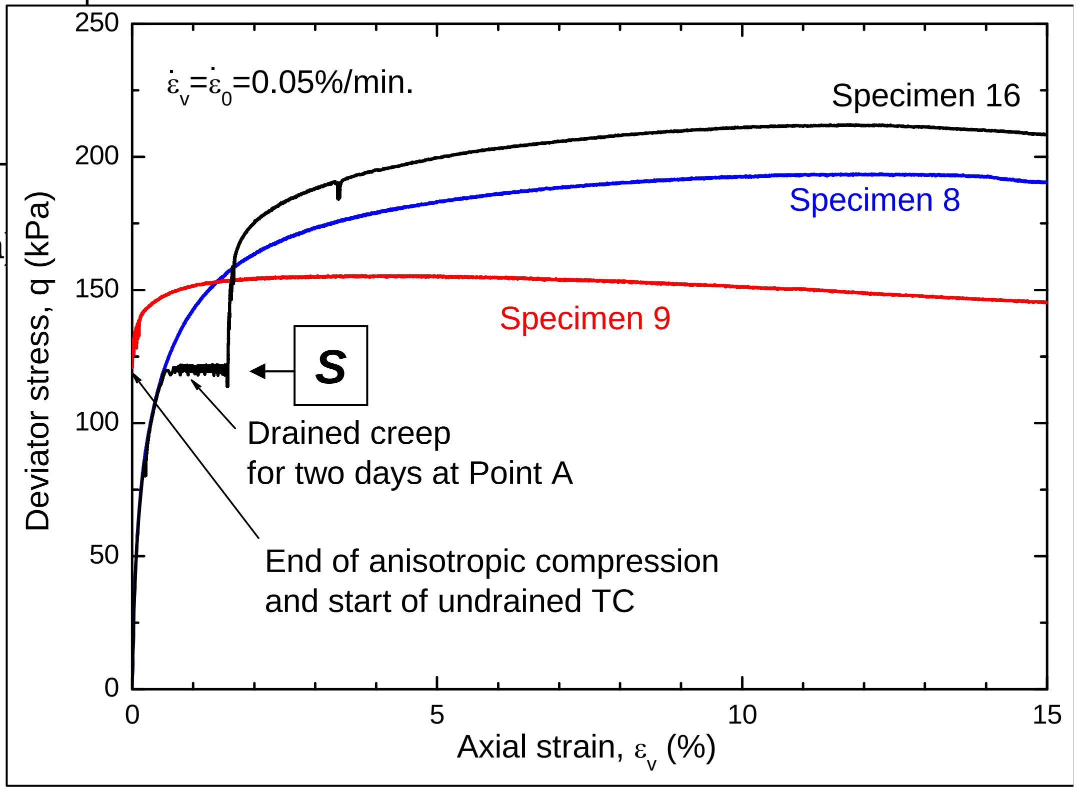


Tatsuoka et al. (1999a) *Hamburg*



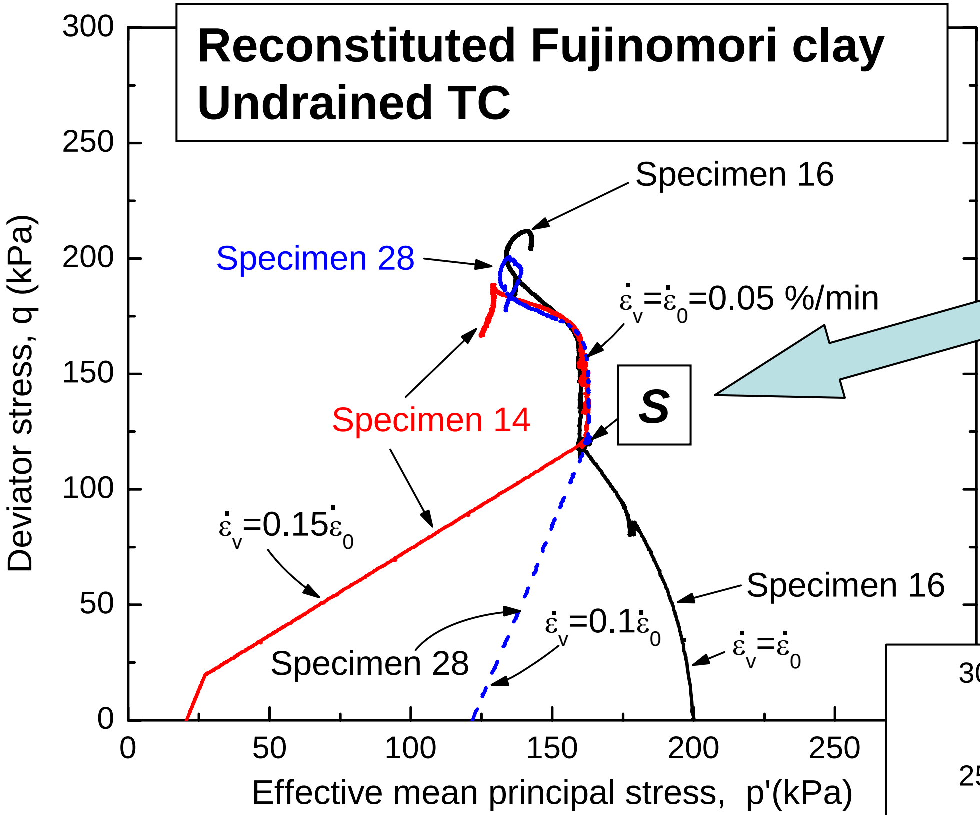
Reconstituted Fujinomori clay
Undrained TC

The yielding is controlled by "drained creep at *S*", little by previous stress paths !



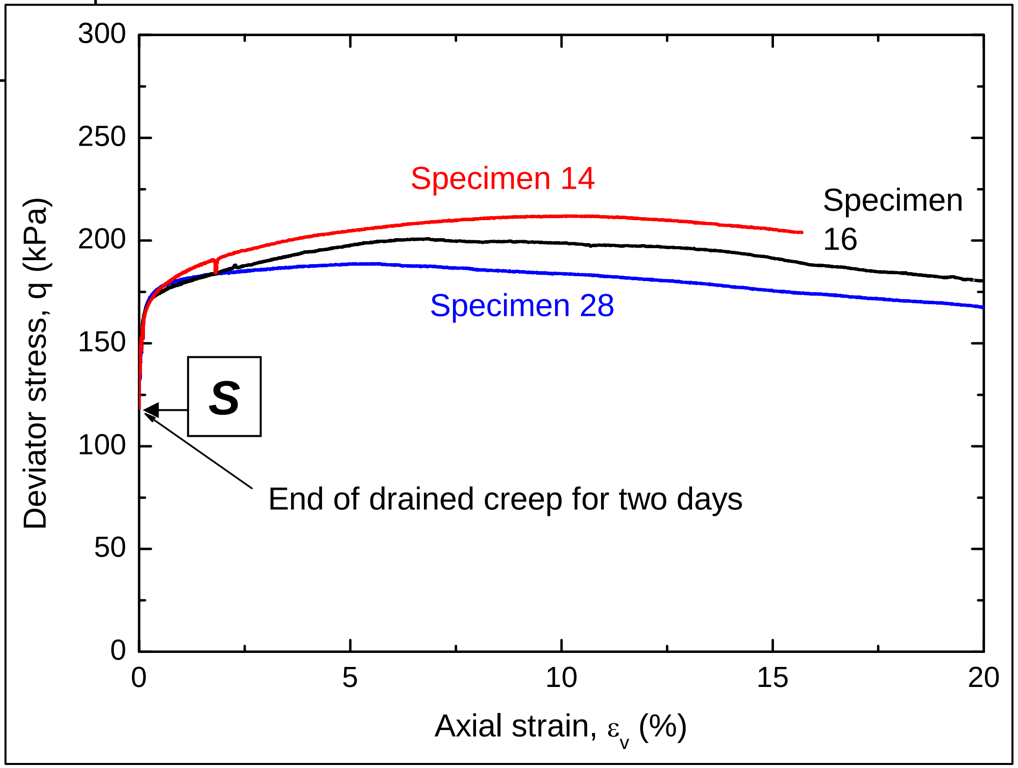
Only specimen 16; drained creep for two days at *S*

Tatsuoka et al. (1999d), *Torino*



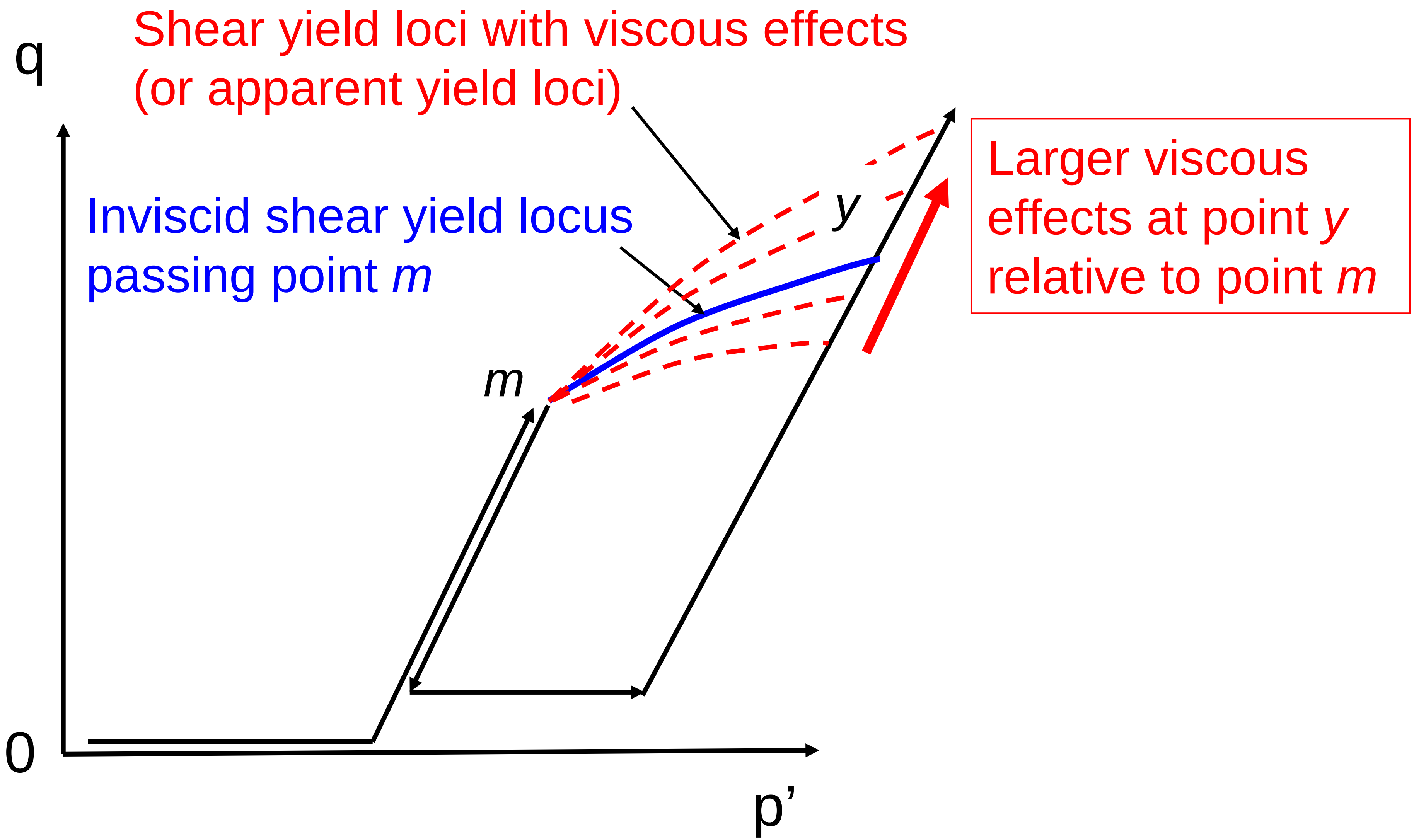
Similar high stiffness zones by "the same drained creep at S" *despite different stress paths until S*.

All specimens; drained creep for two days at *S*

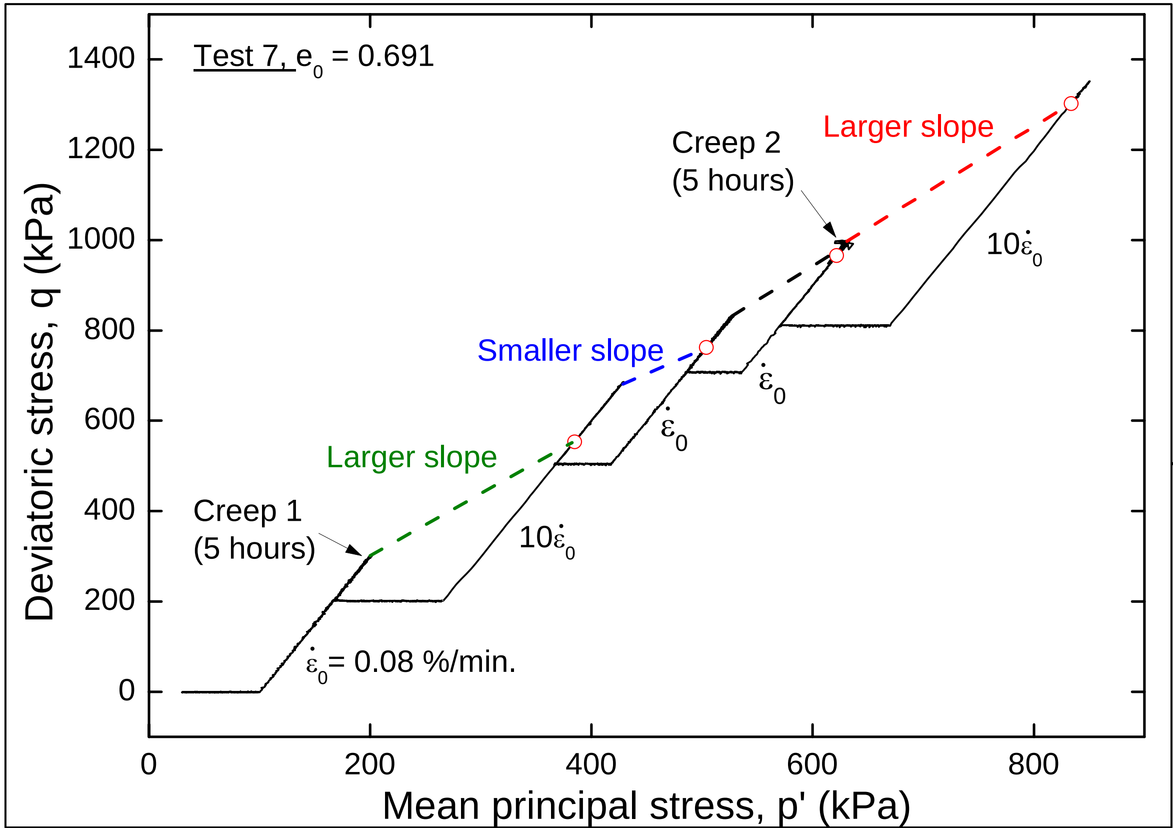


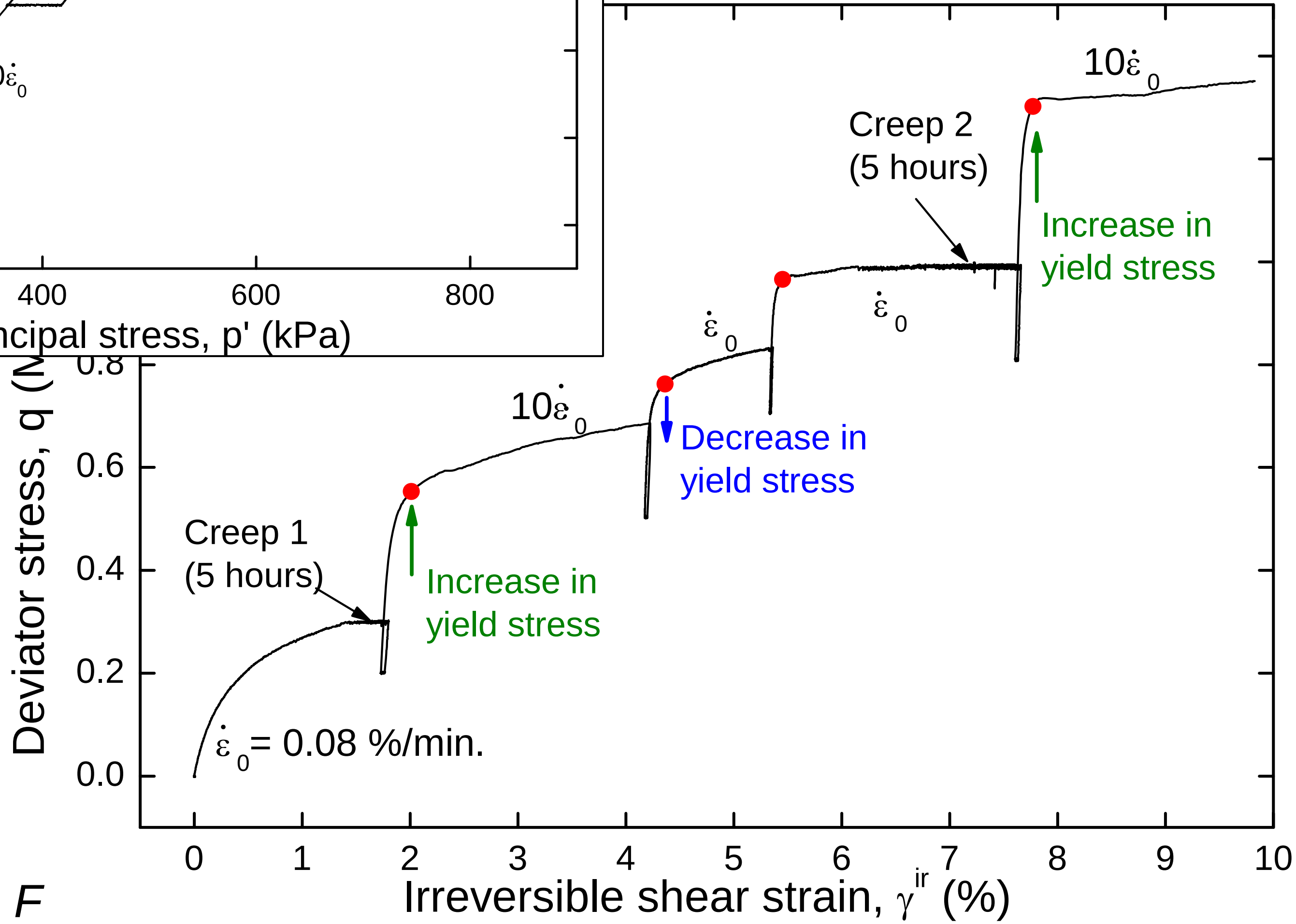
Tested by Momoya, T. (1998); Tatsuoka et al. (1999d), Torino

Viscous effects on shear yield locus



"Creep strain and increased stain rate" increases the yield stress !

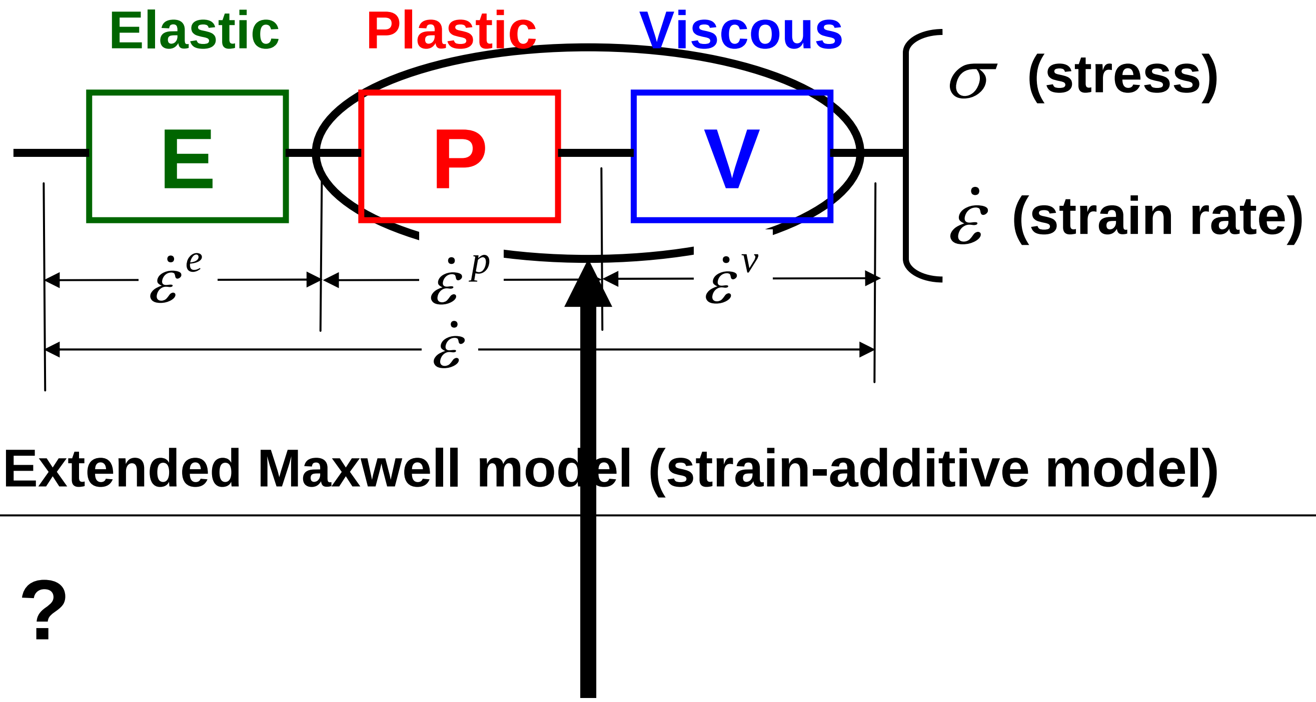




Saturated Toyoura sand in drained TC

Nawir et al. (2003b), *S & F*

Then, how to incorporate viscous effects into a constitutive model ?

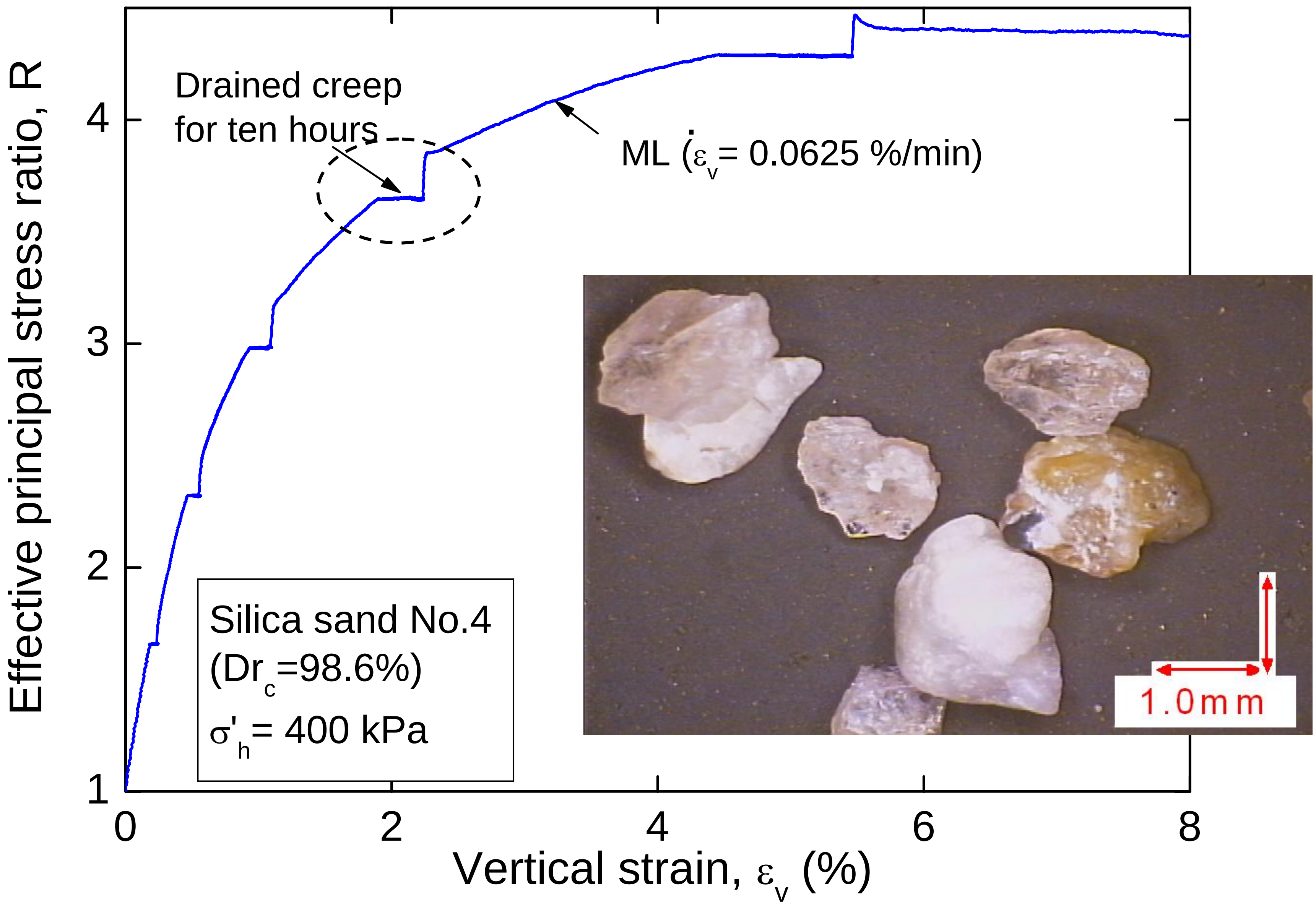


Extended Maxwell model (strain-additive model)

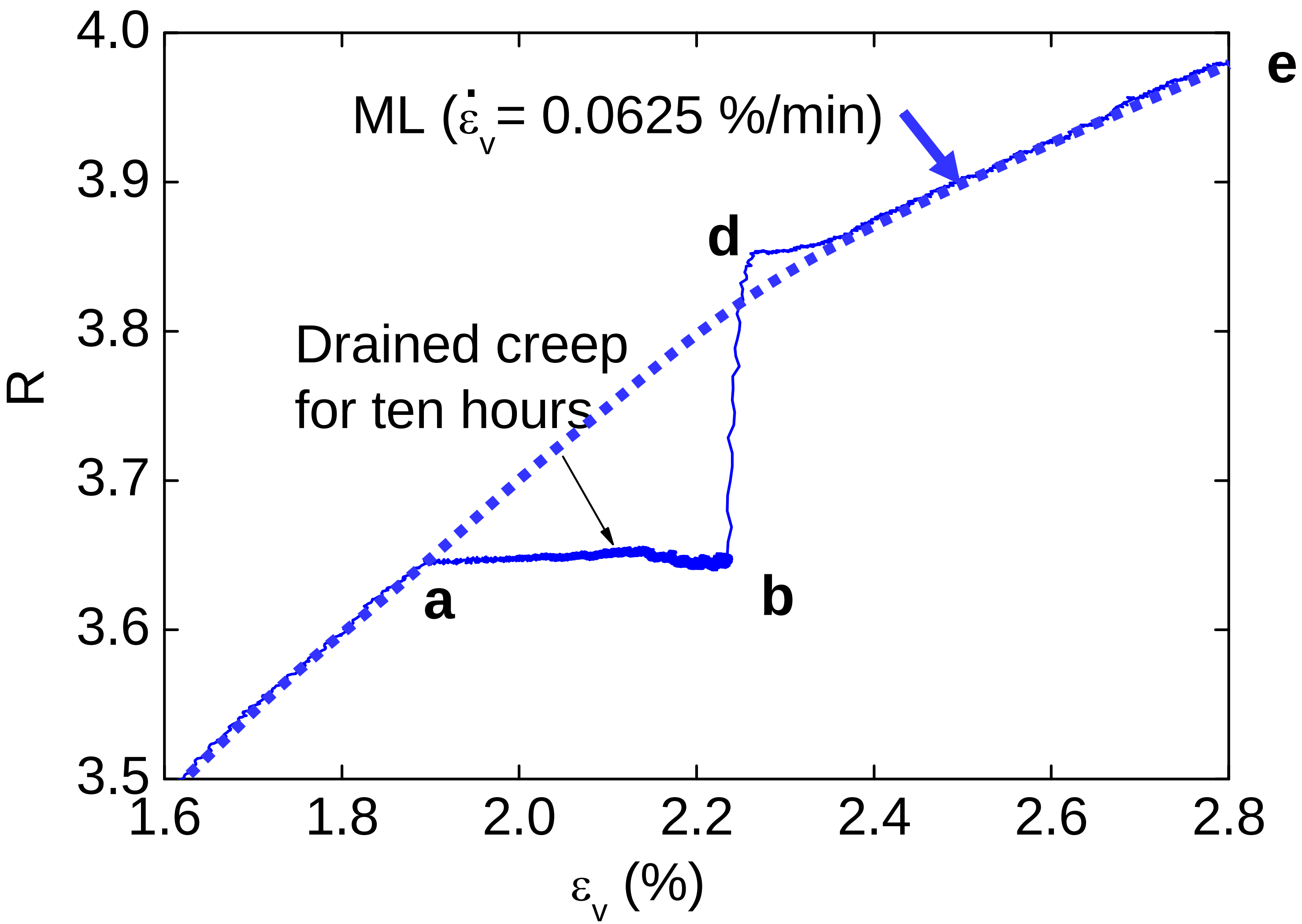
OK ?

No ! they cannot be separated.

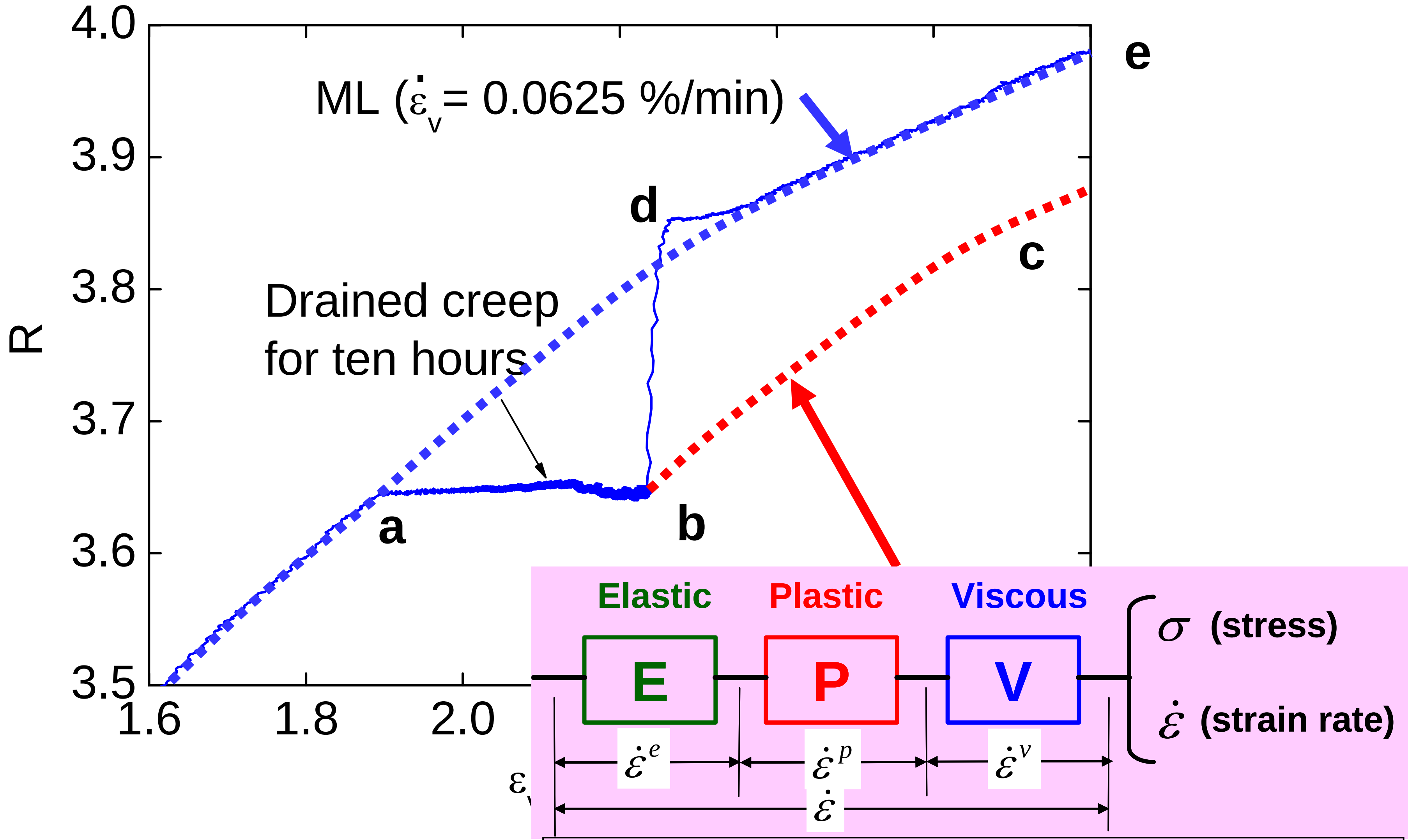
Drained TC tests on air-dried sand



Enomoto et al. (2006a), *Roma*

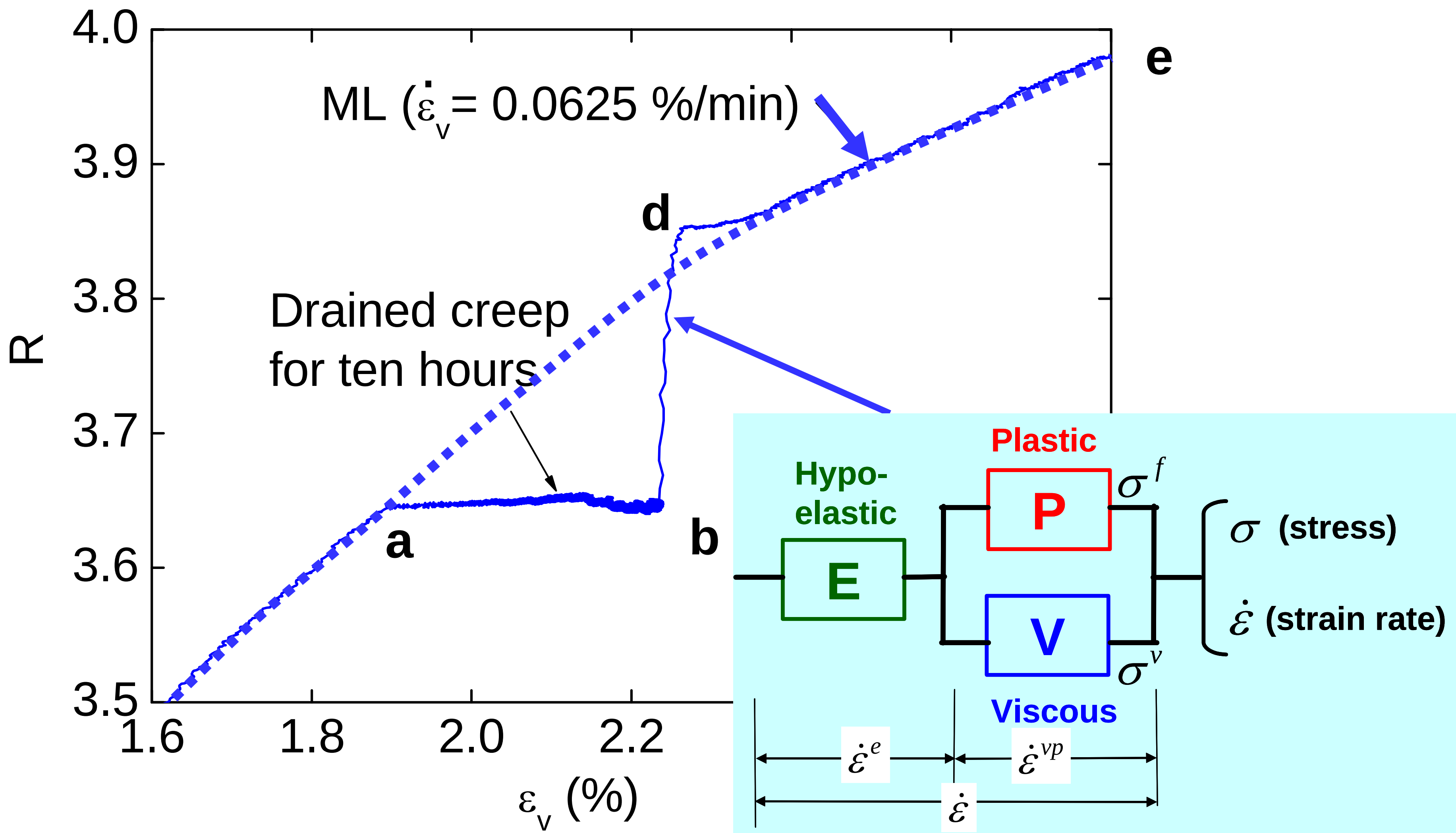


When ML is restarted from **b**, the stress-strain relation rejoins the original one **d**→**e**; i.e., "in-elastic strain during ML (**a**→**d**)" and "creep strain (**a**→**b**)" have the same origin.



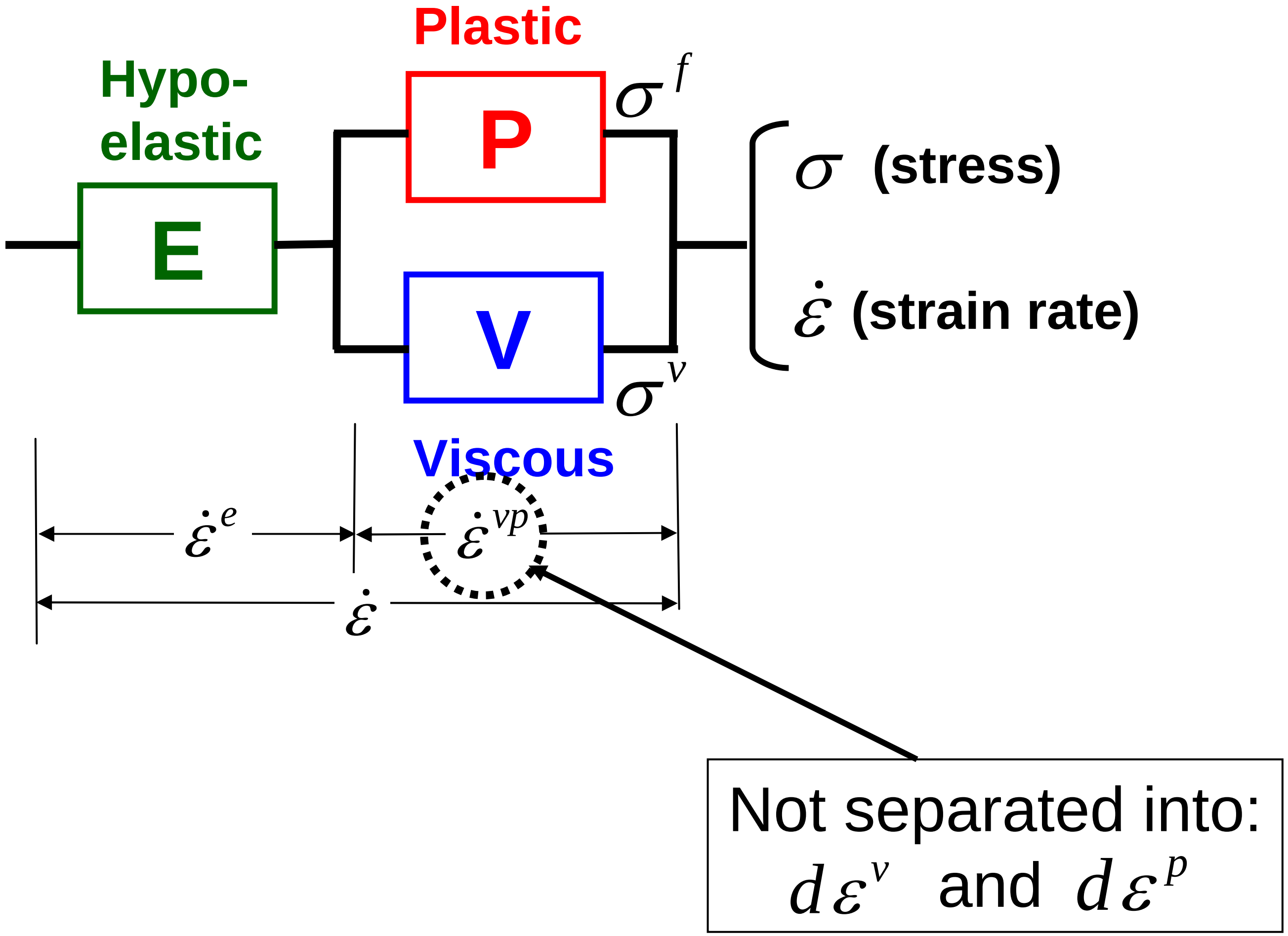
This model wrongly predicts b→c.

Enomoto et al. (2006a), *Roma*

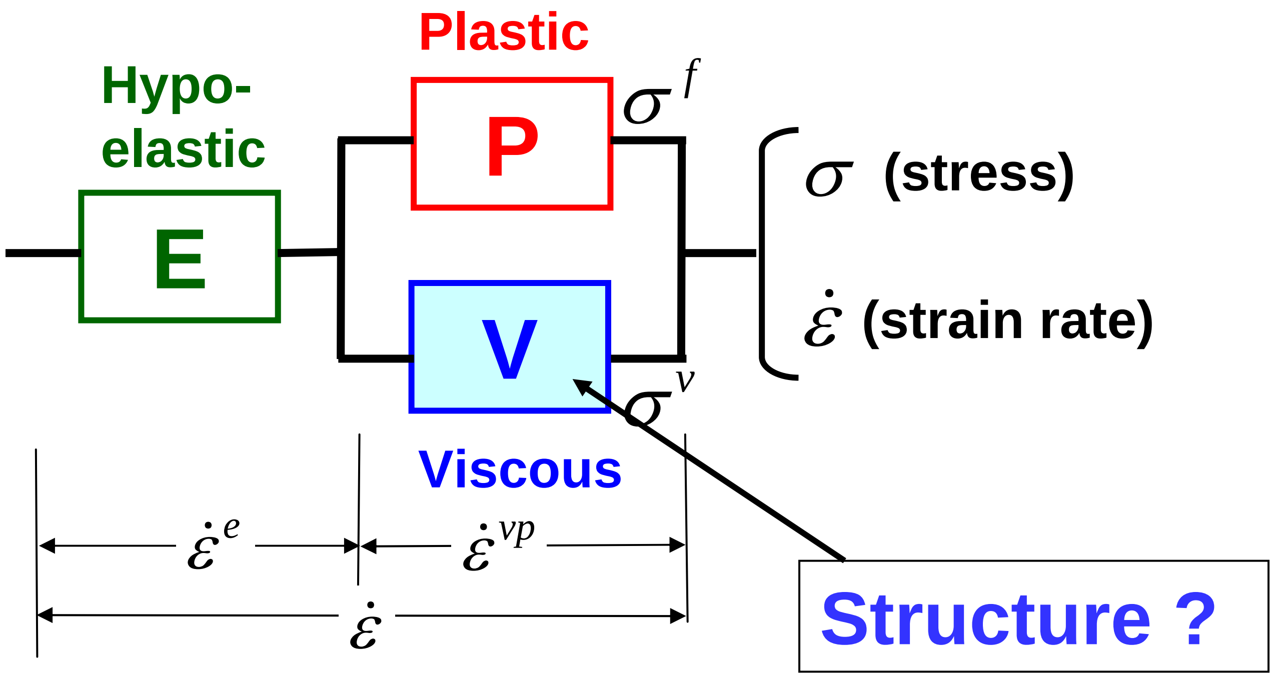


The three-component model can predict the measured behaviour a→b→d→e.

Enomoto et al. (2006a), *Roma*



Non-linear three-component model
(Di Benedetto et al., 2002; Tatsuoka et al., 2002)



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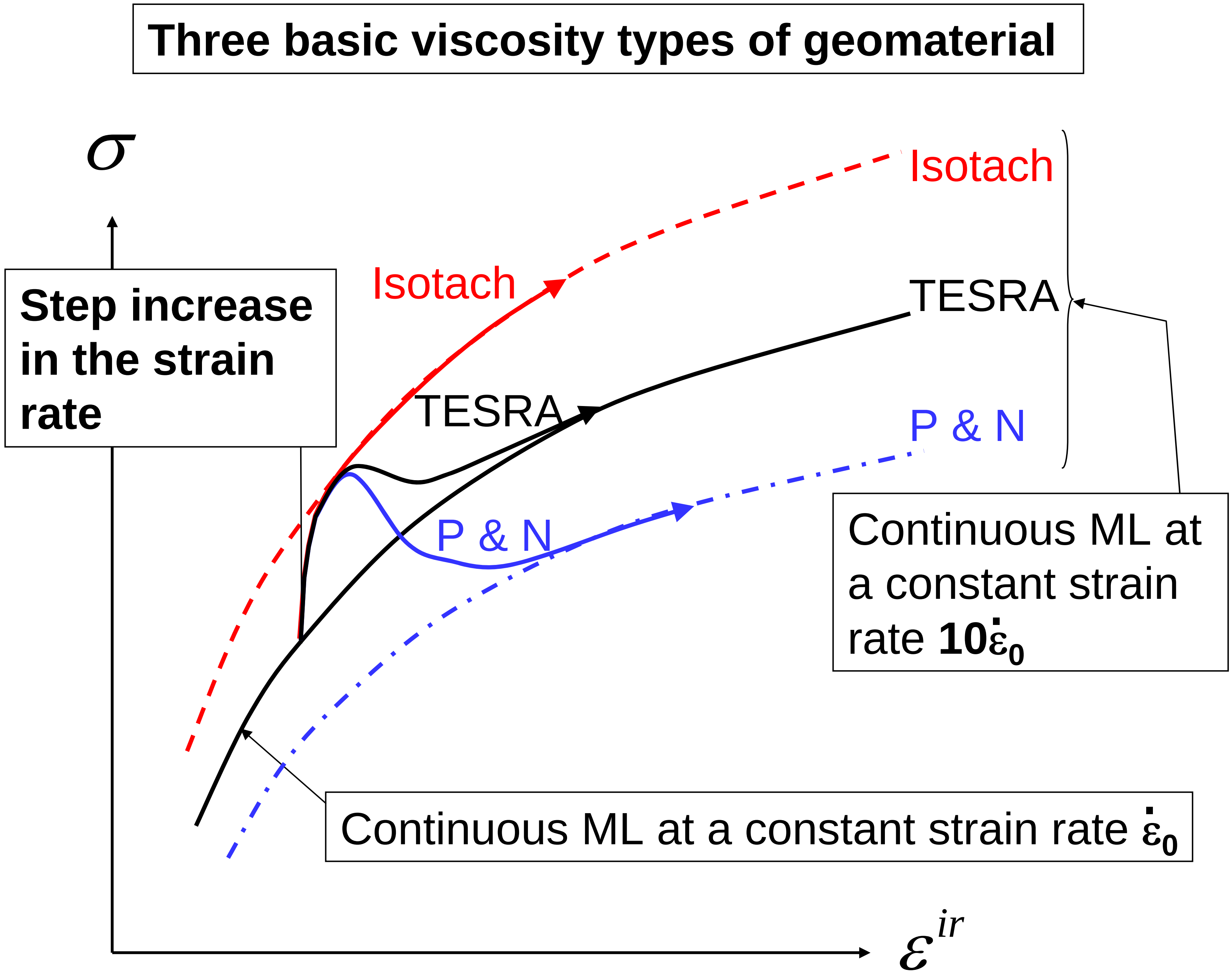
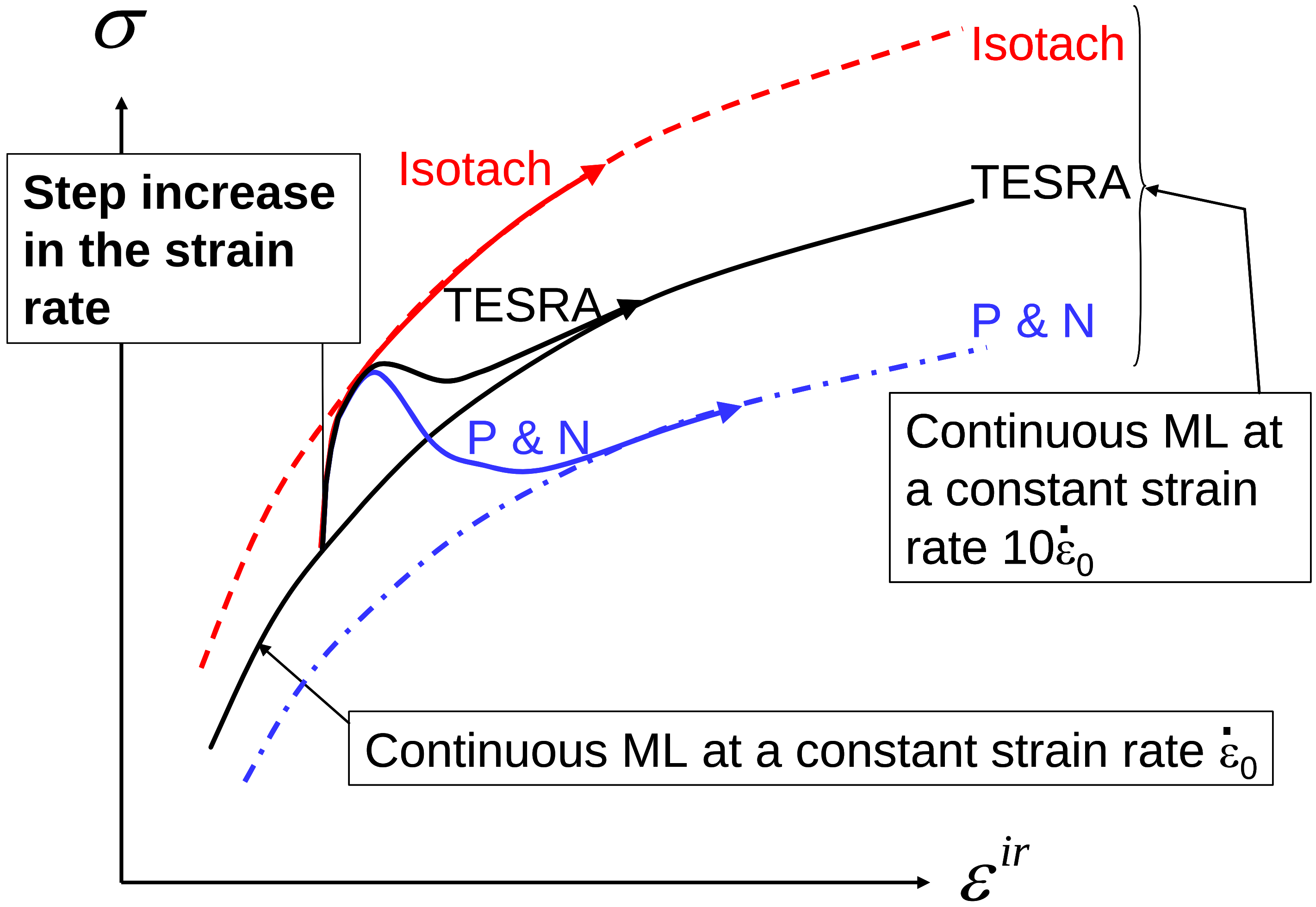
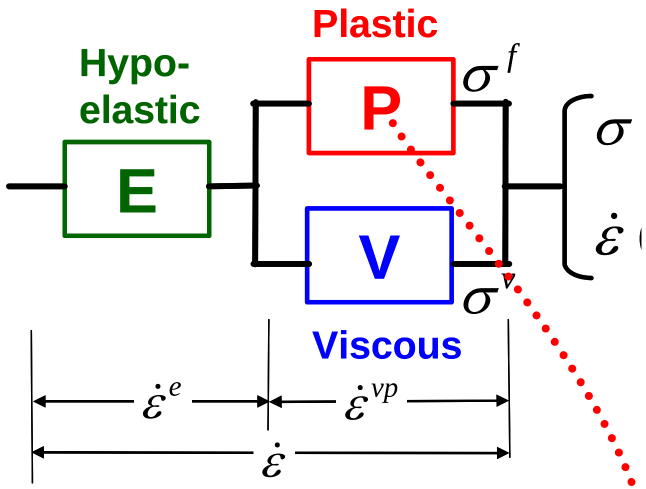

Three basic viscosity types of geomaterial
σ
Step increase in the strain rate
Isotach
TESRA
P & N
Isotach
TESRA
P & N
Continuous ML at a constant strain rate 10$\dot{\varepsilon}_0$
Continuous ML at a constant strain rate $\dot{\varepsilon}_0$
ε^{ir}

Isotach:
- bound materials
- unbound well-graded angular materials in pre-peak



Isotach model（*iso = equal; & tach= velocity; i.e., strain rate*)

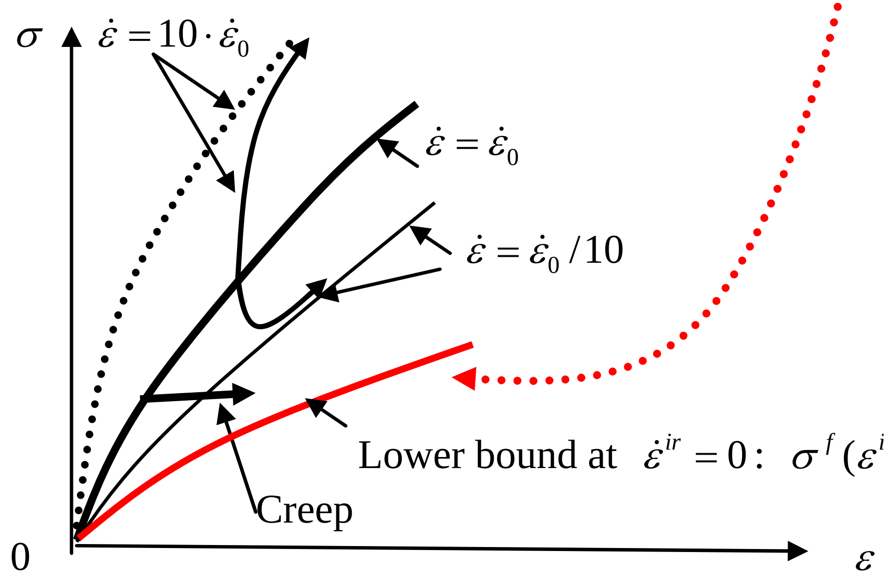


$$\sigma = \sigma^f\left(\varepsilon^{ir}\right) + \sigma^v\left(\varepsilon^{ir}, \dot{\varepsilon}^{ir}\right)$$

$$\sigma^v\left(\varepsilon^{ir}, \dot{\varepsilon}^{ir}\right) = \sigma^f\left(\varepsilon^{ir}\right) \cdot g_v(\dot{\varepsilon}^{ir})$$

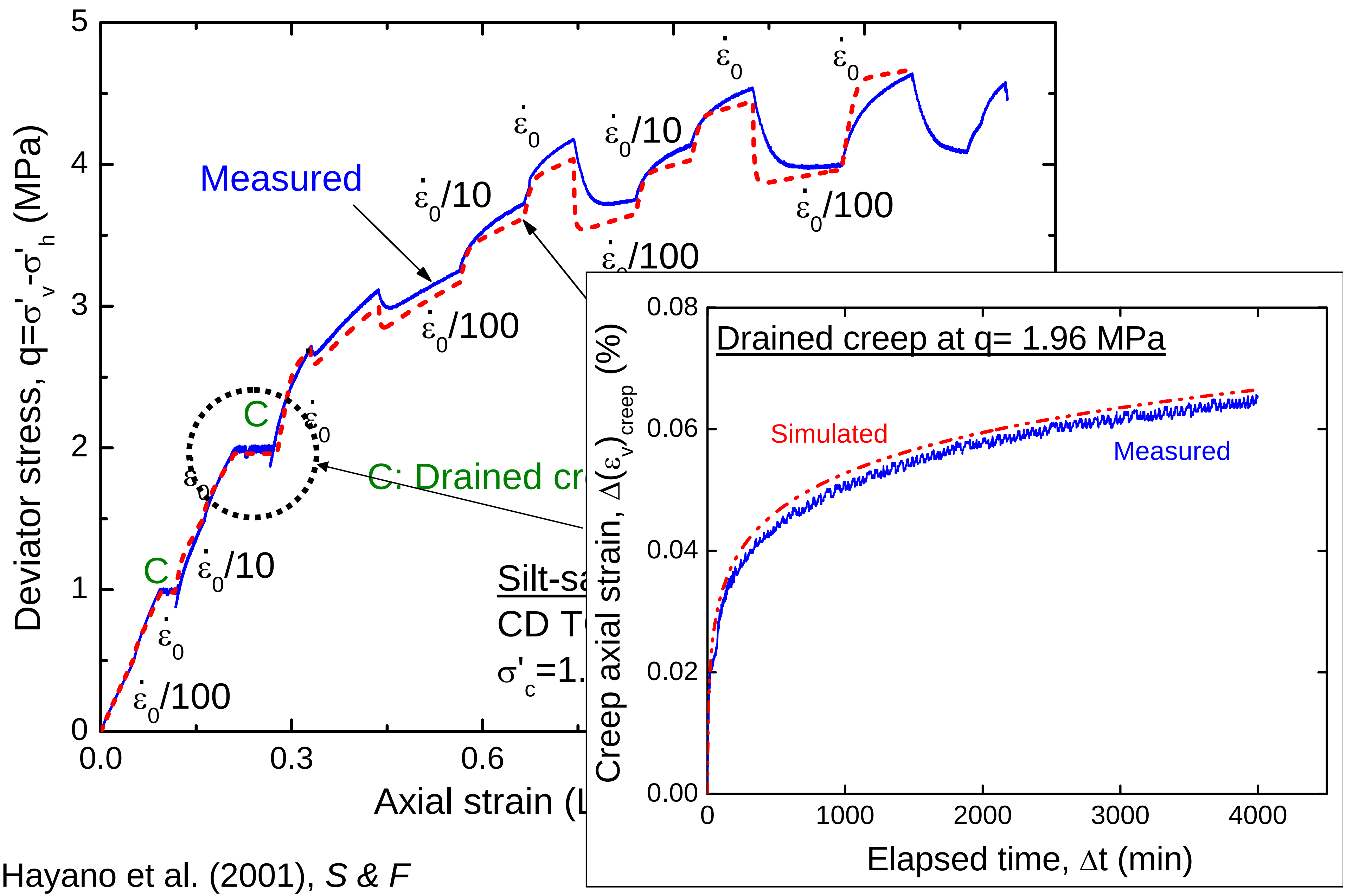
$$g_v(\dot{\varepsilon}^{ir}) = \alpha \cdot [1 - \exp\{1 - (\frac{|\dot{\varepsilon}^{ir}|}{\dot{\varepsilon}_r^{ir}} + 1)^m\}] \quad (\geq 0)$$

σ is always a unique function of ε^{ir} and $\dot{\varepsilon}^{ir}$.
=>Different σ – ε relations develop for different strain rates. Correspondingly, creep deformation and stress relaxation take place.



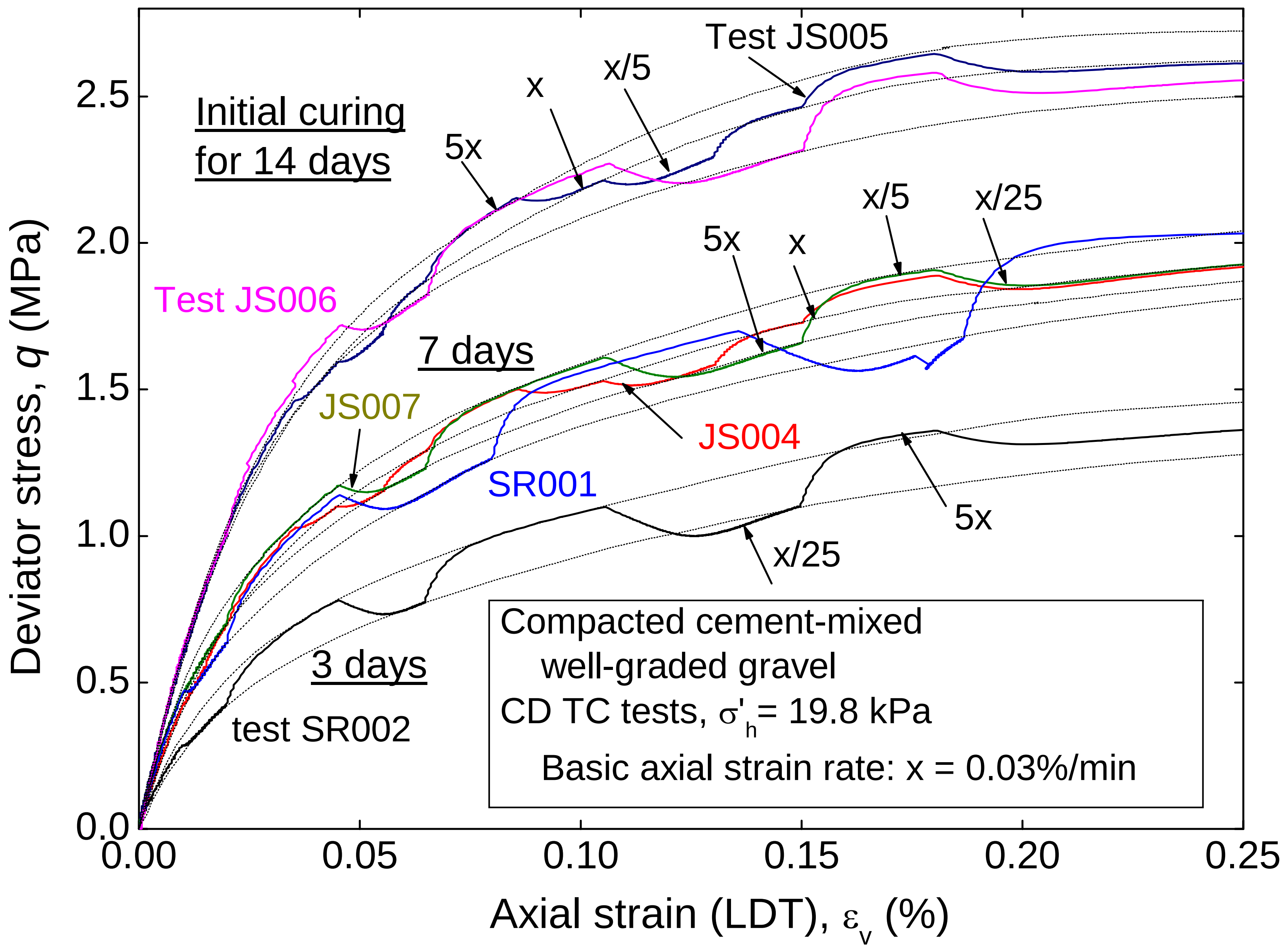
Di Benedetto et al. (2002); Tatsuoka et al. (2002), *S & F*

CD TC on sedimentary soft rock



Hayano et al. (2001), *S & F*

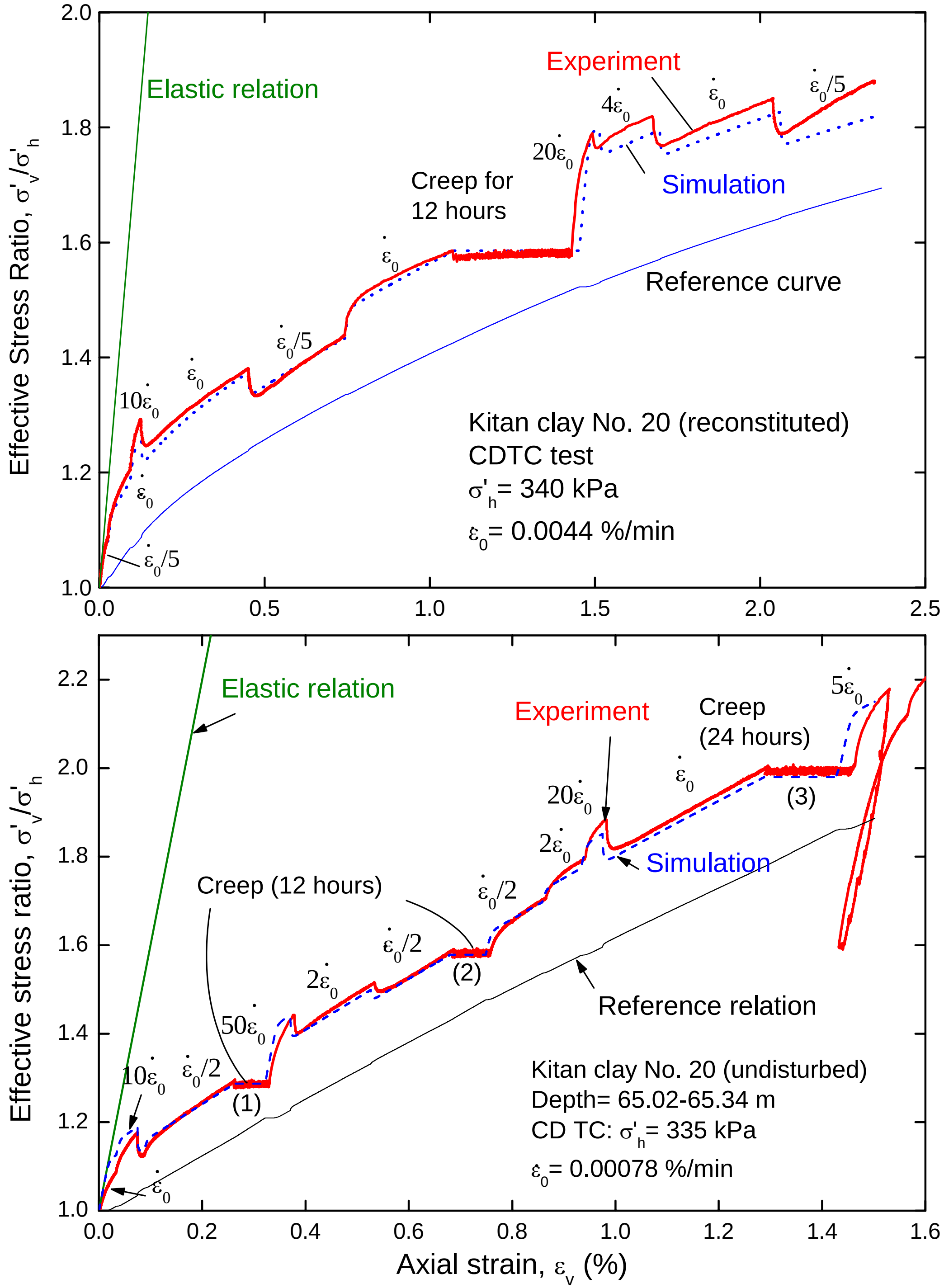
Typical Isotach viscosity for any curing period !



Kongsukprasert & Tatsuoka (2005), *S & F*

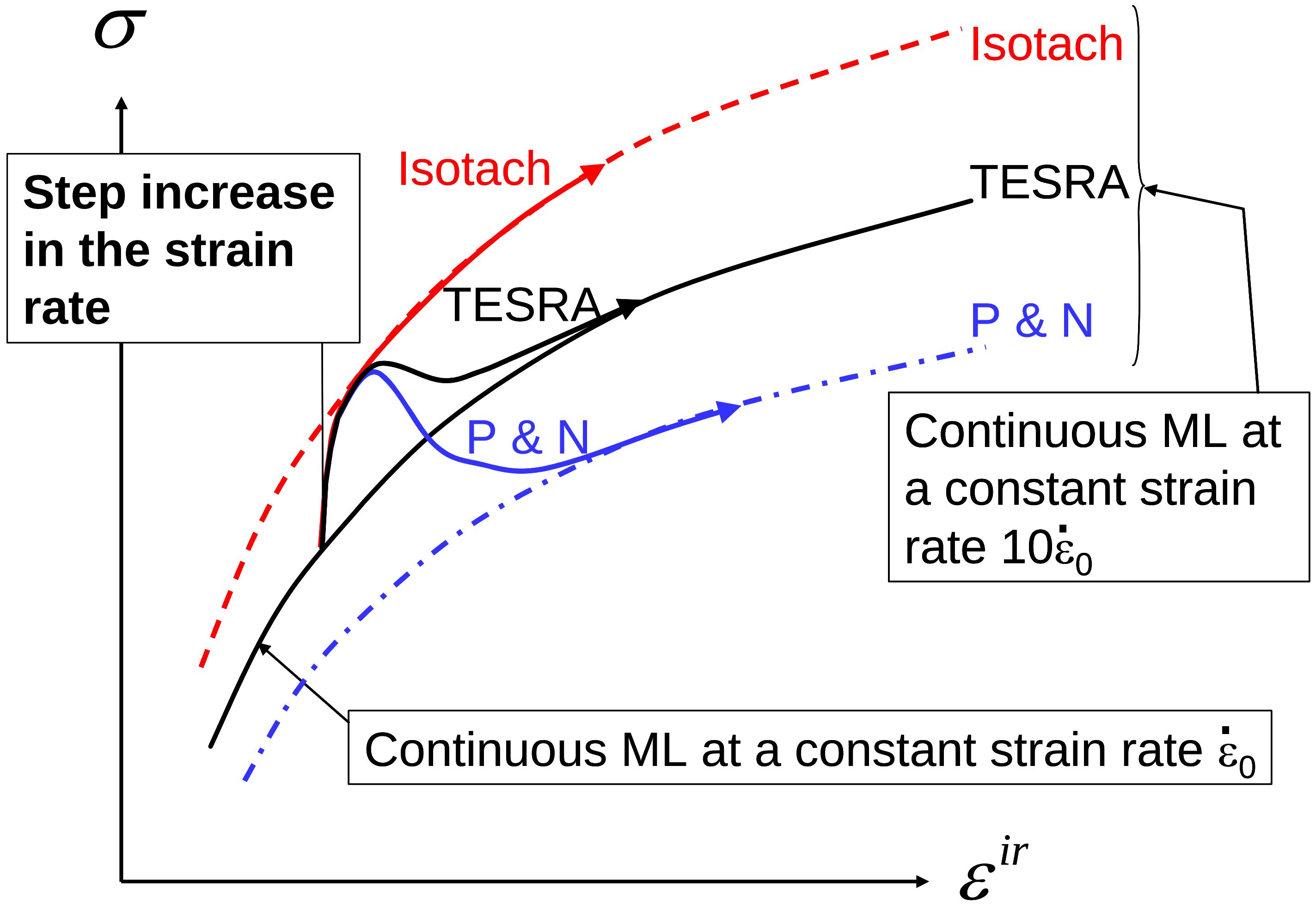
CD TC on reconstituted clay

CD TC on undisturbed stiff clay

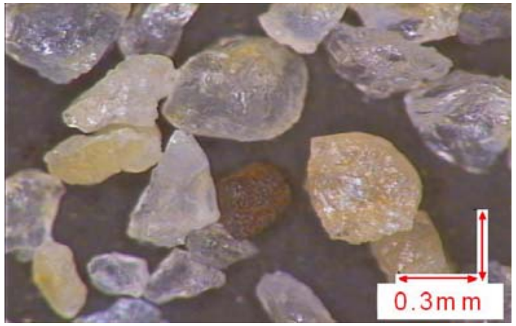


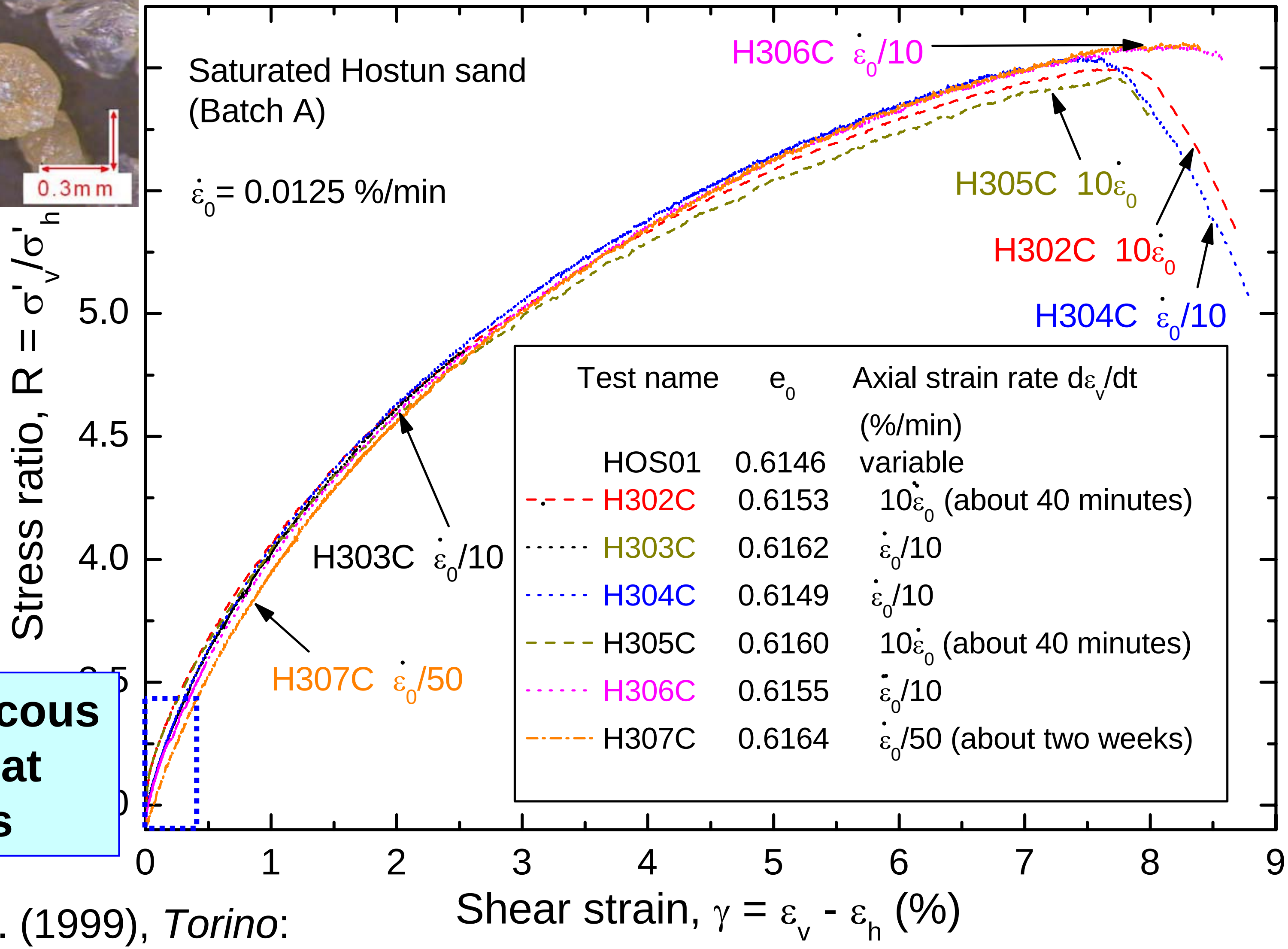
Komoto et al. (2003), *Lyon*

TESRA:
- poorly-graded angular materials, in pre-peak



Drained PSC tests: nearly the same stress-strain curves by ML at strain rates different by a factor of up to 500 times.

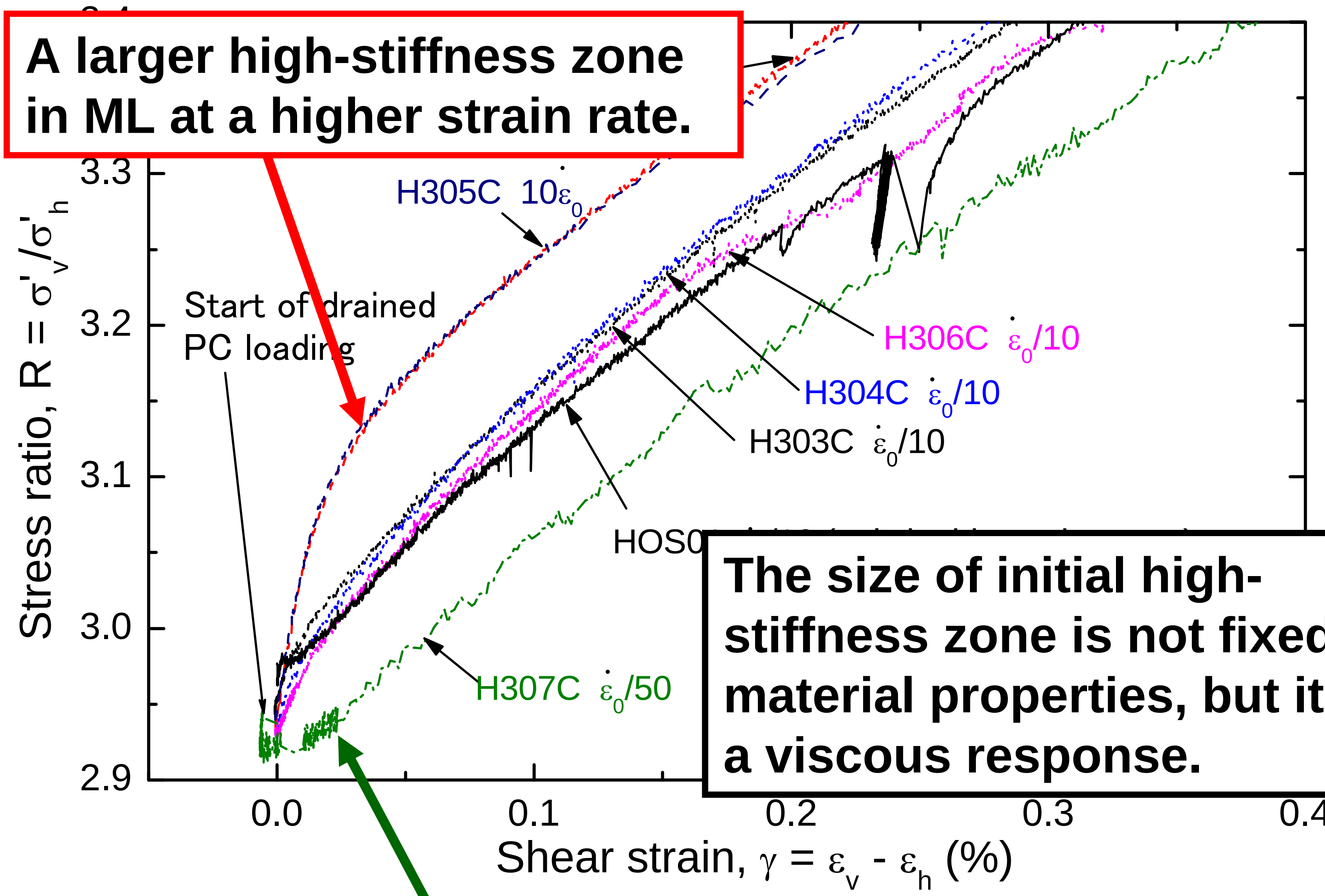




Obvious viscous effects only at small strains

Matsushita et al. (1999), *Torino*:
Di Benedetto et al. (2002), *S & F*

A larger high-stiffness zone in ML at a higher strain rate.

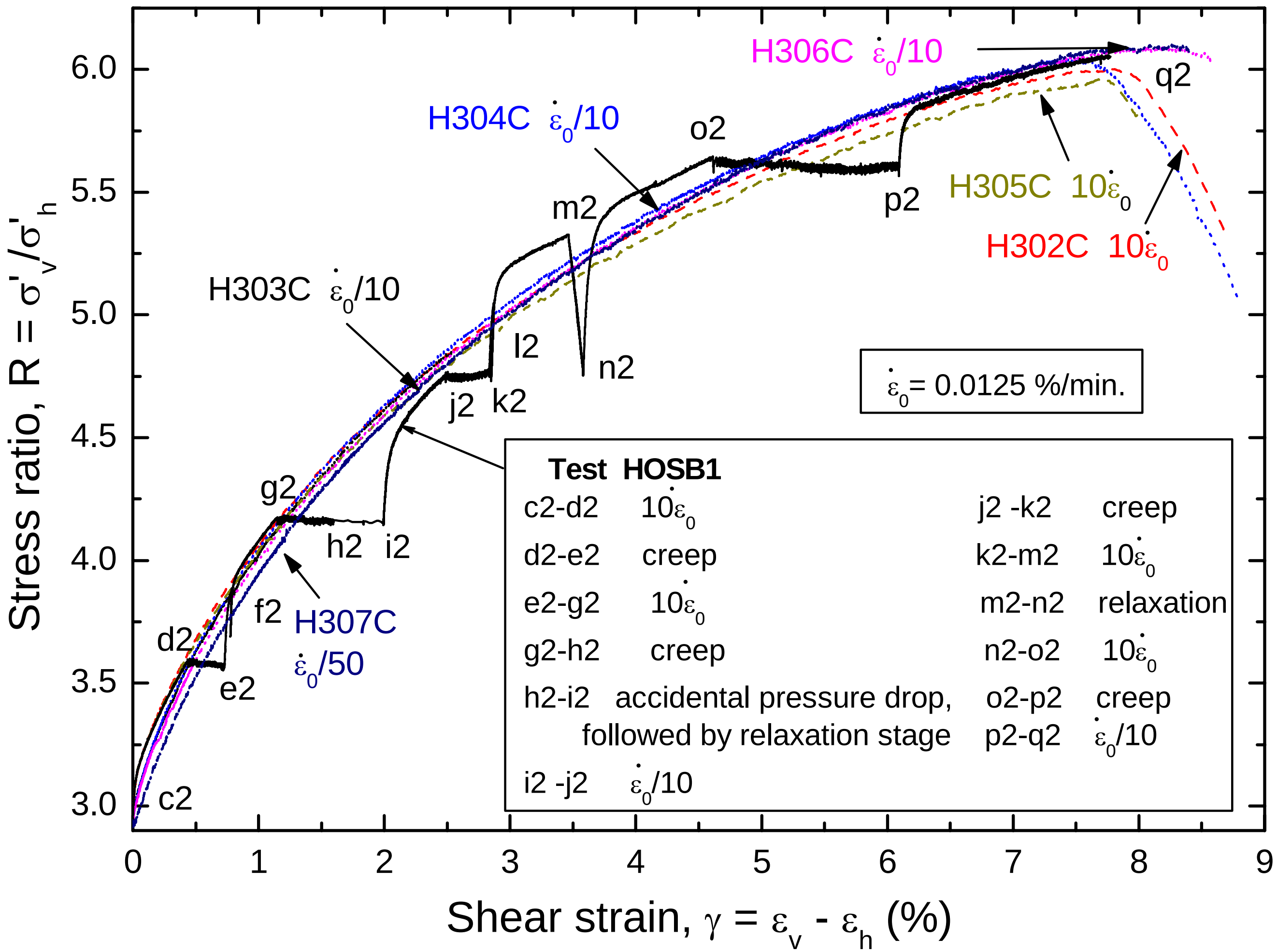


The size of initial high-stiffness zone is not fixed material properties, but it is a viscous response.

No high-stiffness zone in ML at a strain rate lower than the strain rate at the end of sustained loading

Very small differences among the stress-strain relations at strain rates different by a factor of up to 500

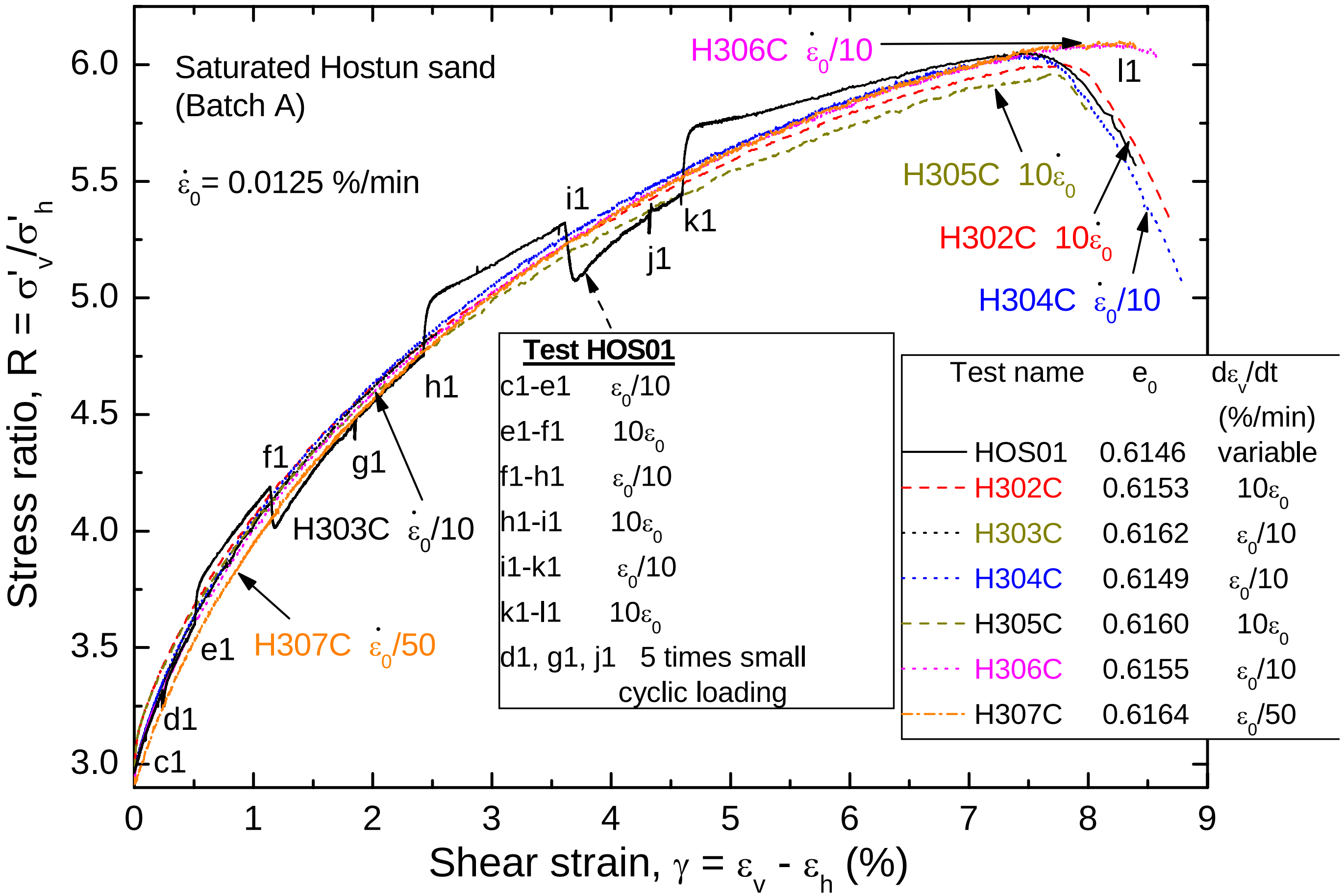
An apparent contradiction !



Significant creep deformation and stress relaxation

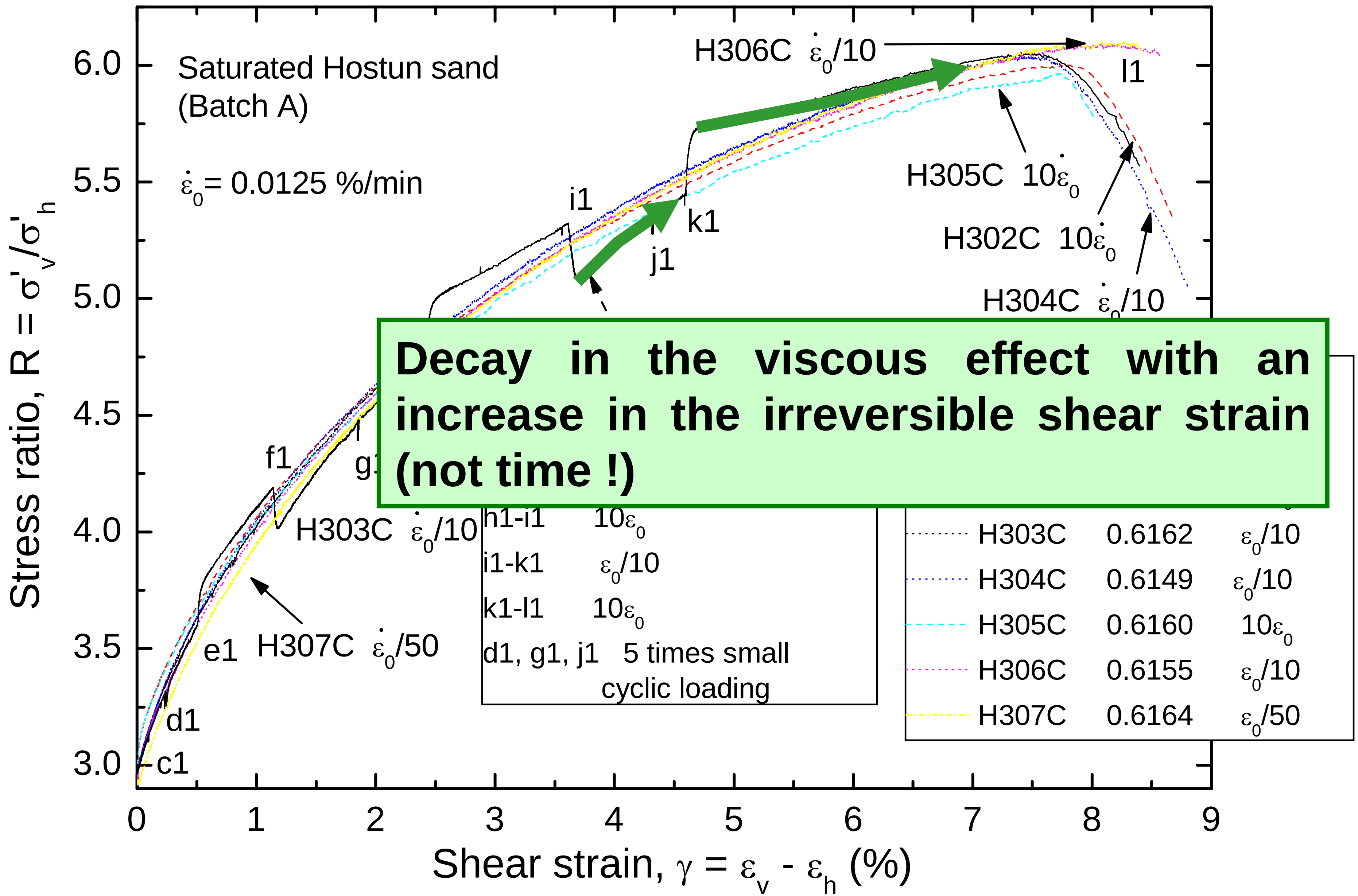
Very small differences among the stress-strain relations at strain rates different by a factor of up to 500

An apparent contradiction !



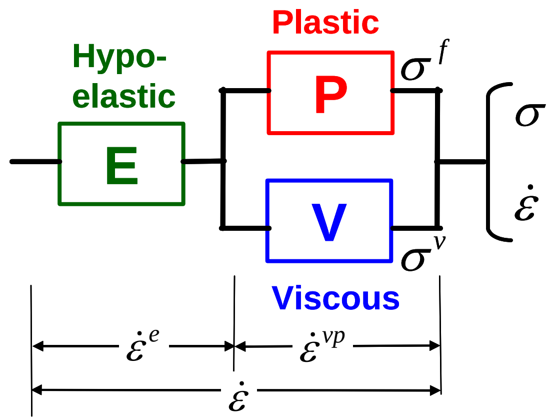
Obvious stress jumps upon a stepwise change in the strain rate by a factor of 100

Key behaviour for constitutive modelling



Decay in the viscous effect with an increase in the irreversible shear strain (not time !)

TESRA (temporary effect of strain rate and acceleration) model



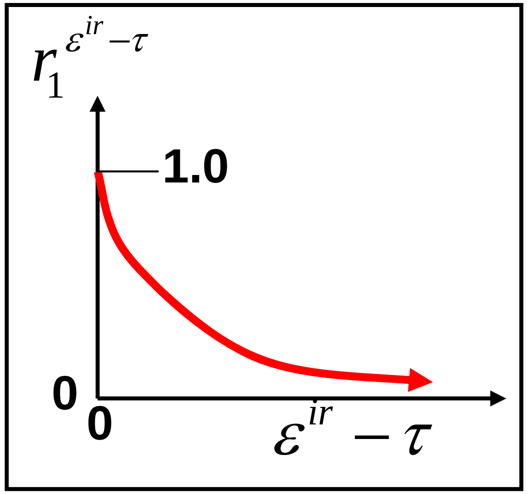
$$\sigma = \sigma^f\left(\varepsilon^{ir}\right) + \sigma^v$$

Same as the Isotach model

$$[\sigma^v]_{(\varepsilon^{ir})} = \int_{\tau=\varepsilon_1^{ir}}^{\varepsilon^{ir}} \left[d\sigma^v\right]_{(\tau,\varepsilon^{ir})} = \int_{\tau=\varepsilon_1^{ir}}^{\varepsilon^{ir}} \left[d\{\sigma^f \cdot g_v(\dot{\varepsilon}^{ir})\}\right]_{(\tau)} \cdot g_{decay}(\varepsilon^{ir} - \tau)$$

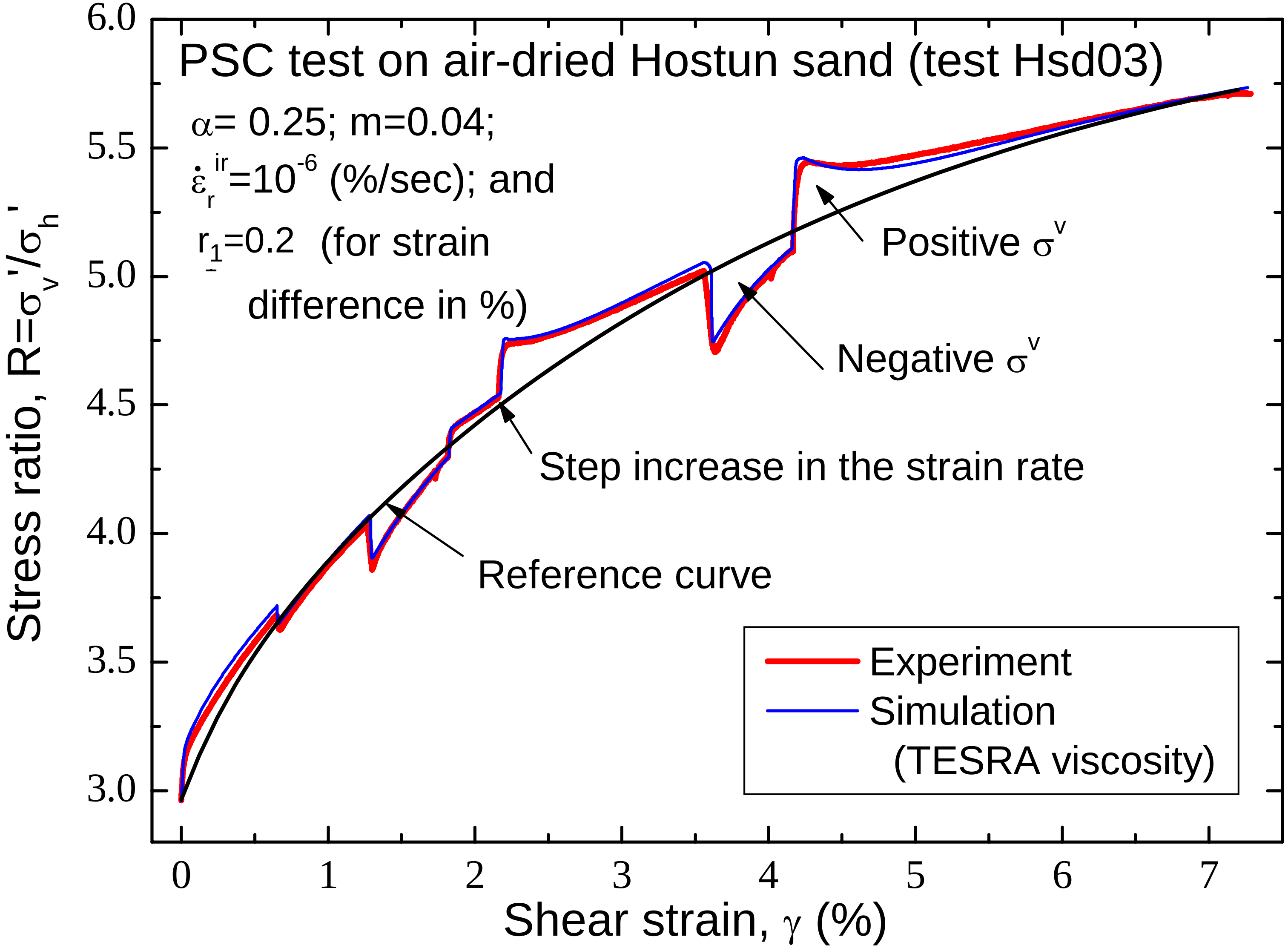
$$(\sigma^v \geq 0; \quad or \quad \leq 0)$$

Decay function: $g_{decay}(\varepsilon^{ir} - \tau) = r_1^{(\varepsilon^{ir} - \tau)}$



As $d\sigma^v$ *is not totally differential, the integration depends on strain history.*

Di Benedetto et al. (2002); Tatsuoka et al. (2002), *S & F*



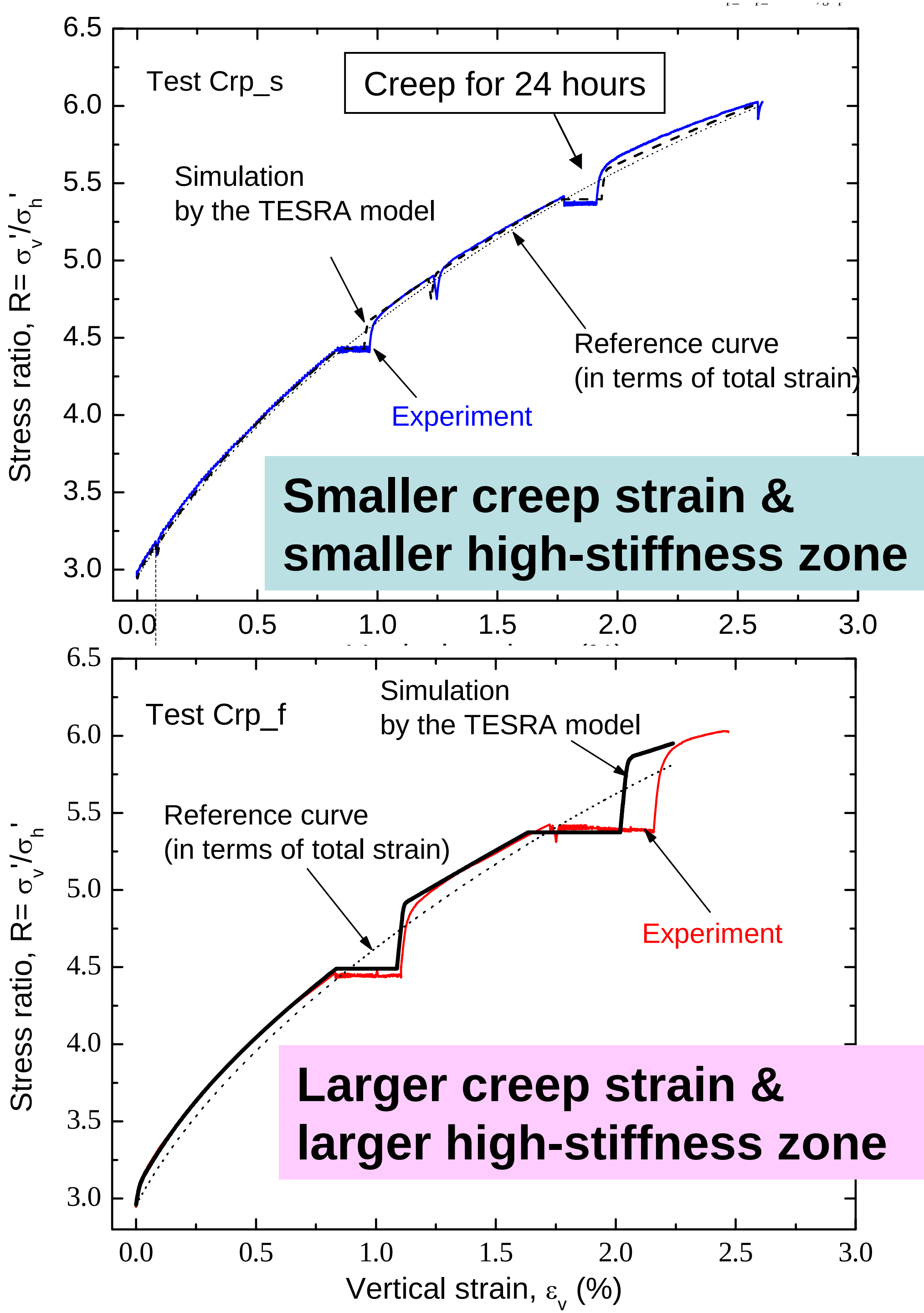
The TESRA model works !

Di Benedetto et al. (2002), *S & F*

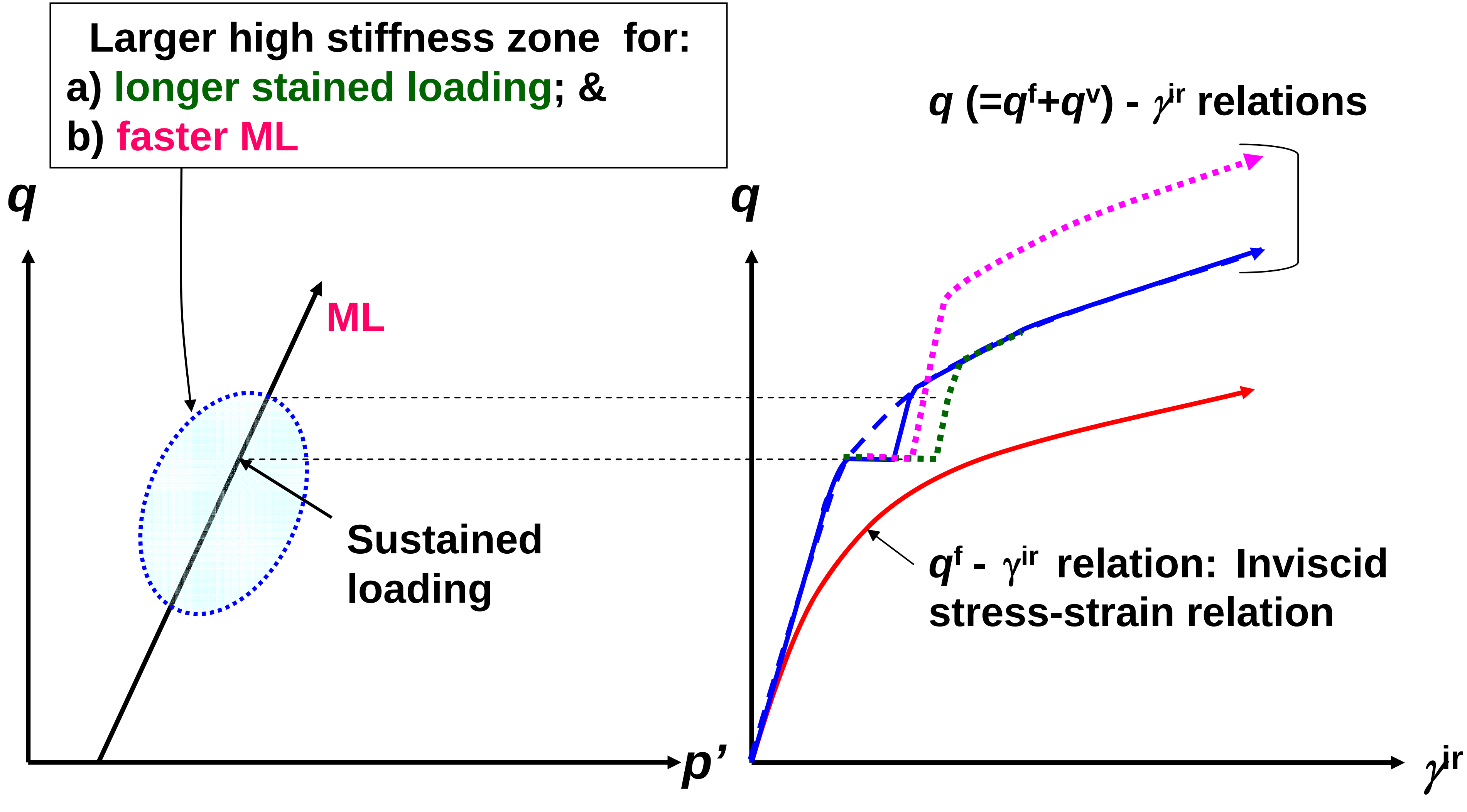
Drained PSC Saturated Toyoura sand (e= 0.74)

Axial strain rate during ML= 0.0025 %/min

Axial strain rate during ML= 0.25 %/min

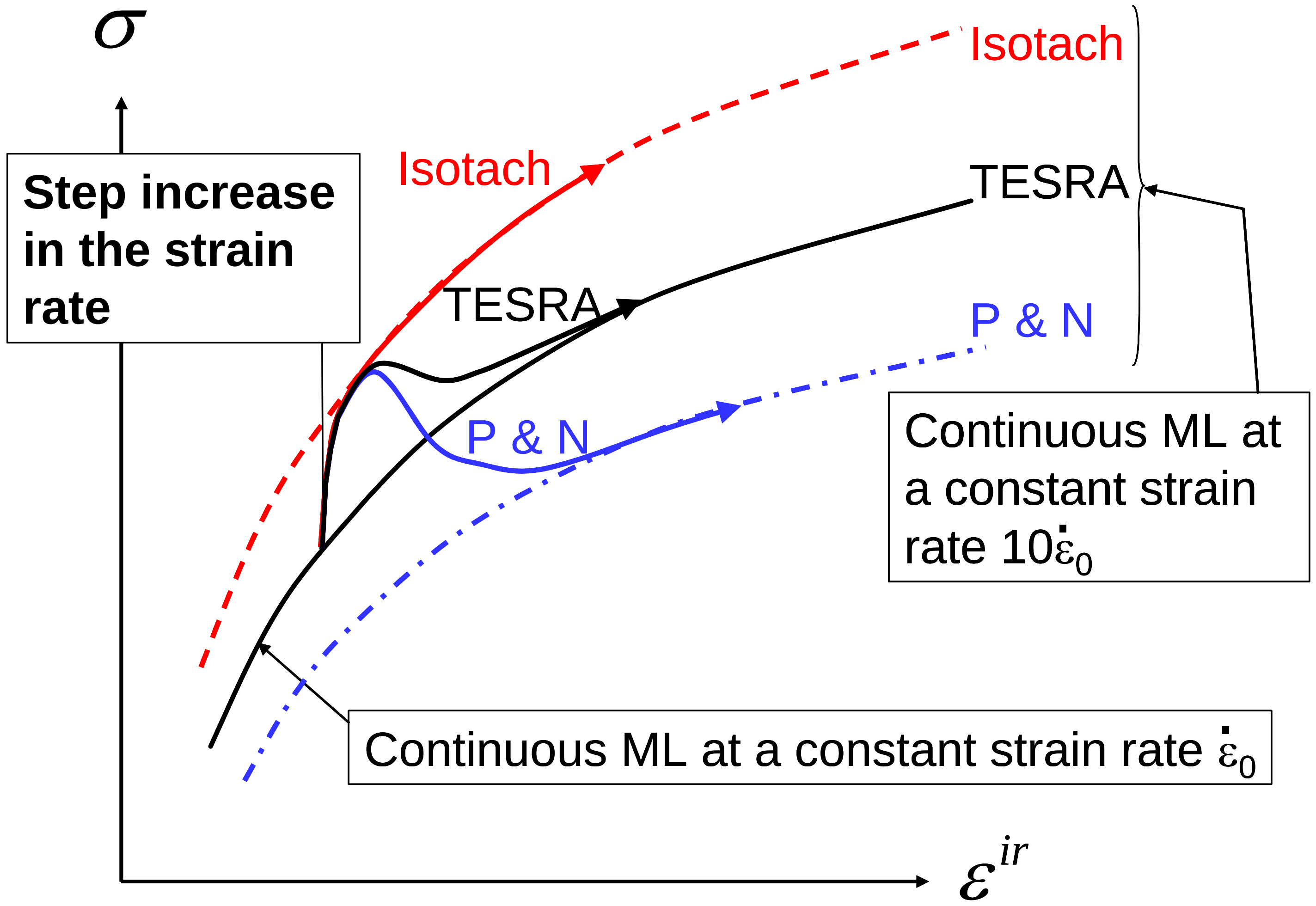


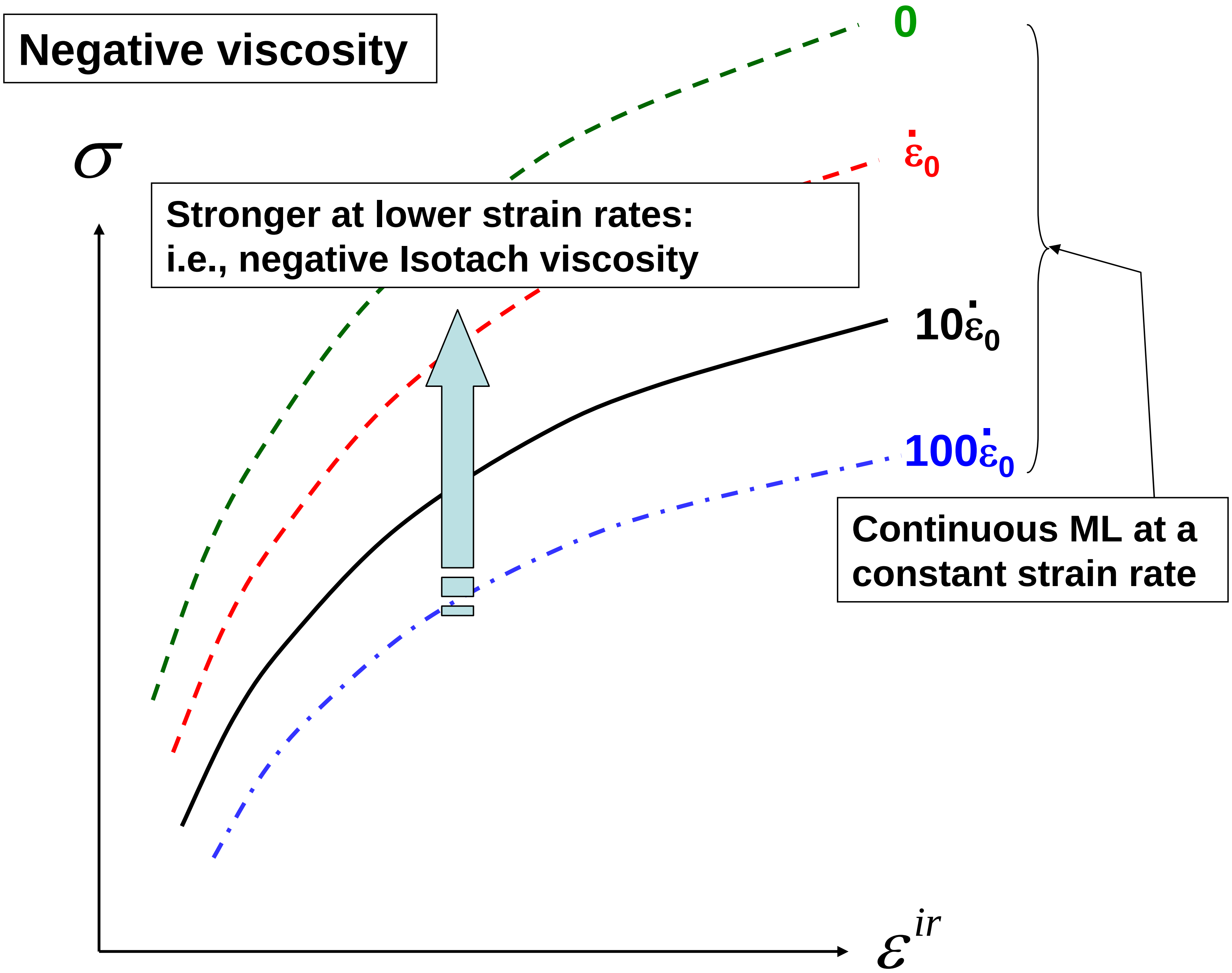
The size of high-stiffness zone is not fixed material properties !



Positive & negative (P & N) viscosity:

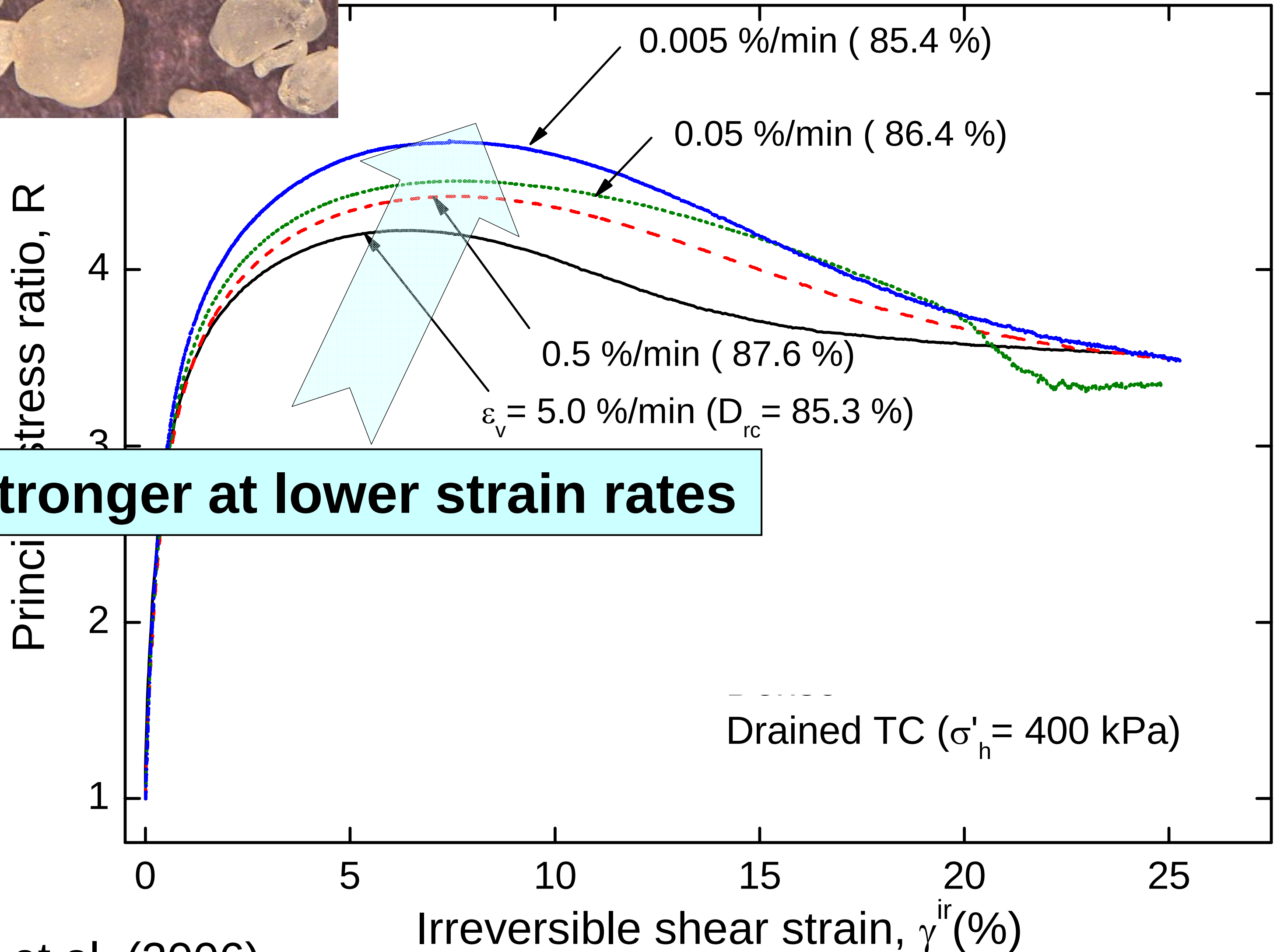
- **poorly-graded round materials**
- **more obvious at larger strains (particularly in post-peak)**




Negative viscosity
0
$\dot{\varepsilon}_0$
σ
Stronger at lower strain rates:
i.e., negative Isotach viscosity
$10\dot{\varepsilon}_0$
$100\dot{\varepsilon}_0$
Continuous ML at a
constant strain rate
ε^{ir}

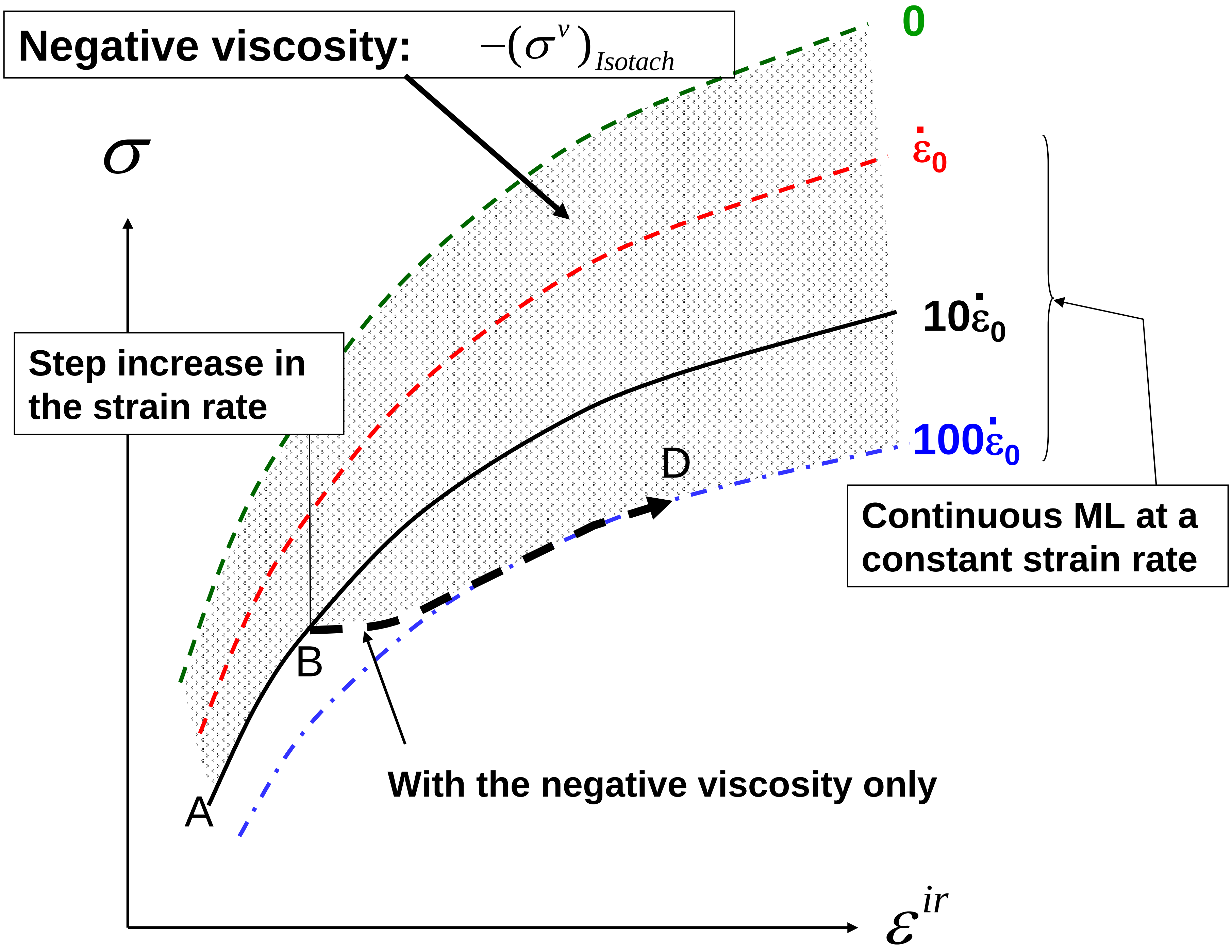
Air-dried Albany sand

Dense (D_r= 85 – 88 %); stiff round particle
(D_{50}= 0.30 mm, U_c=2.2, F_C= 0.1 %) ;

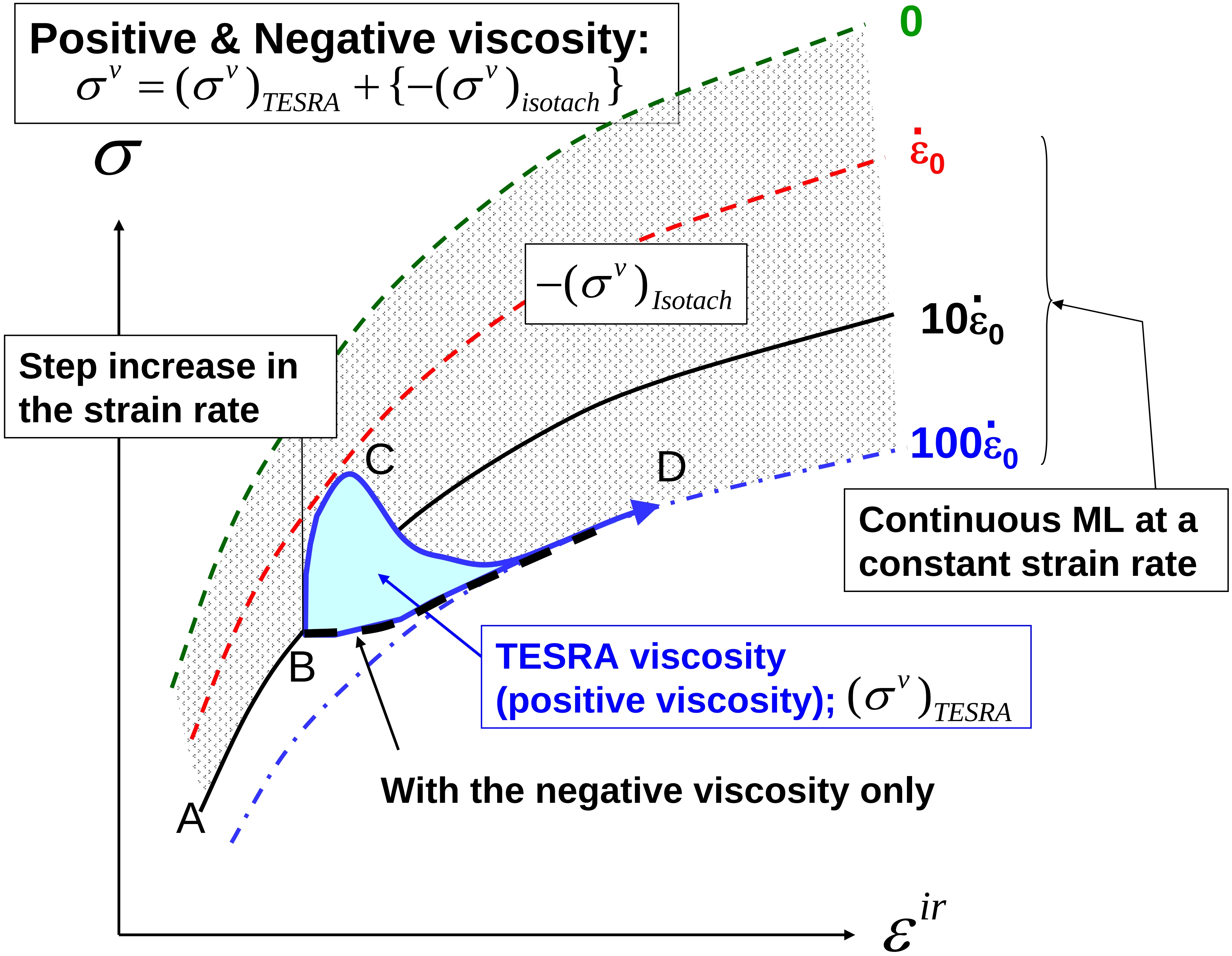


Stronger at lower strain rates

Enomoto et al. (2006)

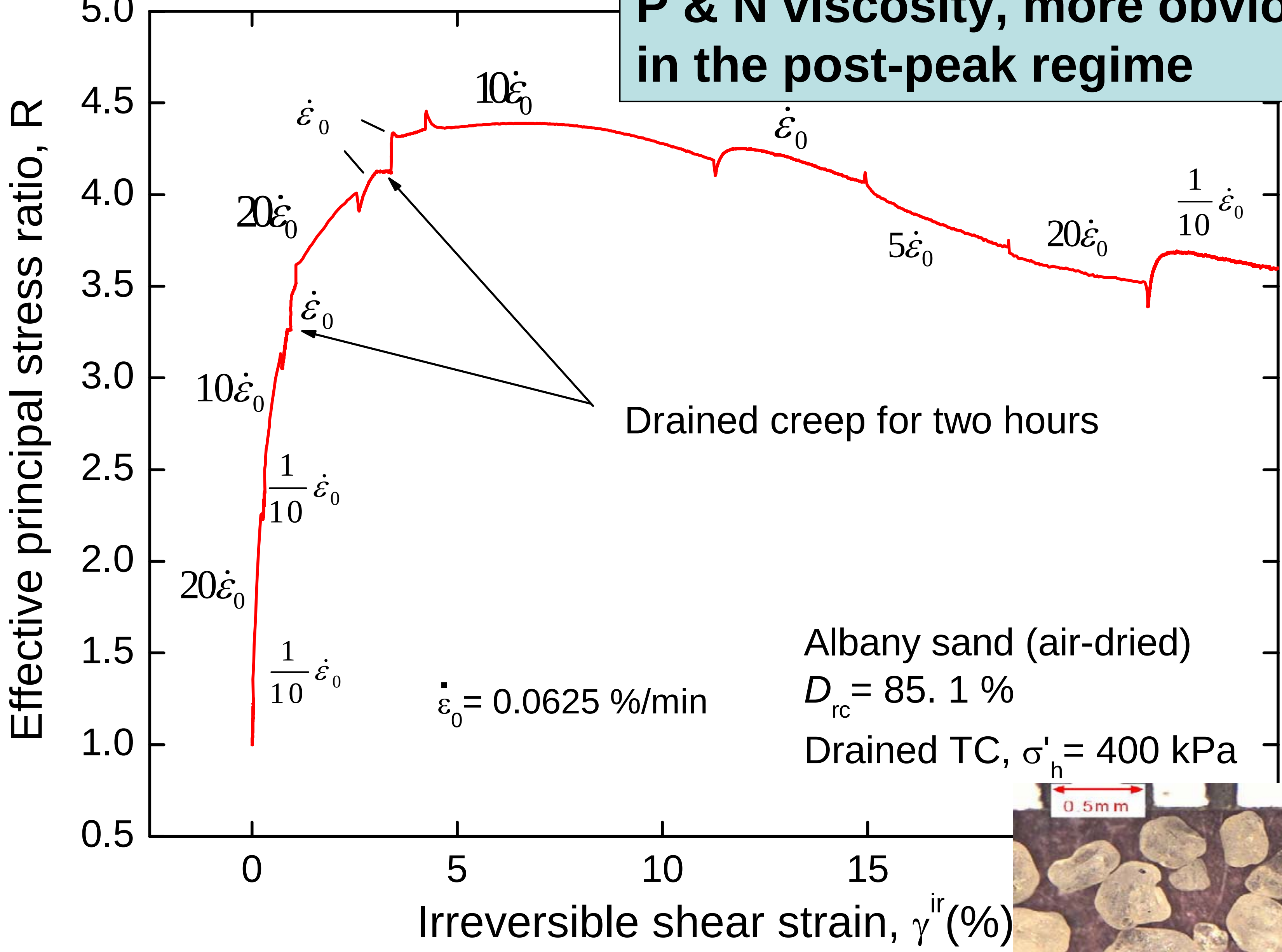


Negative viscosity: $-(\sigma^{v})_{Isotach}$
0
$\dot{\varepsilon}_0$
$10\dot{\varepsilon}_0$
$100\dot{\varepsilon}_0$
σ
Step increase in the strain rate
Continuous ML at a constant strain rate
D
B
A
With the negative viscosity only
ε^{ir}

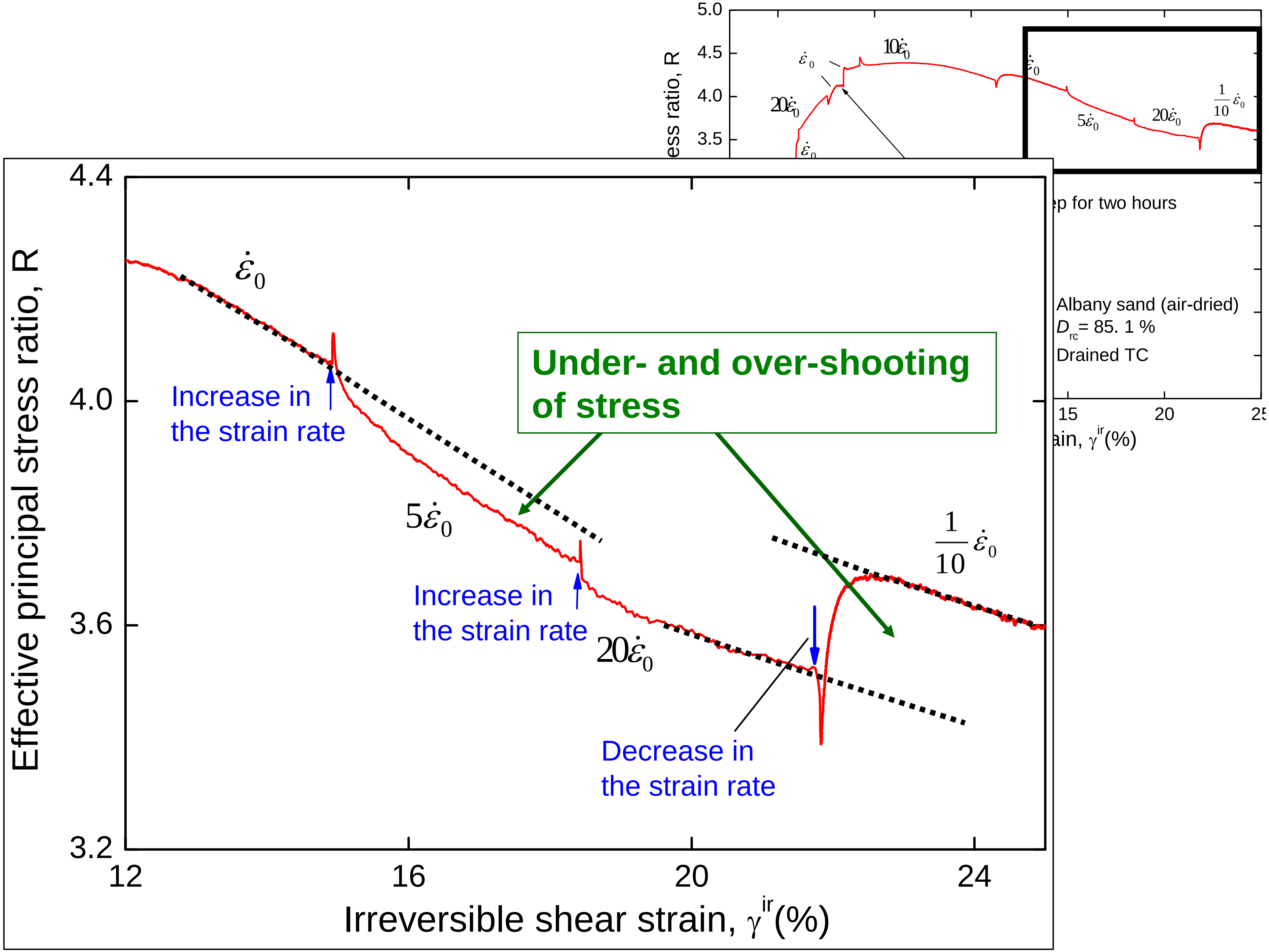


Positive & Negative viscosity:
$\sigma^v = (\sigma^v)_{TESRA} + \{-(\sigma^v)_{isotach}\}$
σ
0
$\dot{\varepsilon}_0$
$-(\sigma^v)_{Isotach}$
$10\dot{\varepsilon}_0$
Step increase in the strain rate
$100\dot{\varepsilon}_0$
C
D
Continuous ML at a constant strain rate
B
TESRA viscosity (positive viscosity); $(\sigma^v)_{TESRA}$
A
With the negative viscosity only
ε^{ir}

P & N viscosity, more obvious in the post-peak regime



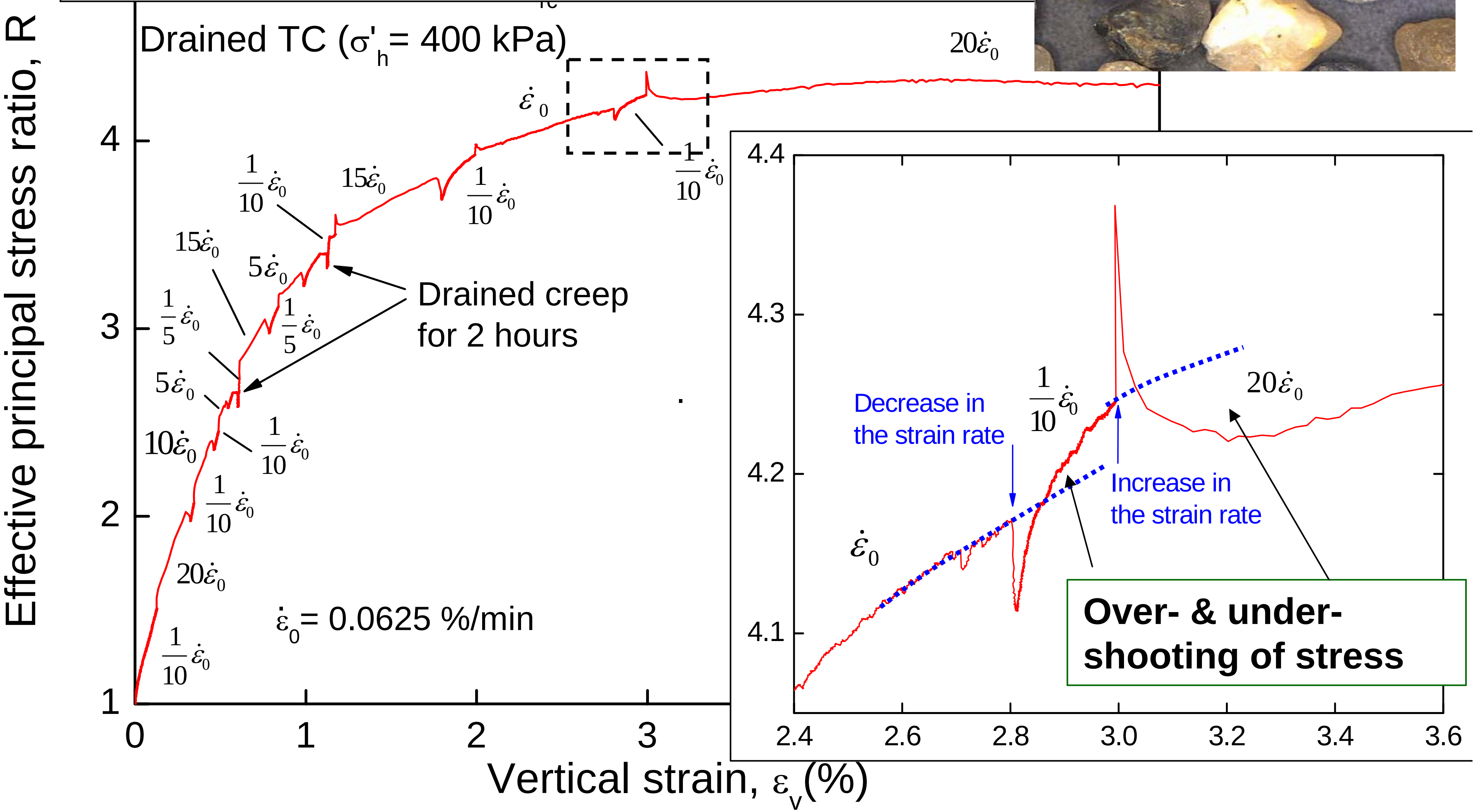
Enomoto et al. (2006)



Under- and over-shooting of stress
Increase in the strain rate
Increase in the strain rate
Decrease in the strain rate
$\dot{\varepsilon}_0$
$5\dot{\varepsilon}_0$
$20\dot{\varepsilon}_0$
$\frac{1}{10}\dot{\varepsilon}_0$
$10\dot{\varepsilon}_0$
Effective principal stress ratio, R
Irreversible shear strain, γ^{ir}(%)
4.4
4.0
3.6
3.2
12
16
20
24
5.0
4.5
3.5
15
25
Albany sand (air-dried)
D_{rc} = 85. 1 %
Drained TC

Another example of P & N viscosity …..

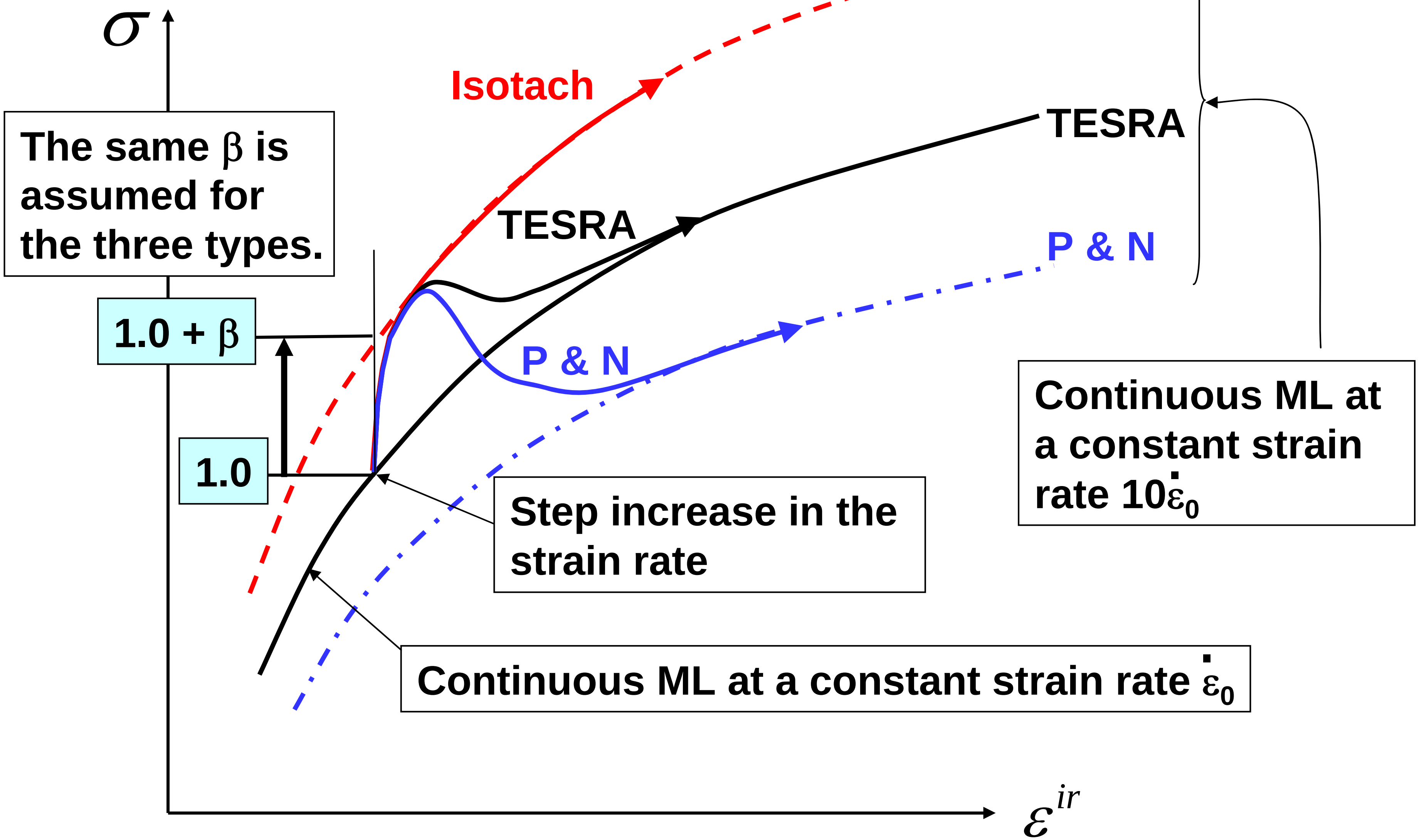
Hime gravel;
sub-round particle (D_{50}= 1.54 mm, U_c= 3.55)



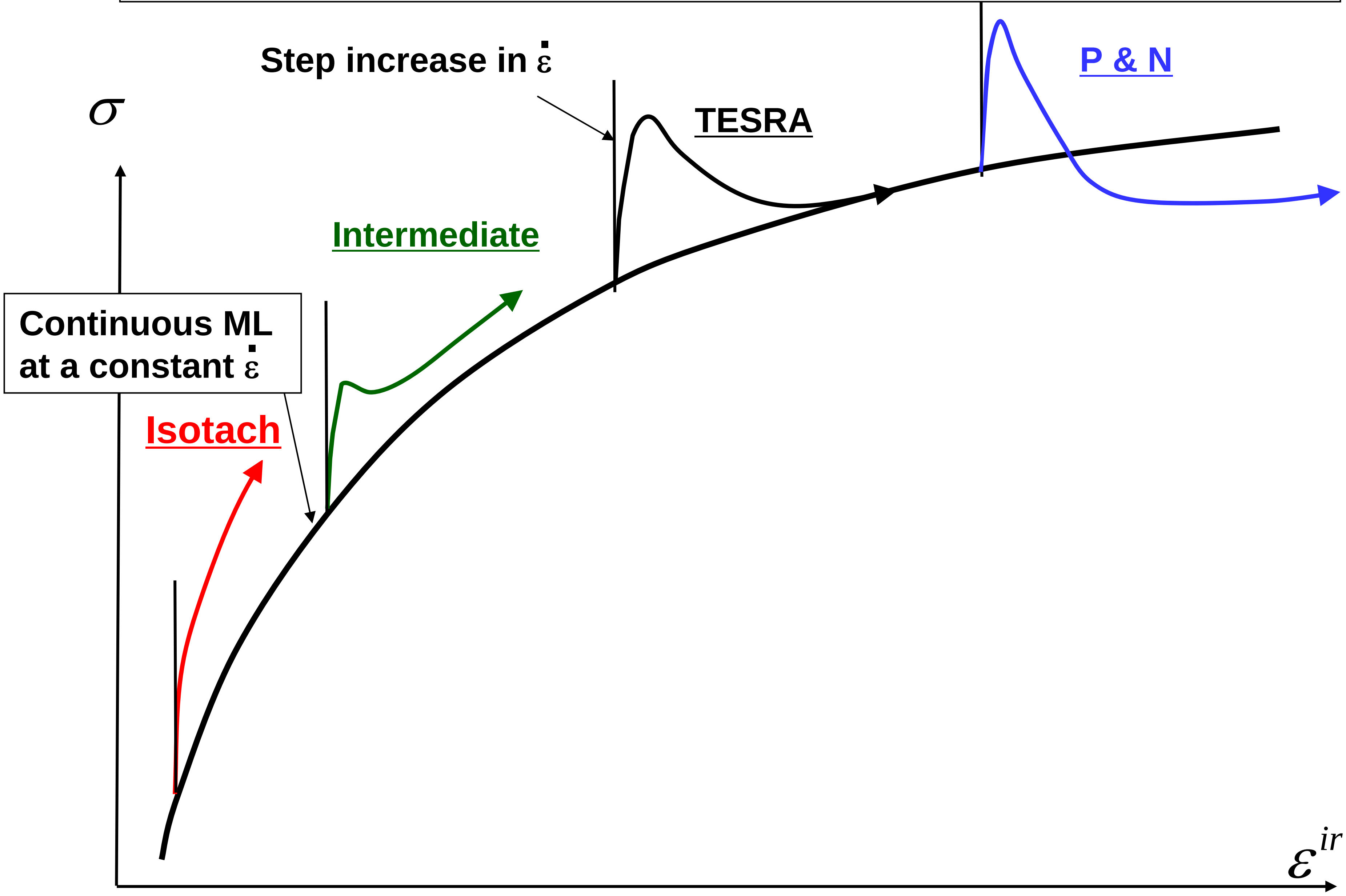
Kawabe et al. (2006)

Summary of viscosity -1

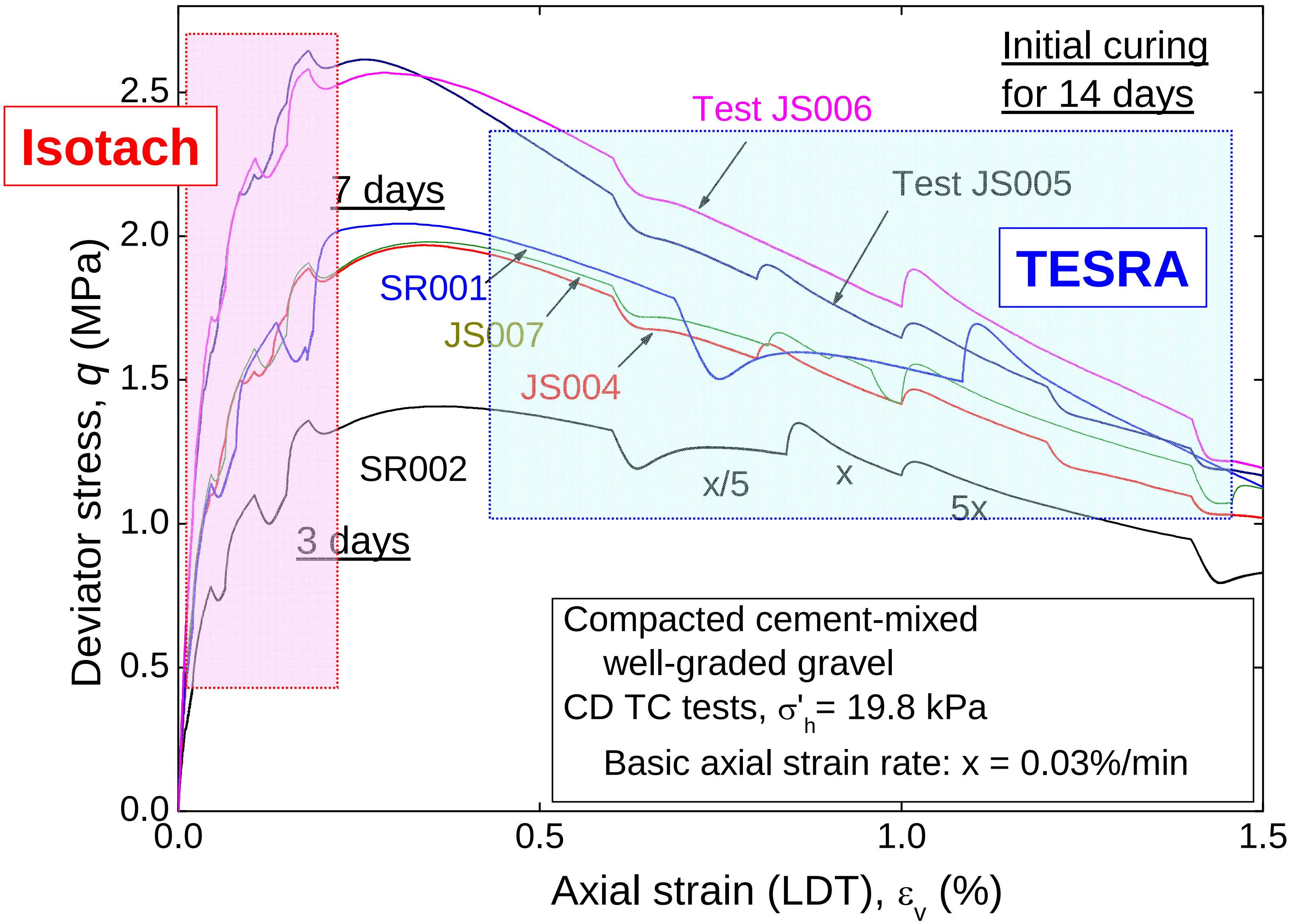
β : rate-sensitivity coefficient,
the rate of stress change for a strain rate change by a factor of 10



Summary -2: The viscosity type may change with an increase in the irreversible strain.

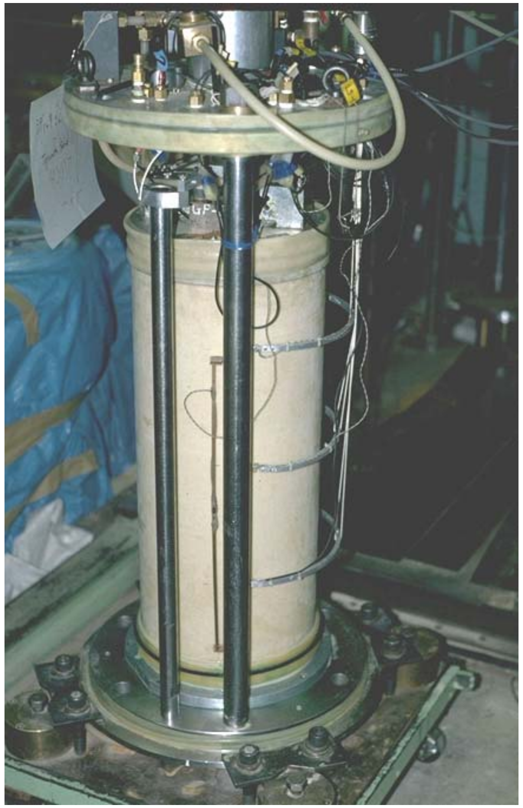


Change in the viscous property, *due to damage to bonding at inter-particle contact points ?*



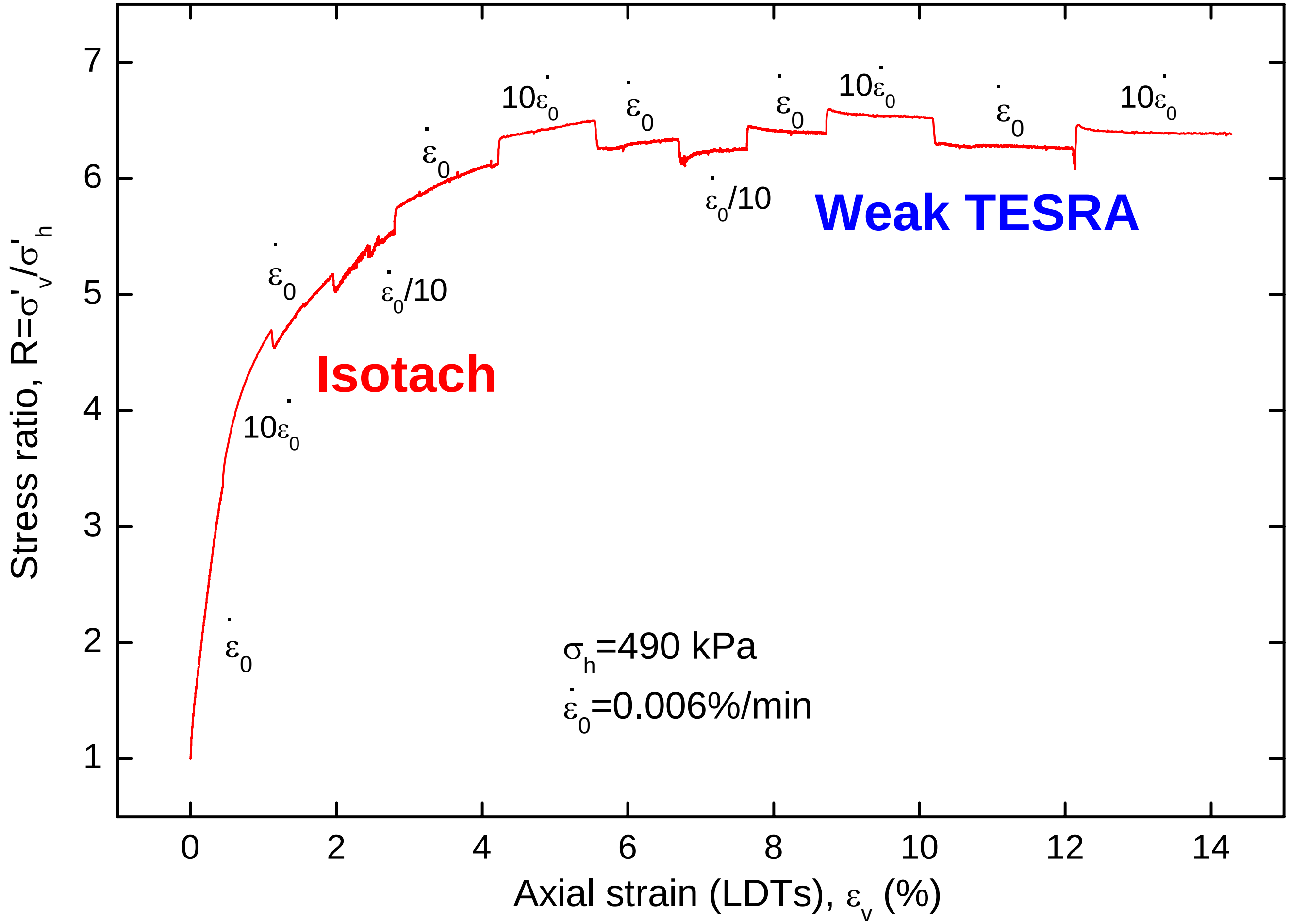
Kongsukprasert & Tatsuoka (2005), *S & F*

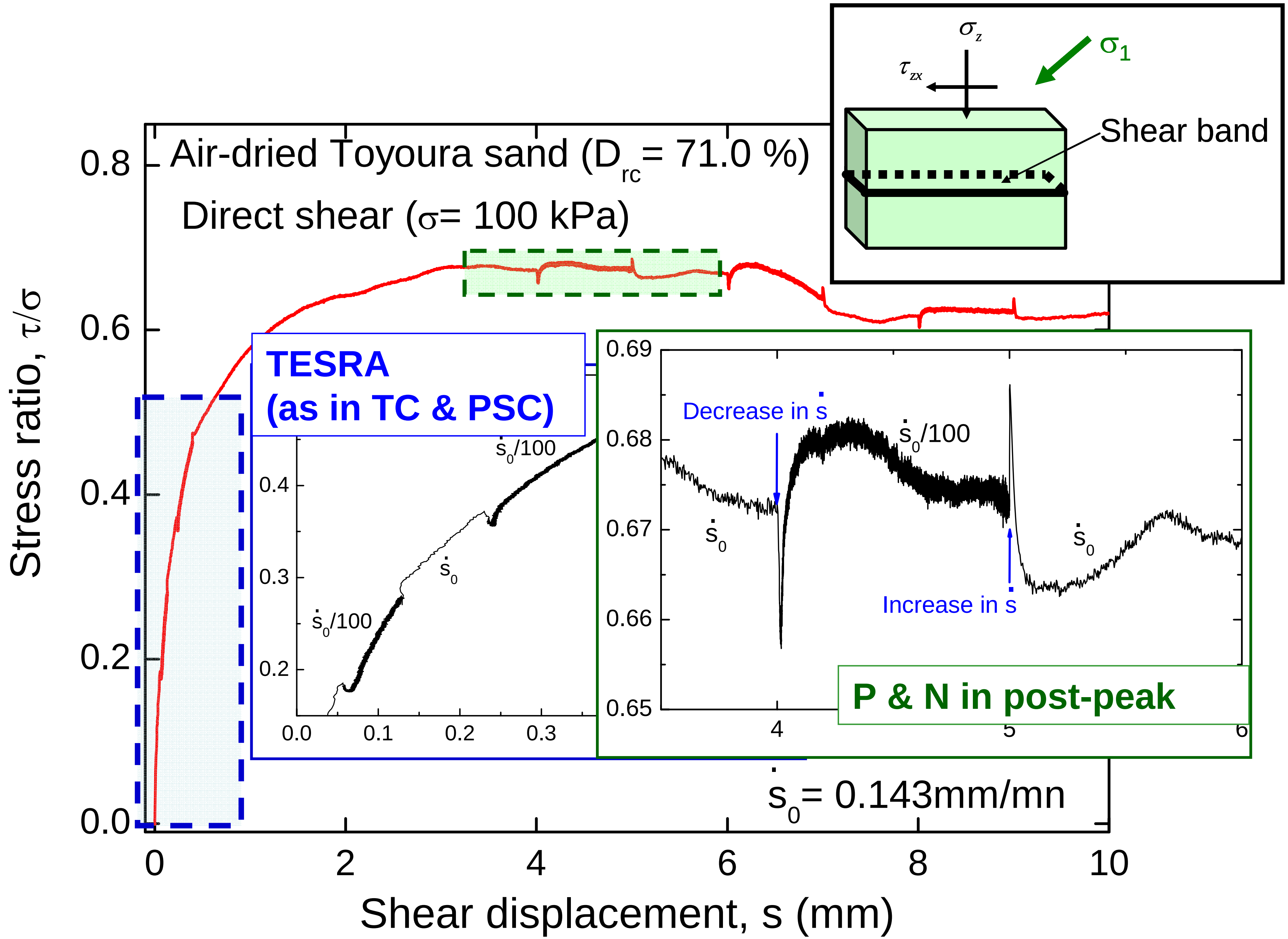
CD TC on compacted well-graded gravel; angular, D_{max}= 38 mm, D_{50}= 3.5 mm and U_c= 12.75



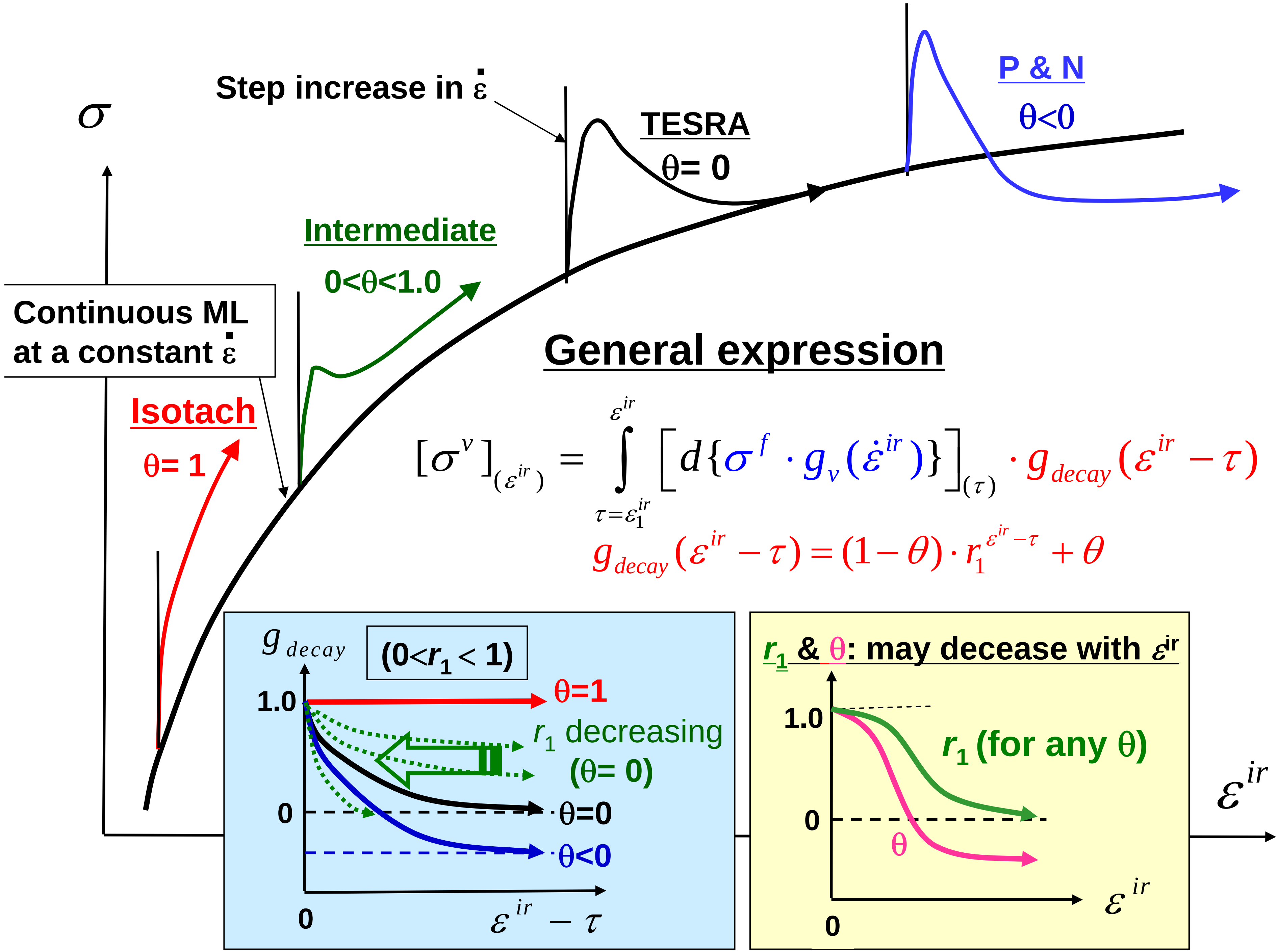
Specimen (30 cm-dia. & 60 cm-high)

AhnDan et at. (2006)





Duttine et al. (2006)


σ
Step increase in ε̇
Continuous ML at a constant ε̇
Isotach
θ= 1
Intermediate
0<θ<1.0
TESRA
θ= 0
P & N
θ<0
General expression
$$[\sigma^v]_{(\varepsilon^{ir})} = \int_{\tau=\varepsilon_1^{ir}}^{\varepsilon^{ir}} \left[d\{\sigma^f \cdot g_v(\dot{\varepsilon}^{ir})\}\right]_{(\tau)} \cdot g_{decay}(\varepsilon^{ir} - \tau)$$
$$g_{decay}(\varepsilon^{ir} - \tau) = (1-\theta)\cdot r_1^{\varepsilon^{ir}-\tau} + \theta$$
g_{decay}
($0<r_1<1$)
1.0
θ=1
r_1 decreasing
(θ= 0)
0
θ=0
θ<0
0
$\varepsilon^{ir} - \tau$
r_1 & θ: may decease with ε^{ir}
1.0
r_1 (for any θ)
0
θ
0
ε^{ir}
ε^{ir}

Viscosity type (θ) / Influencing factors	Isotach → TESRA → Positive & negative (θ=1) (θ=0) (θ<0)
Particle shape (stiff particles)	More angular → More round
Grading characteristics	Less uniformly graded → More poorly graded
Particle size (if saturated)	Smaller (*clay*) → Larger (*sand/gravel*)
Particle crushability	More crushable ?? → Less crushable ??
Inter-particle bonding	Stronger → Weaker → Null (*rock/cement-mixed soil*) (*unbound granular materials*)
Strain level	Smaller strain → Larger strain (in particular, post-peak)
Inter-particle contact point	More stable (more cohesive & larger co-ordination numbers) → Less stable (less cohesive & smaller co-ordination number)

Introduction: in-elastic strain by plasticity, viscosity and cyclic loading, all affected by ageing effect

Elasto-plasticity: yielding characteristics

Viscosity: three types (*Isotach*, *TESRA* and *P&N*); and viscosity of other materials

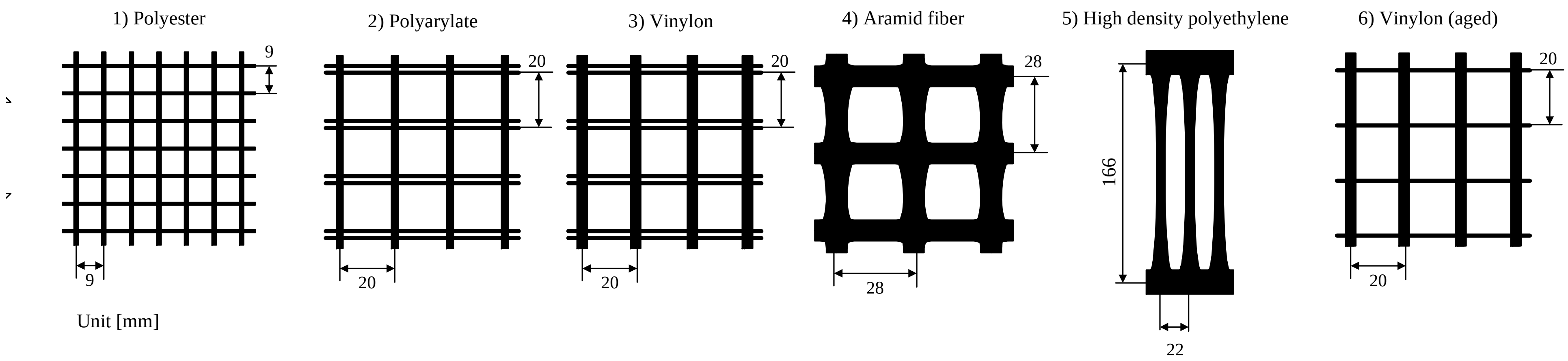
Cyclic loading effect: interactions and particle shape effect

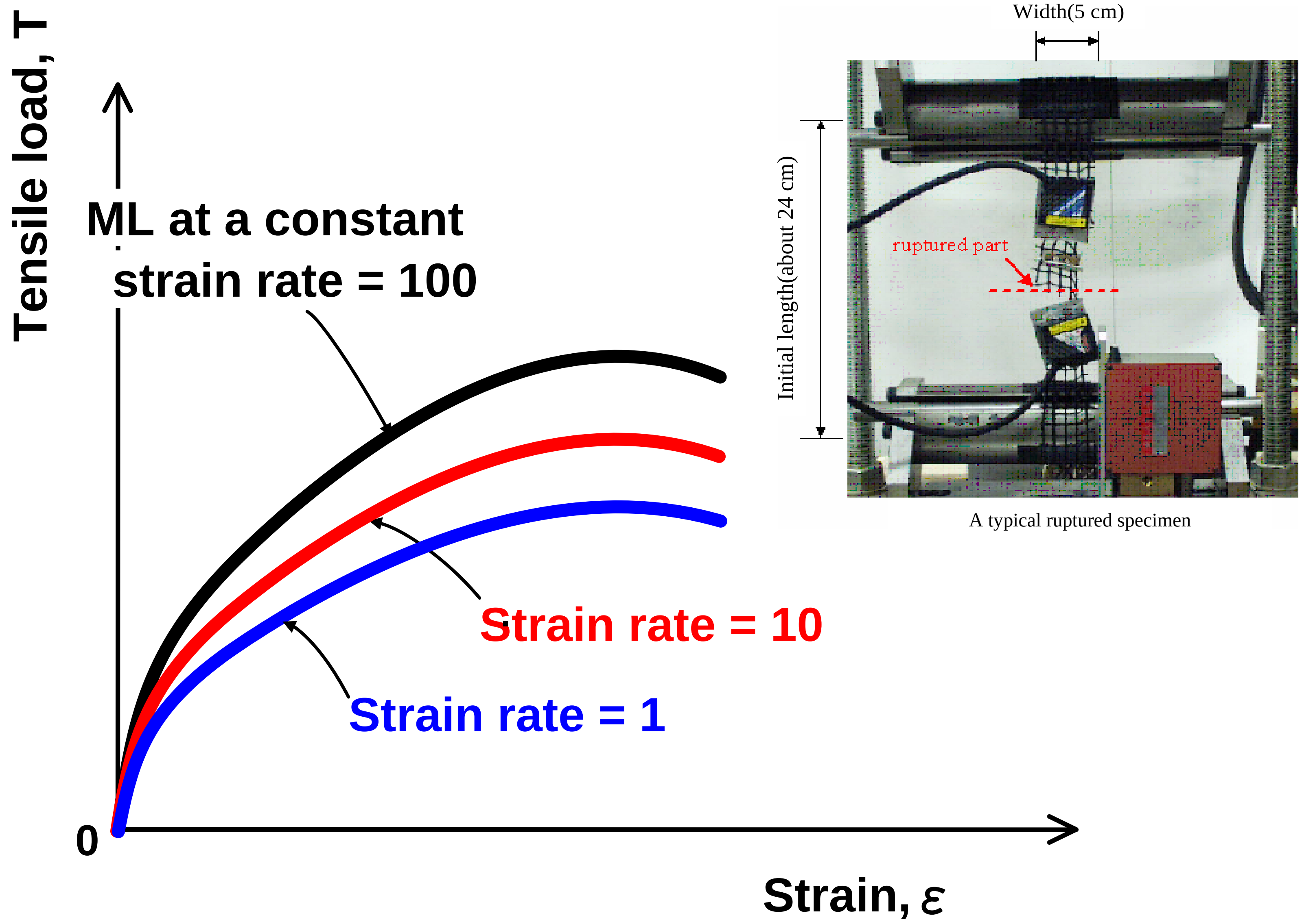
Ageing effect

1D consolidation of clay

Summary

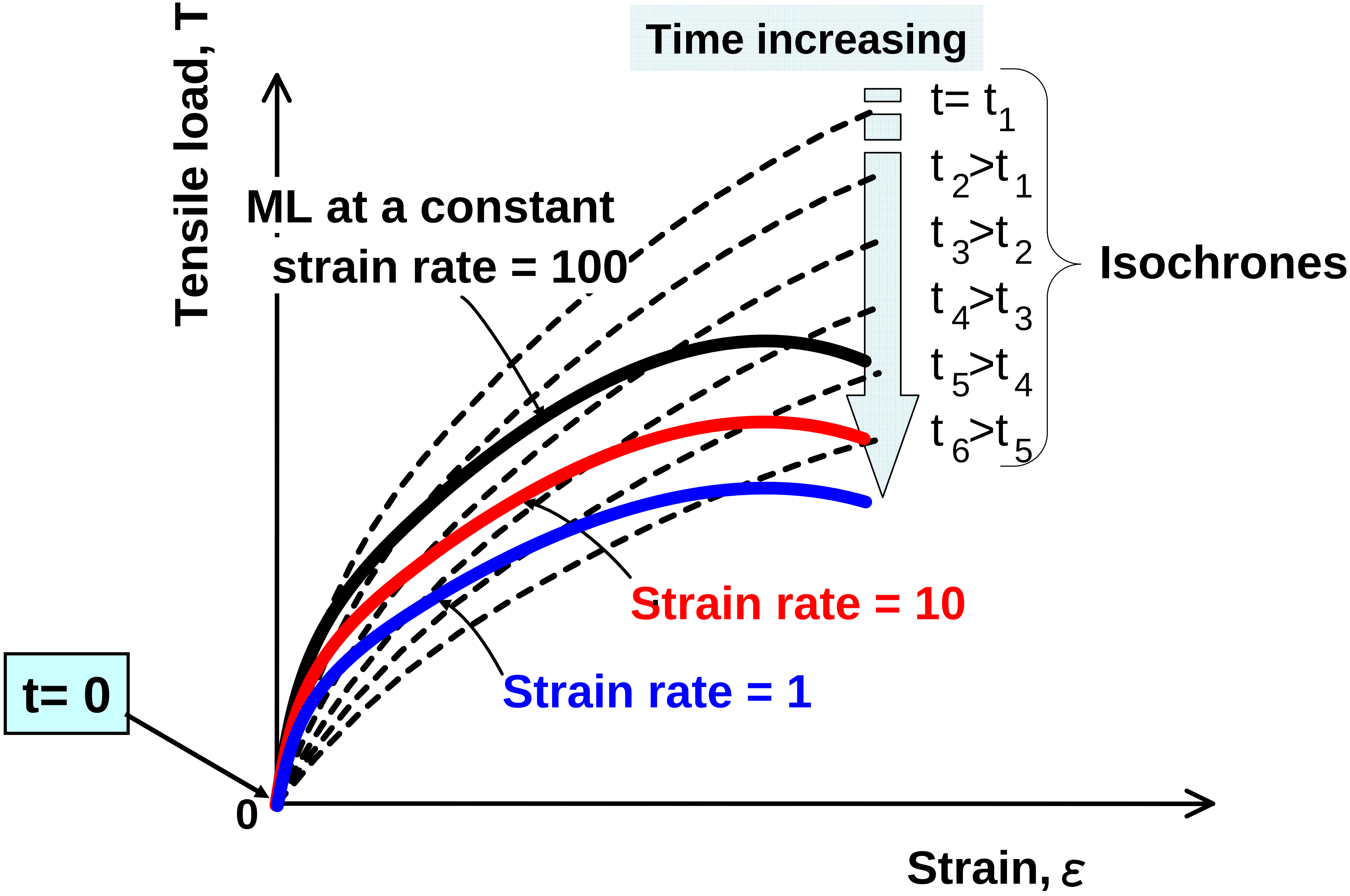
Viscous property of polymer geosynthetic reinforcement is one of the most important design factors



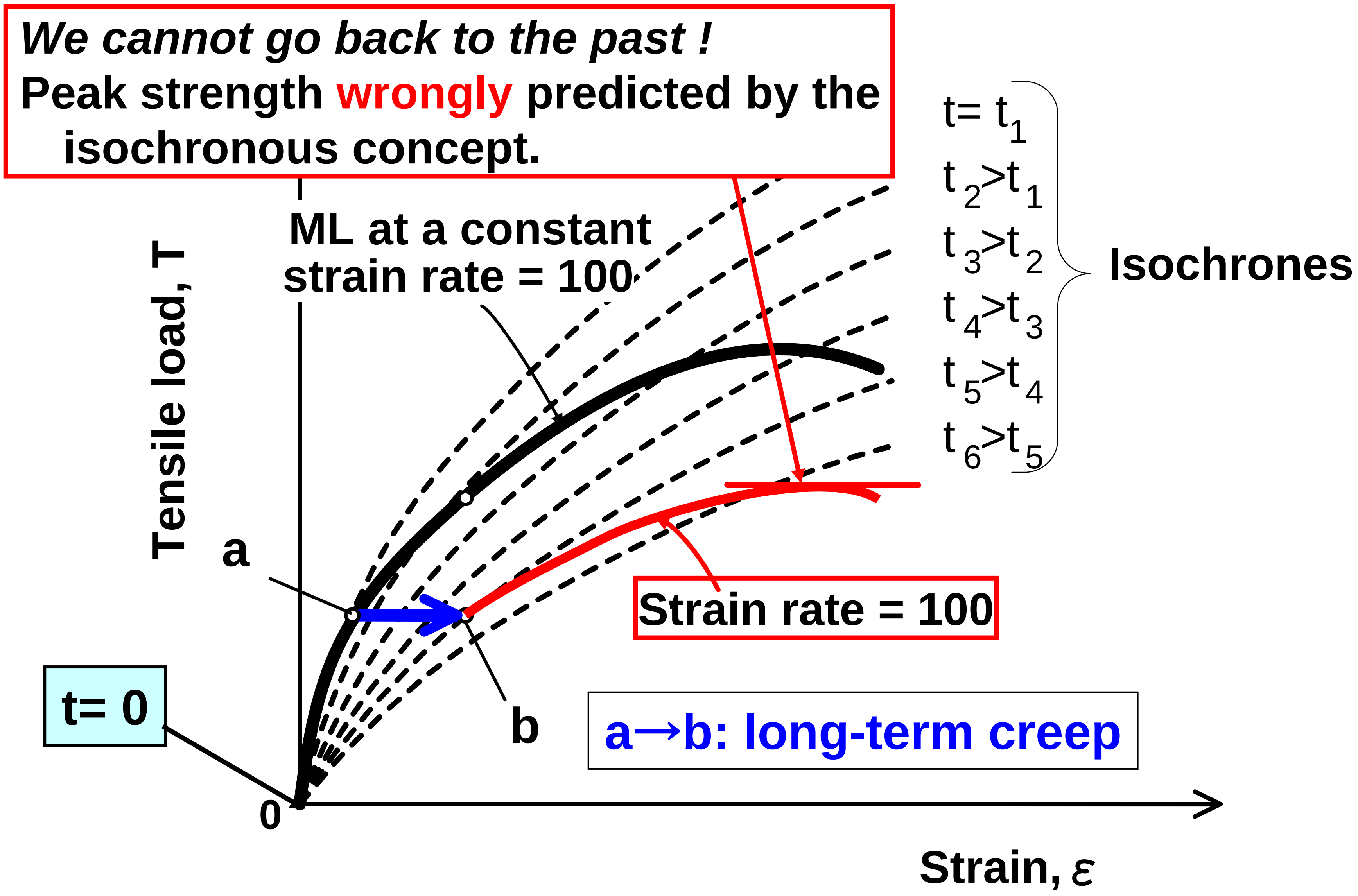


A typical ruptured specimen

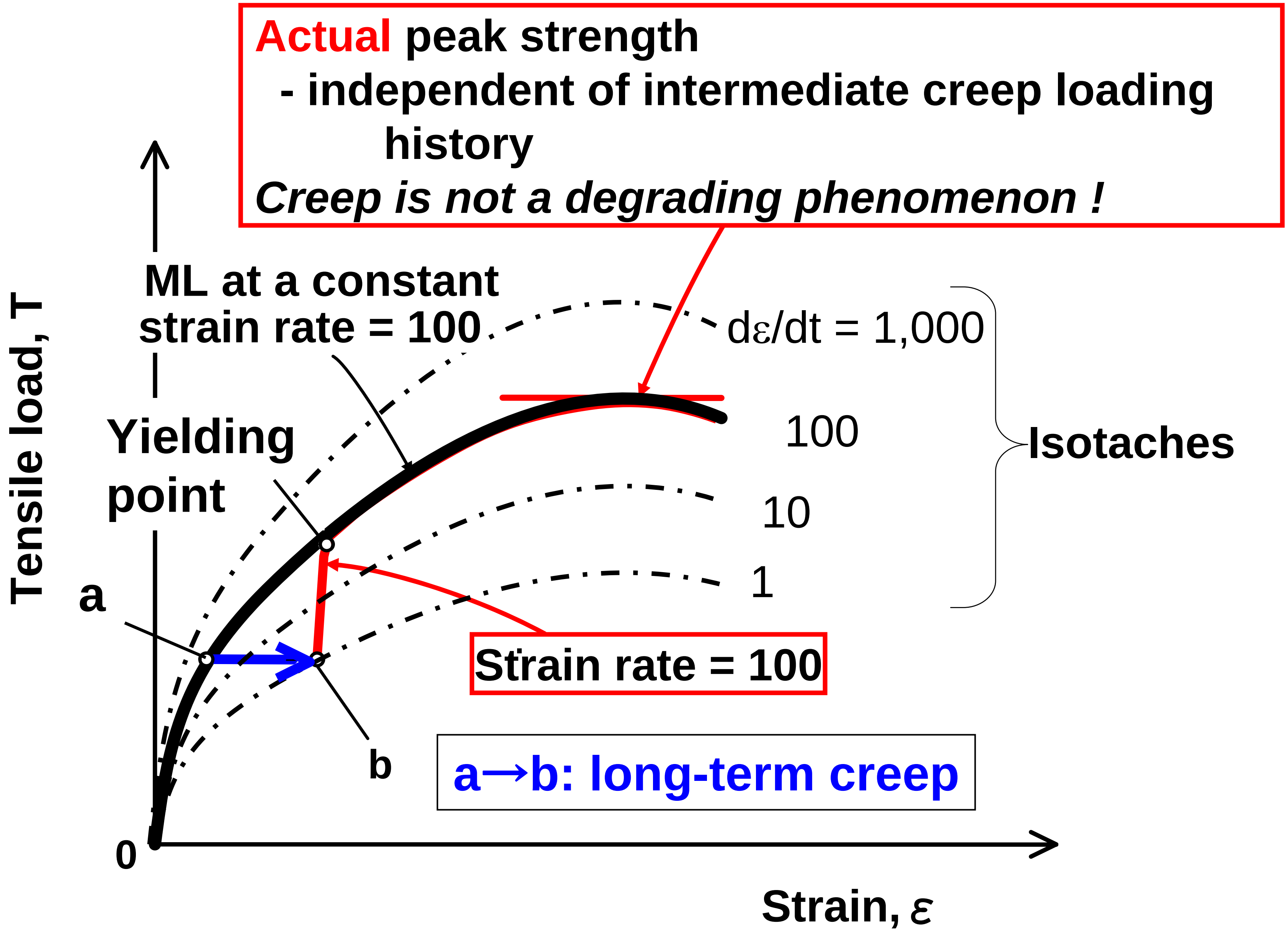
Tensile rupture tests



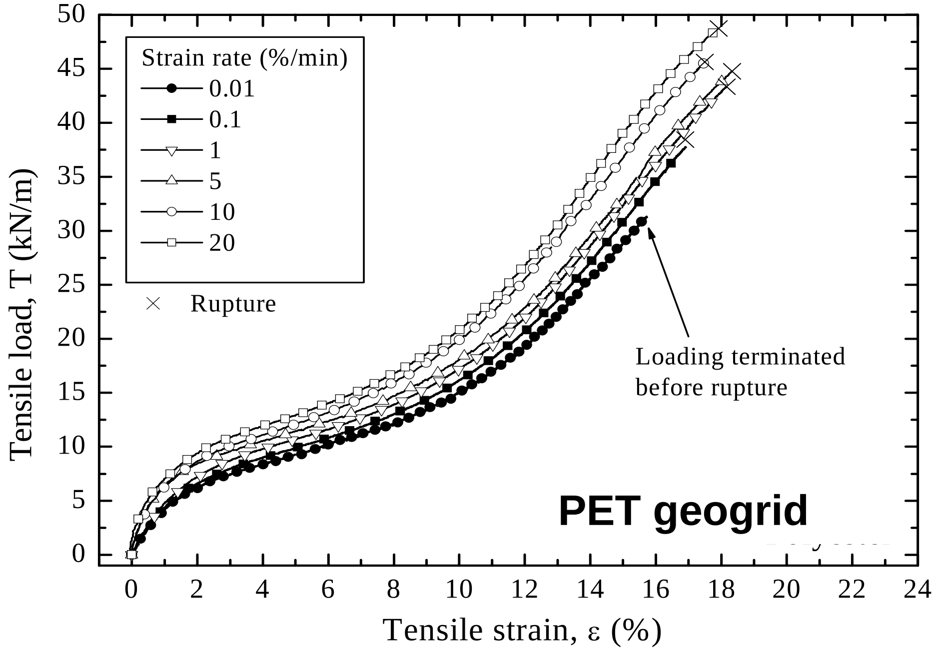
Interpretation by the isochronous concept

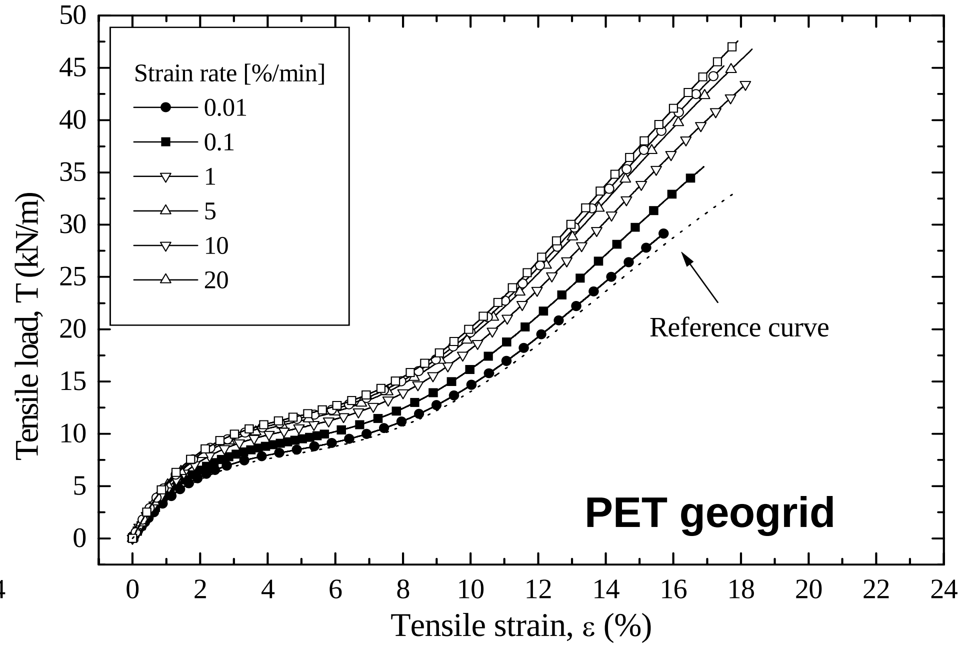


We cannot go back to the past !
Peak strength wrongly predicted by the isochronous concept.
ML at a constant strain rate = 100
Tensile load, T
Strain, ε
t= t1
t2>t1
t3>t2
t4>t3
t5>t4
t6>t5
Isochrones
a
b
0
t= 0
Strain rate = 100
a→b: long-term creep



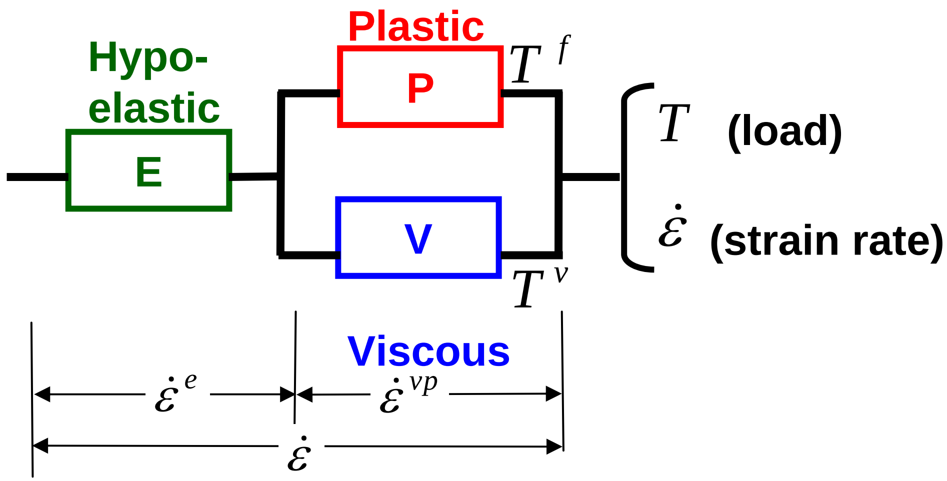
Actual peak strength
- independent of intermediate creep loading history
Creep is not a degrading phenomenon !
ML at a constant strain rate = 100
dε/dt = 1,000
100
10
1
Isotaches
Yielding point
Tensile load, T
a
b
0
Strain rate = 100
a→b: long-term creep
Strain, ε





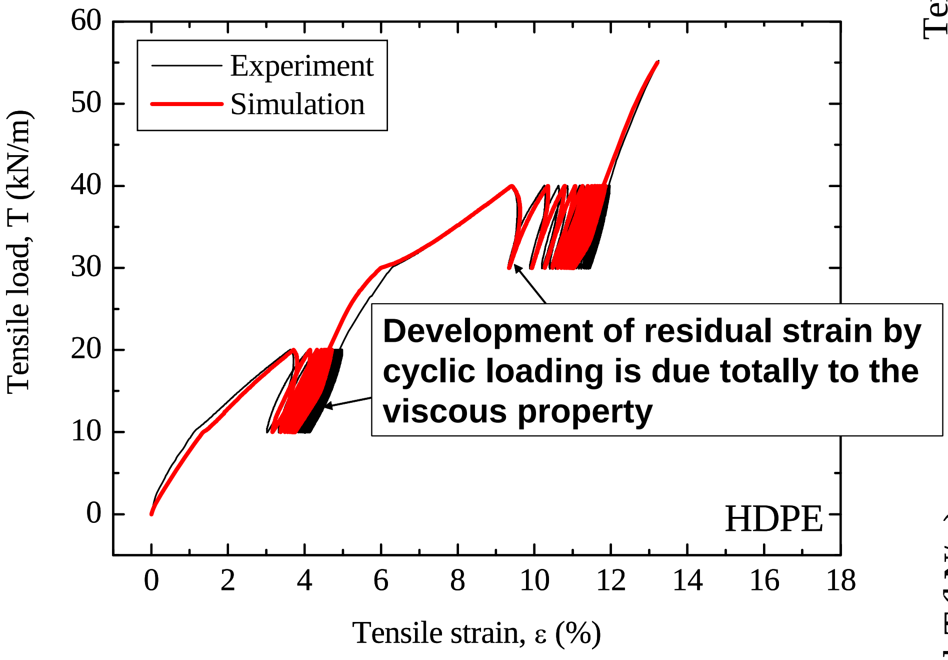
Experiment: ML at different strain rates

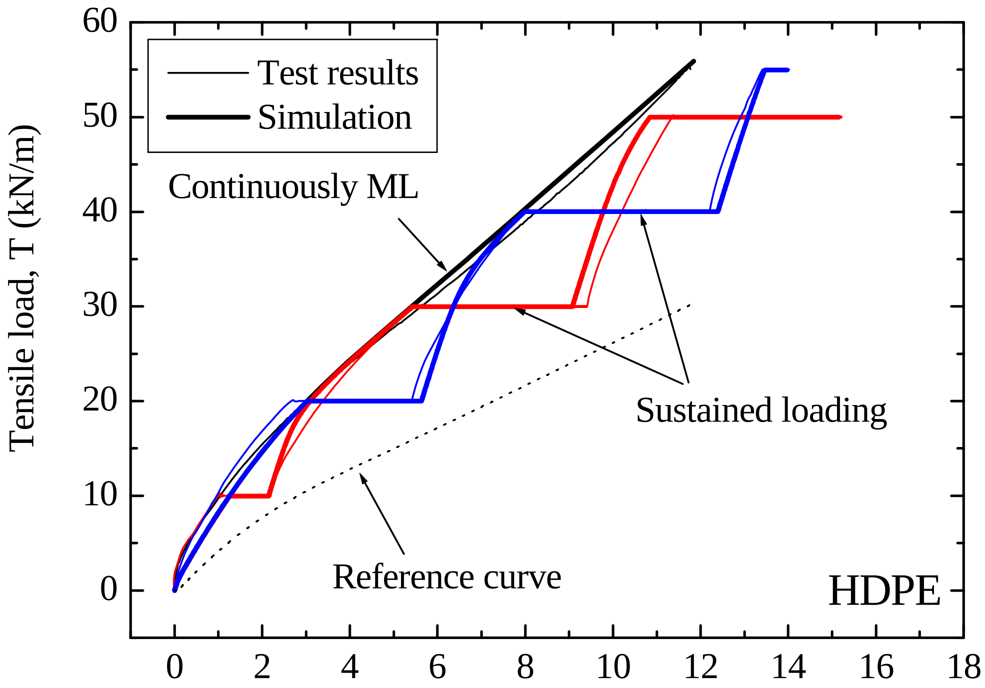
Simulation $[0<\theta<1, r_1=f(\varepsilon^{ir})]$

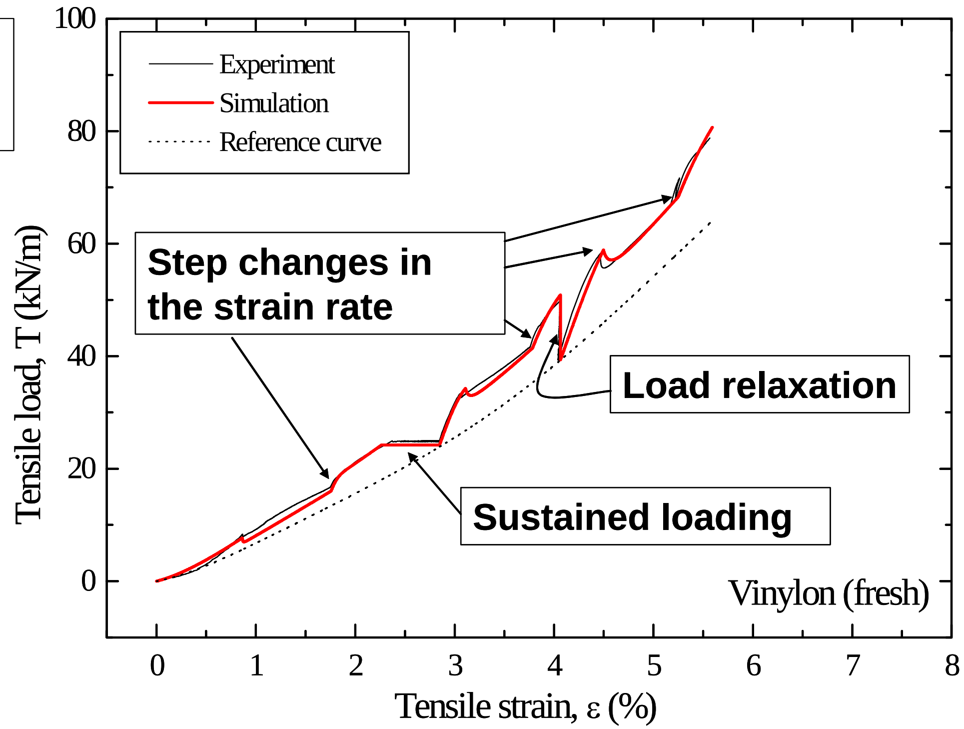


Hirakawa et al. (2004)

Simulation by the three-component model (Isotach)

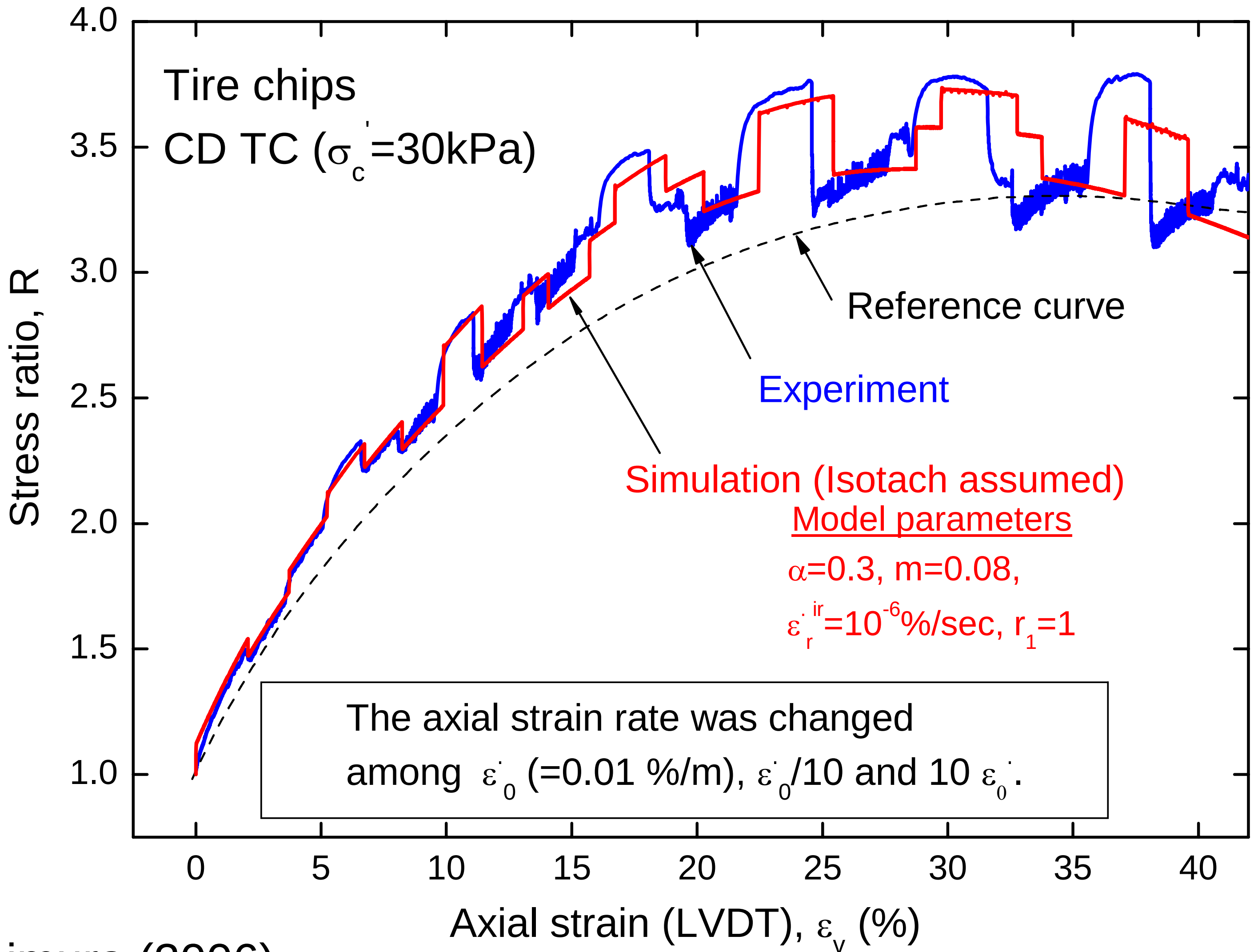






Hirakawa et al. (2004);
Kongkitkul et al. (2004)

Change from Isotach to TESRA

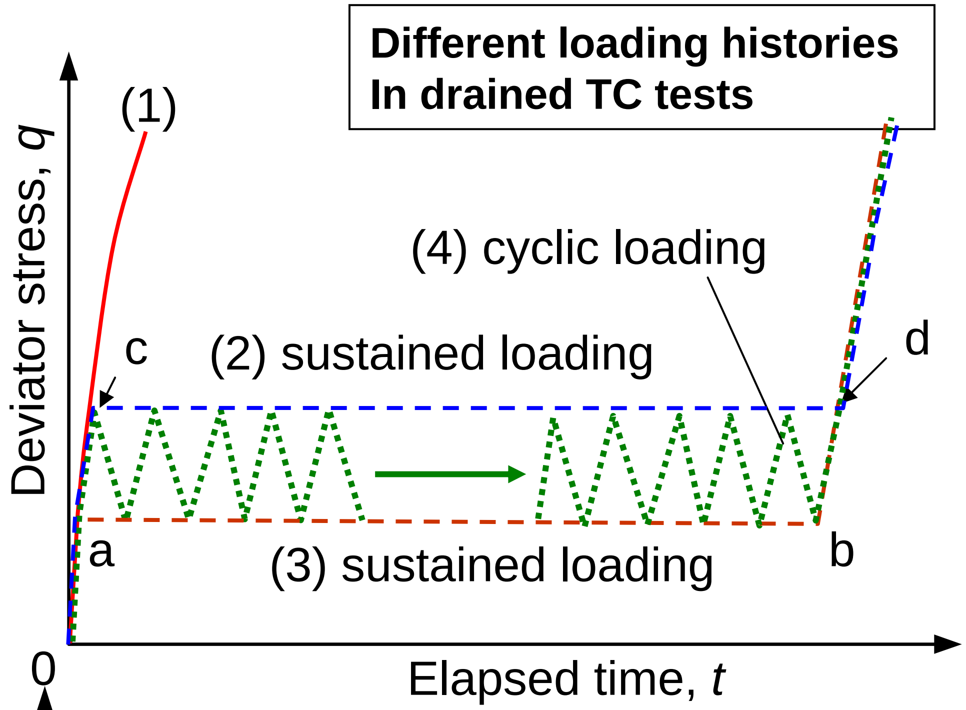


Nirmalan and Uchimura (2006)

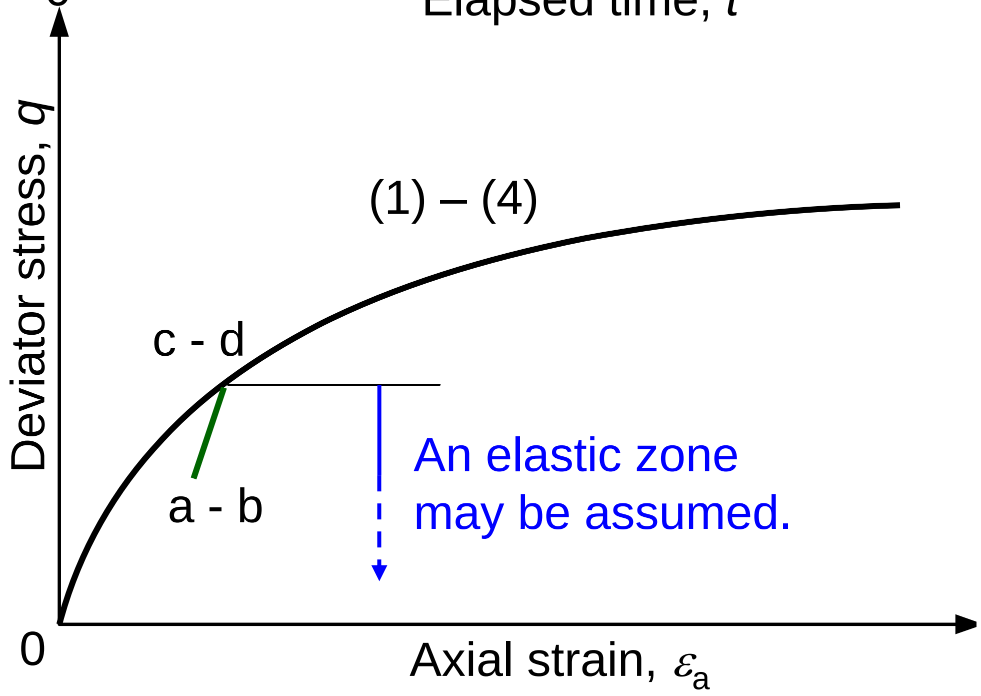
- Introduction: in-elastic strain by plasticity, viscosity and cyclic loading, all affected by ageing effect
- Elasto-plasticity: yielding characteristics
- Viscosity: three types (*Isotach*, *TESRA* and *P&N*); and viscosity of other materials
- **Cyclic loading effect: interactions** and particle shape effect
- Ageing effect
- 1D consolidation of clay
- Summary

Elasto-plastic

- **no viscosity**
- **no cyclic loading effect**
- **no ageing effect**



A unique stress-strain curve for all tests 1 – 4.

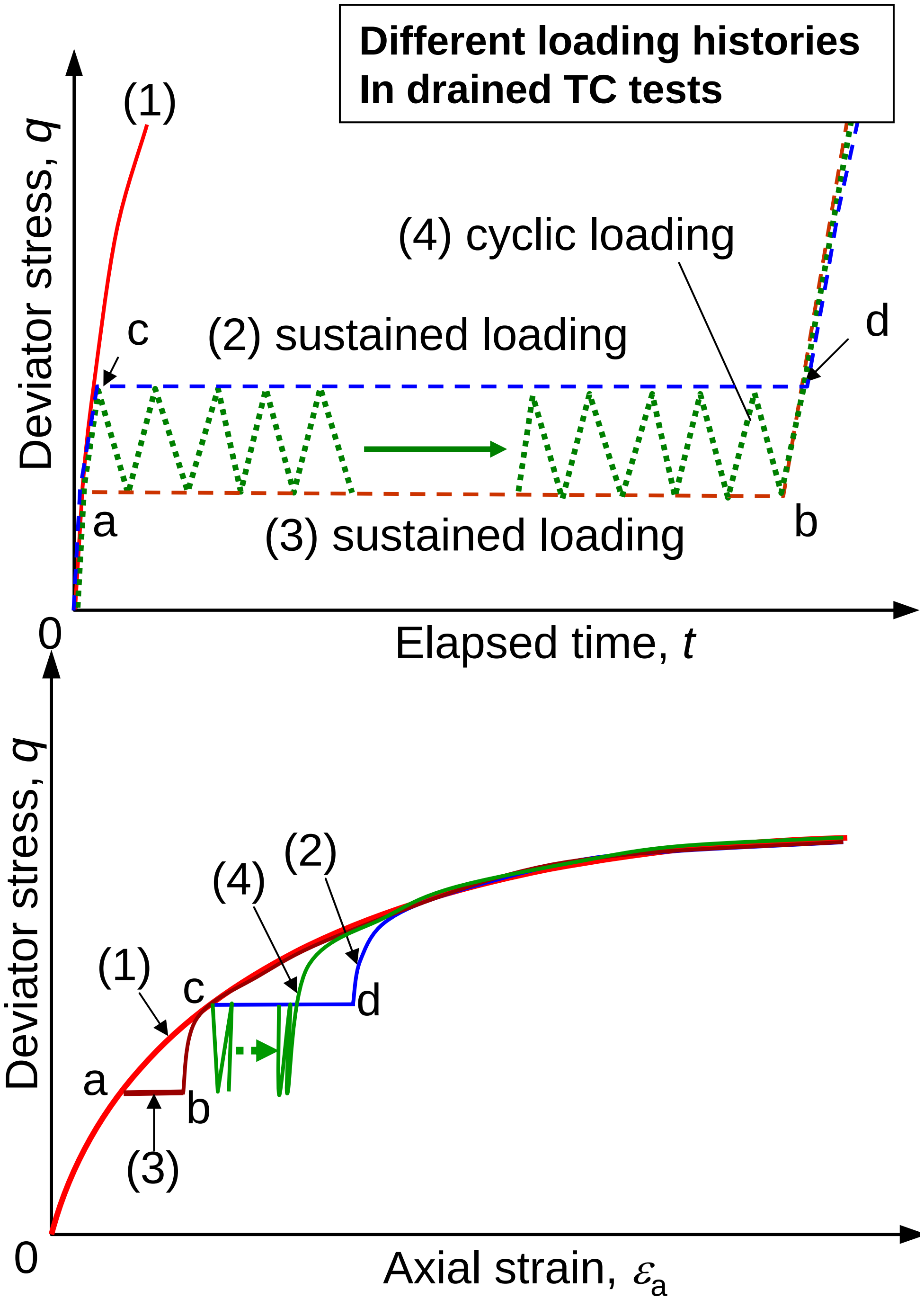


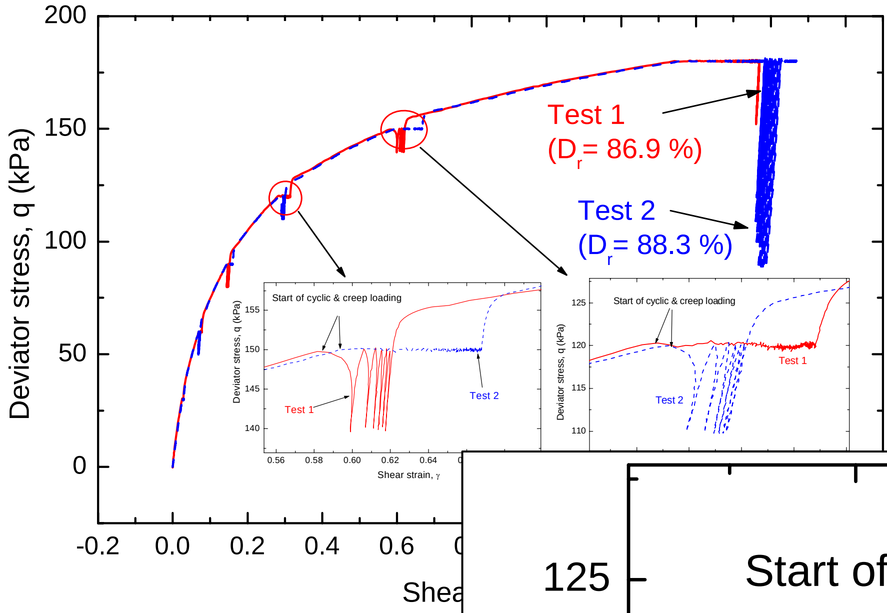
Elasto-viscoplastic

- **no cyclic loading effect**
- **no ageing effect**

During cyclic loading in test 4, irreversible strain develops due solely to viscous effects.

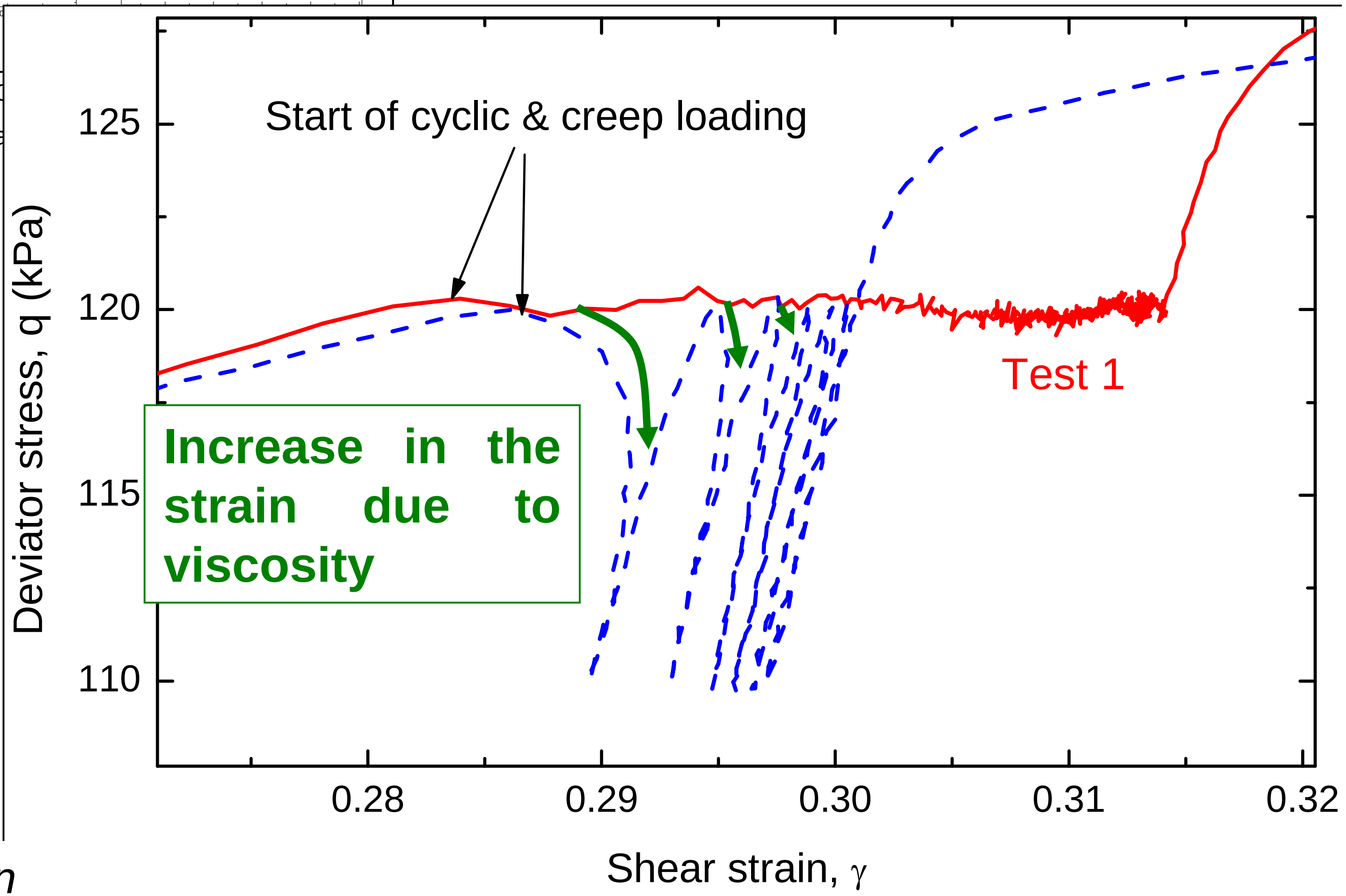
More relevant as the cyclic stress amplitude and the number of loading cycle become smaller.





The residual strain by cyclic loading is much smaller than the creep strain for the same loading period (10 minutes).

Air-dried Toyoura sand TC (σ'_h= 40 kPa)



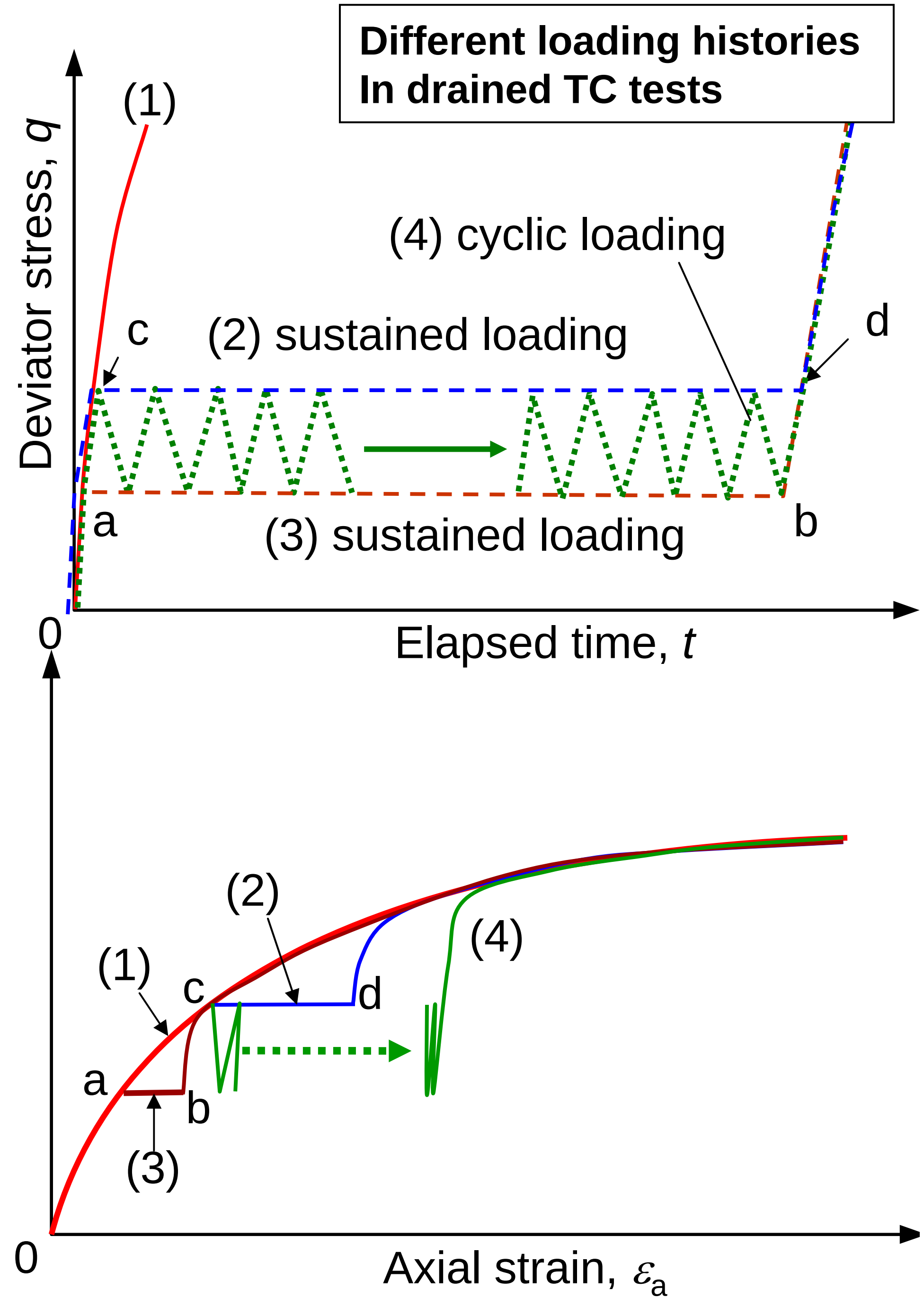
Ko et al. (2003), *Lyon*

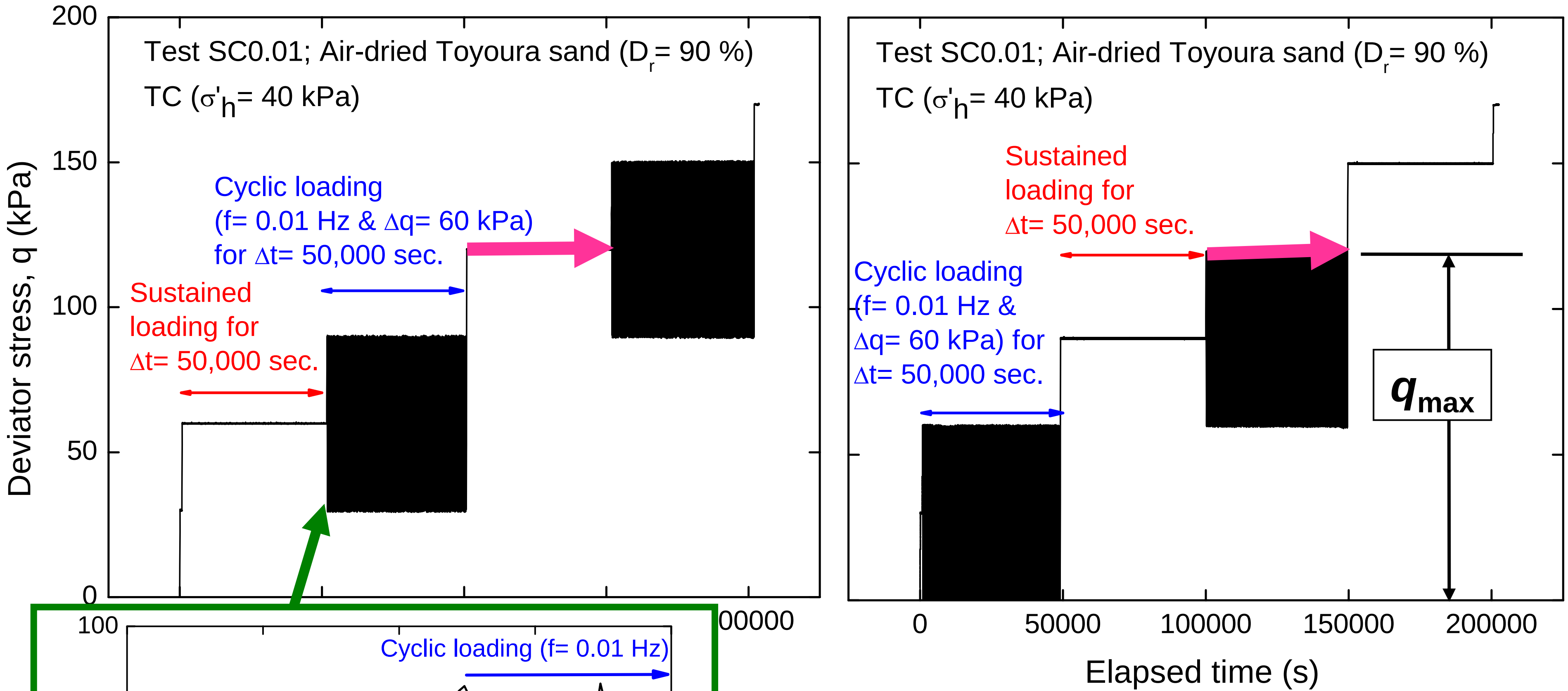
Elasto-viscoplastic

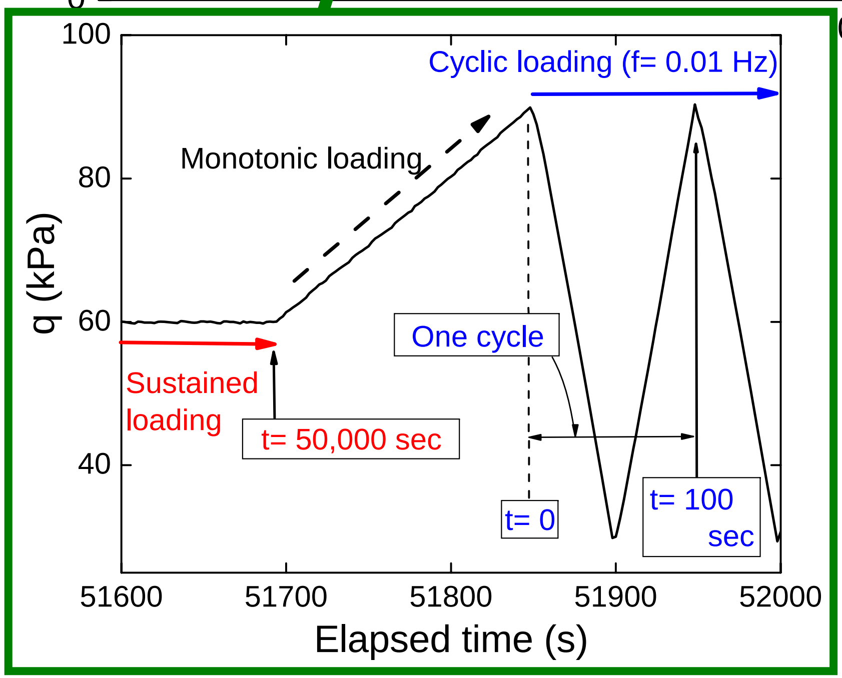
- **cyclic loading effect**
- **no ageing effect**

During cyclic loading in test 4, irreversible strain develops due to both viscous effect and cyclic loading effect.

More relevant as the cyclic stress amplitude and the number of loading cycle become larger.







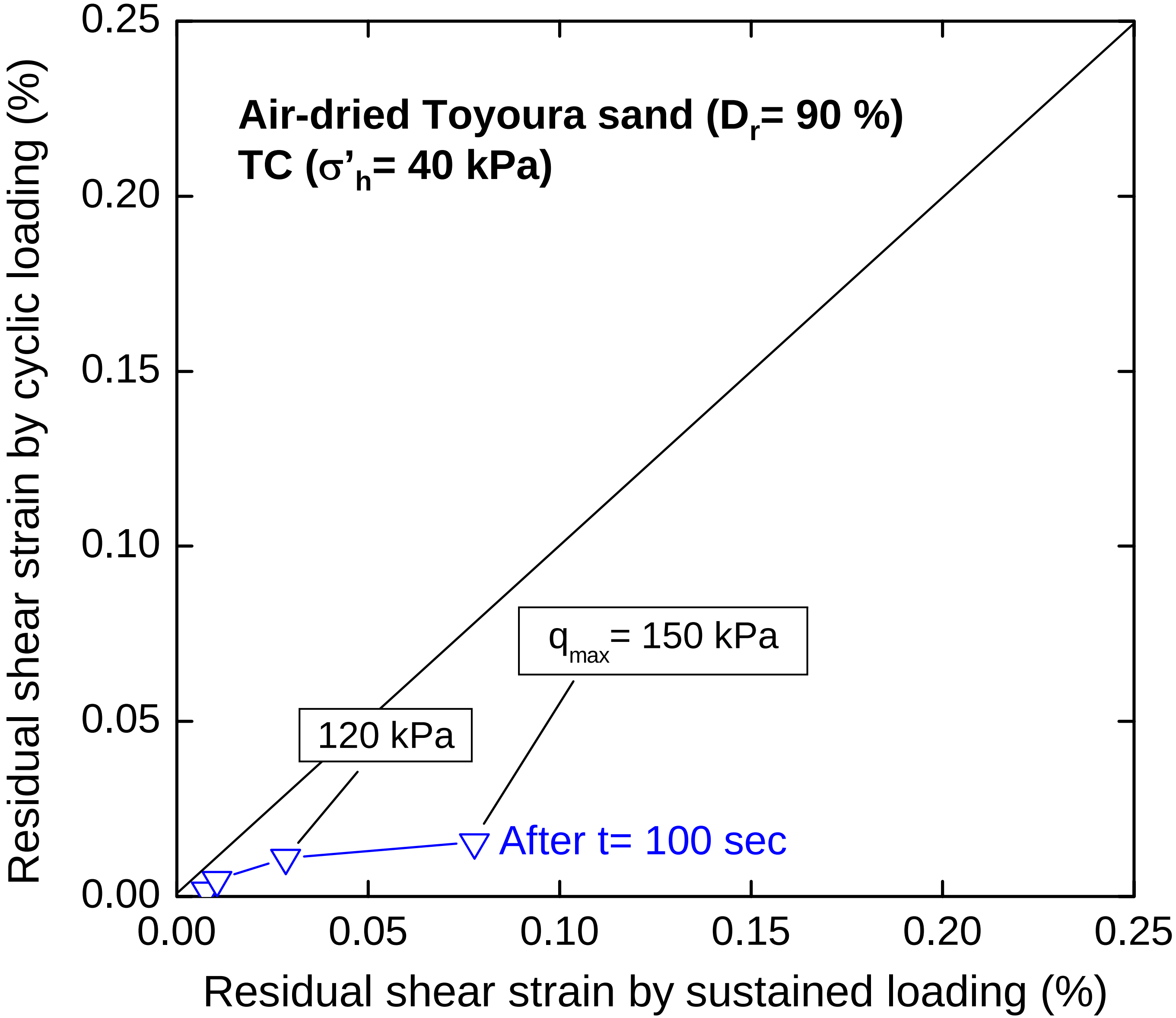
Comparison of residual strains by cyclic and sustained loading for the same q_{max} and the same duration,

***t*= 50, 0000 sec, 500 cycles (long)**

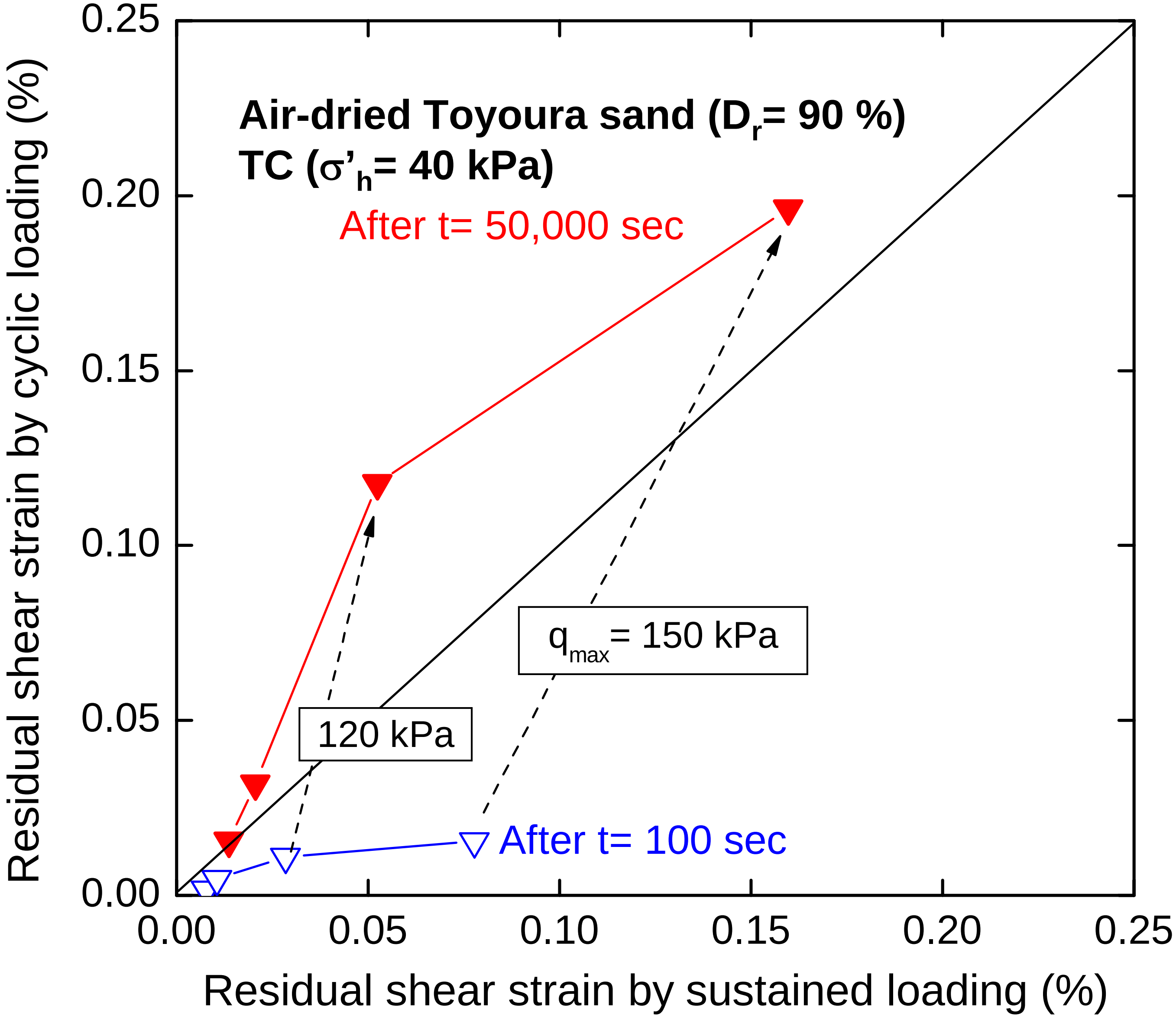
and

***t*= 100 sec, one cycle (short);**

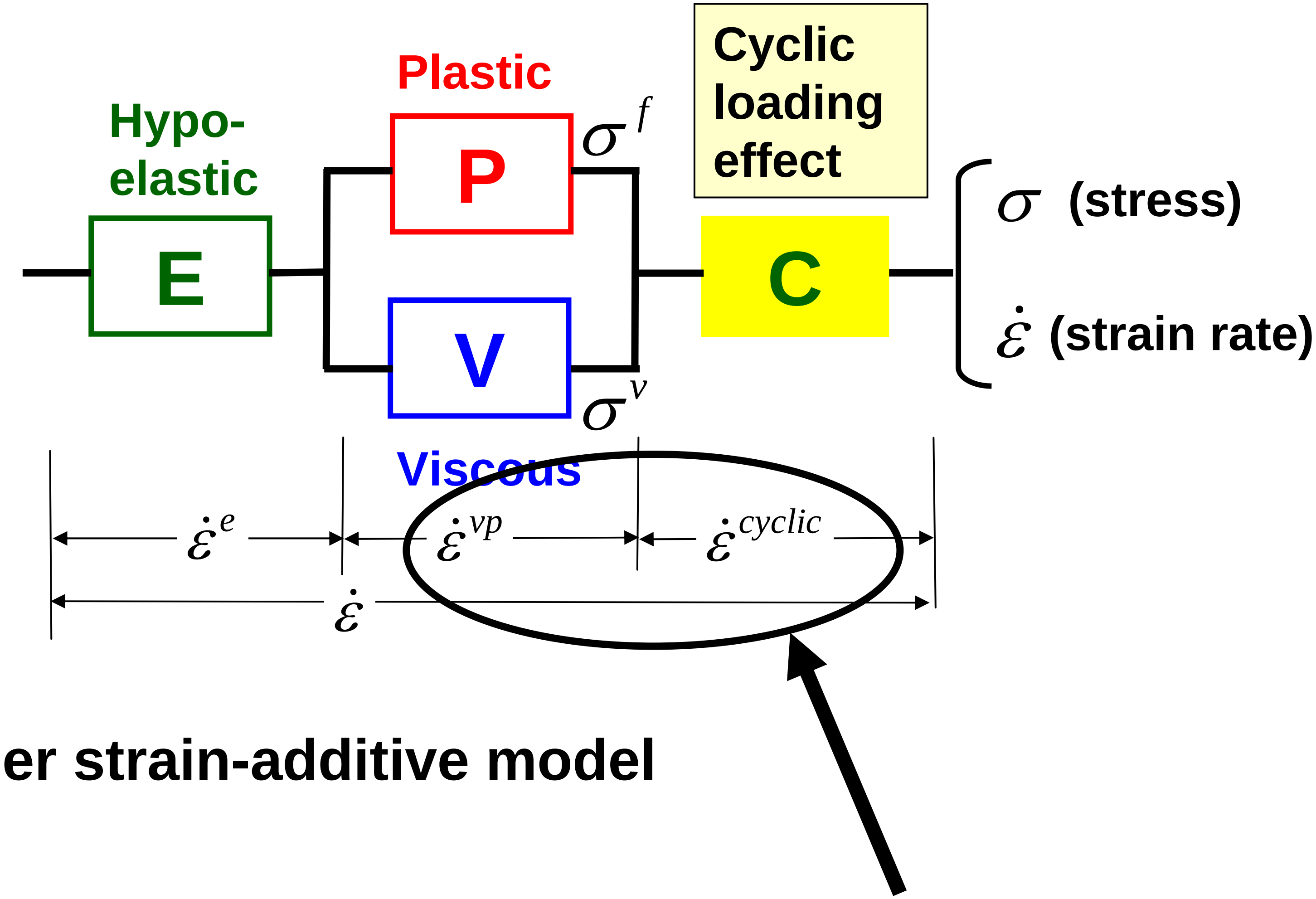
Residual strain by cyclic loading is smaller in relatively short time……



But, the residual strain by cyclic loading becomes larger after a relatively long period……

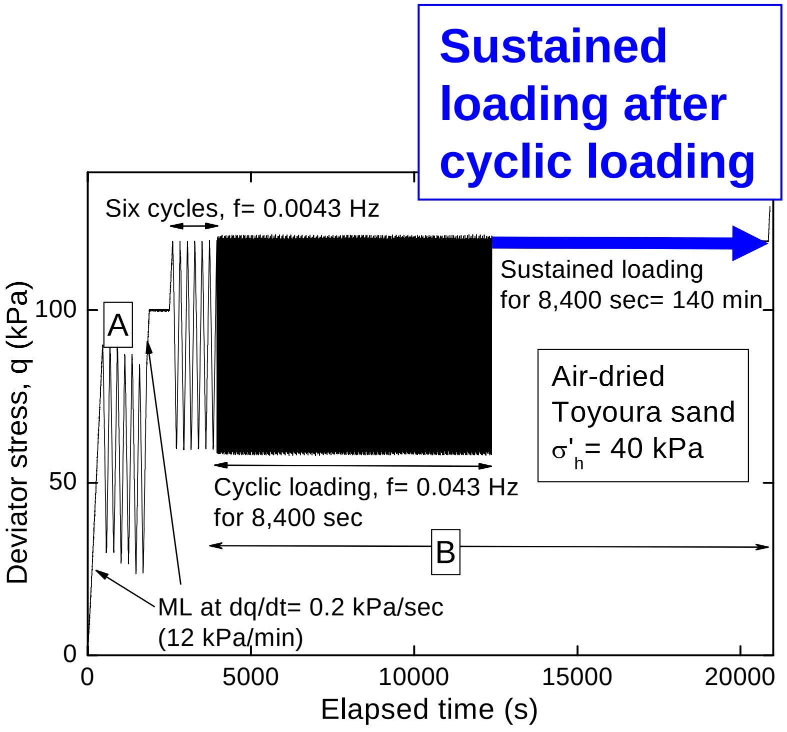


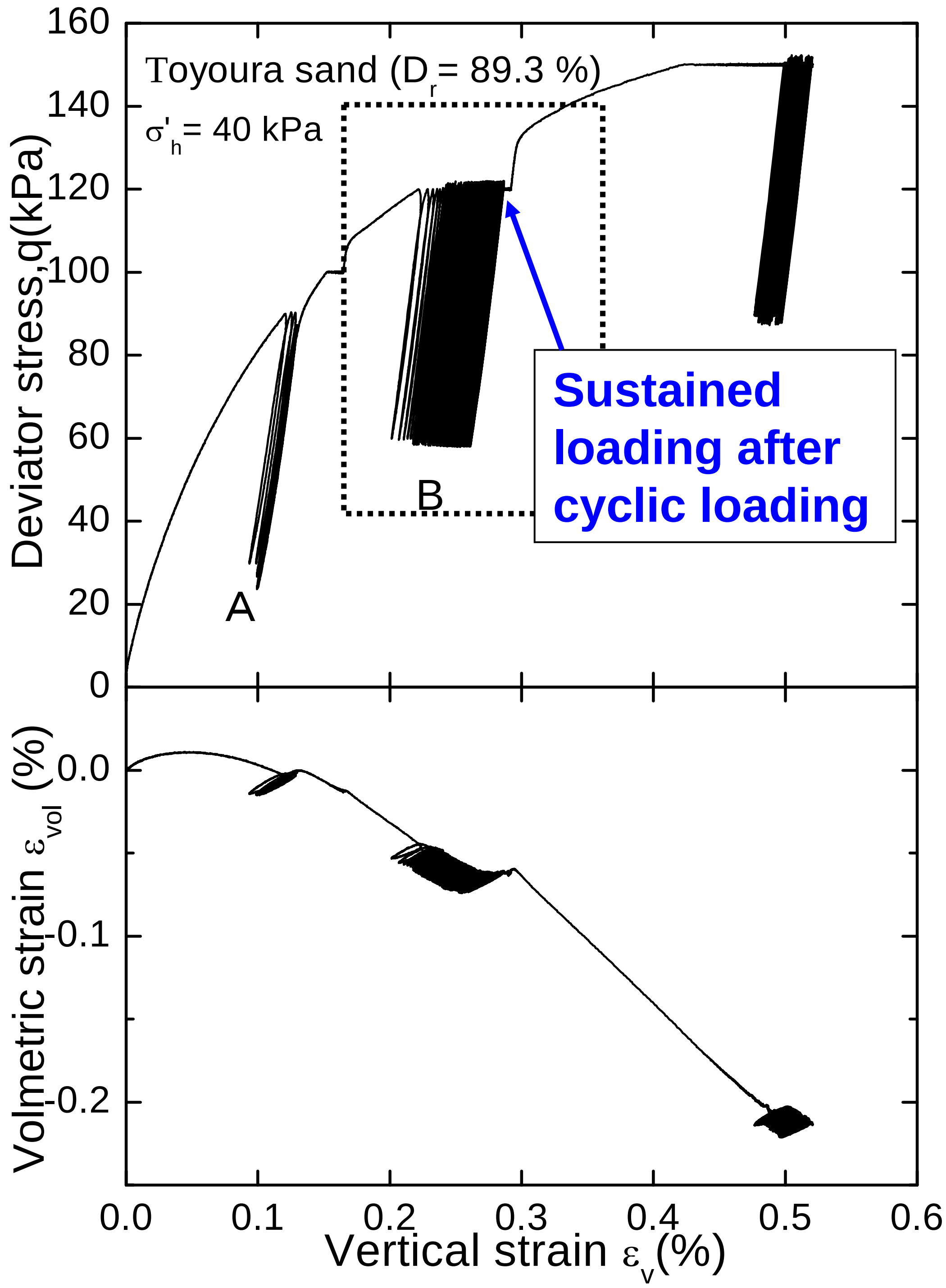
Then, how to incorporate cyclic loading effect into a constitutive model ?



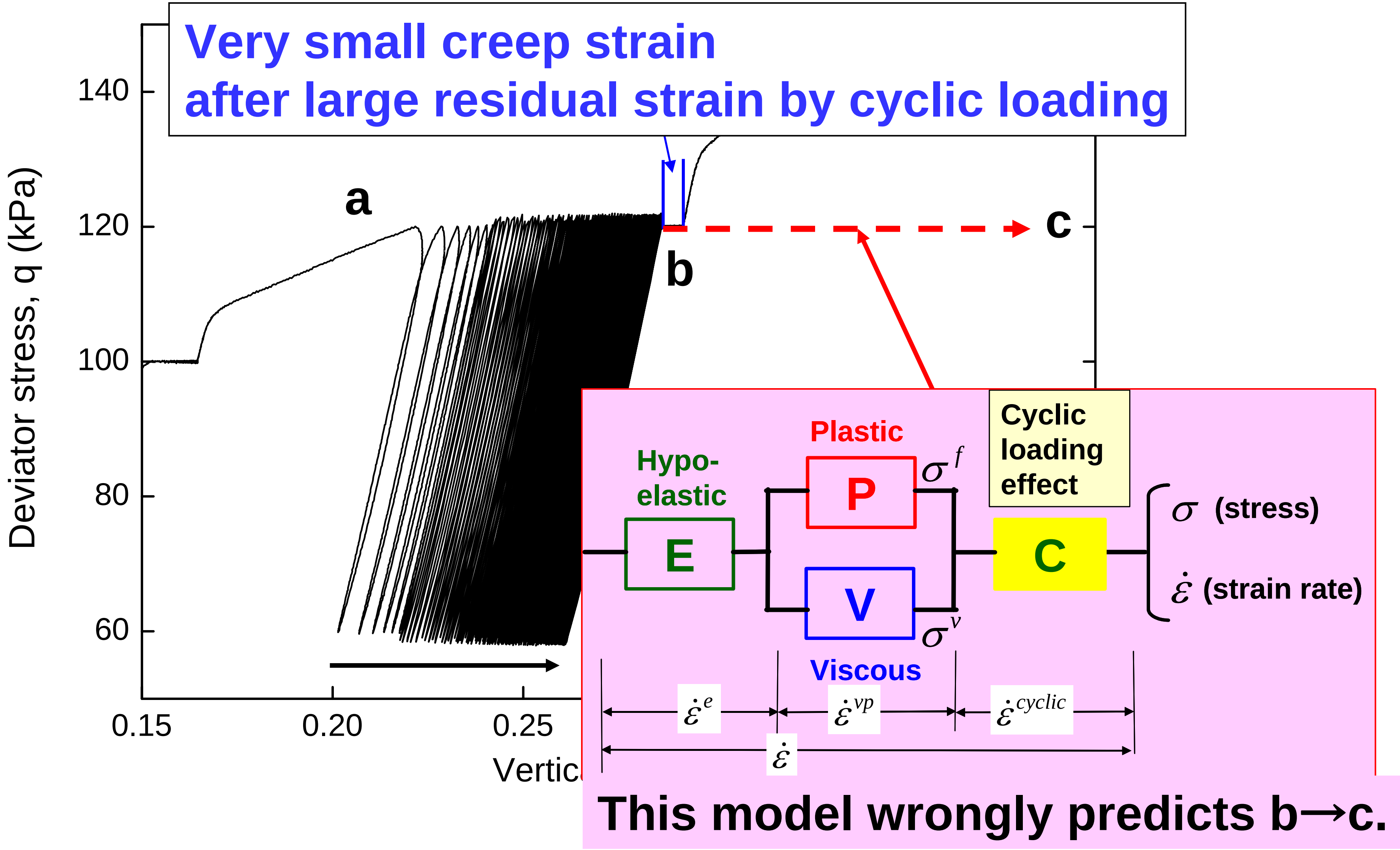
Another strain-additive model OK?

No ! they cannot be separated.

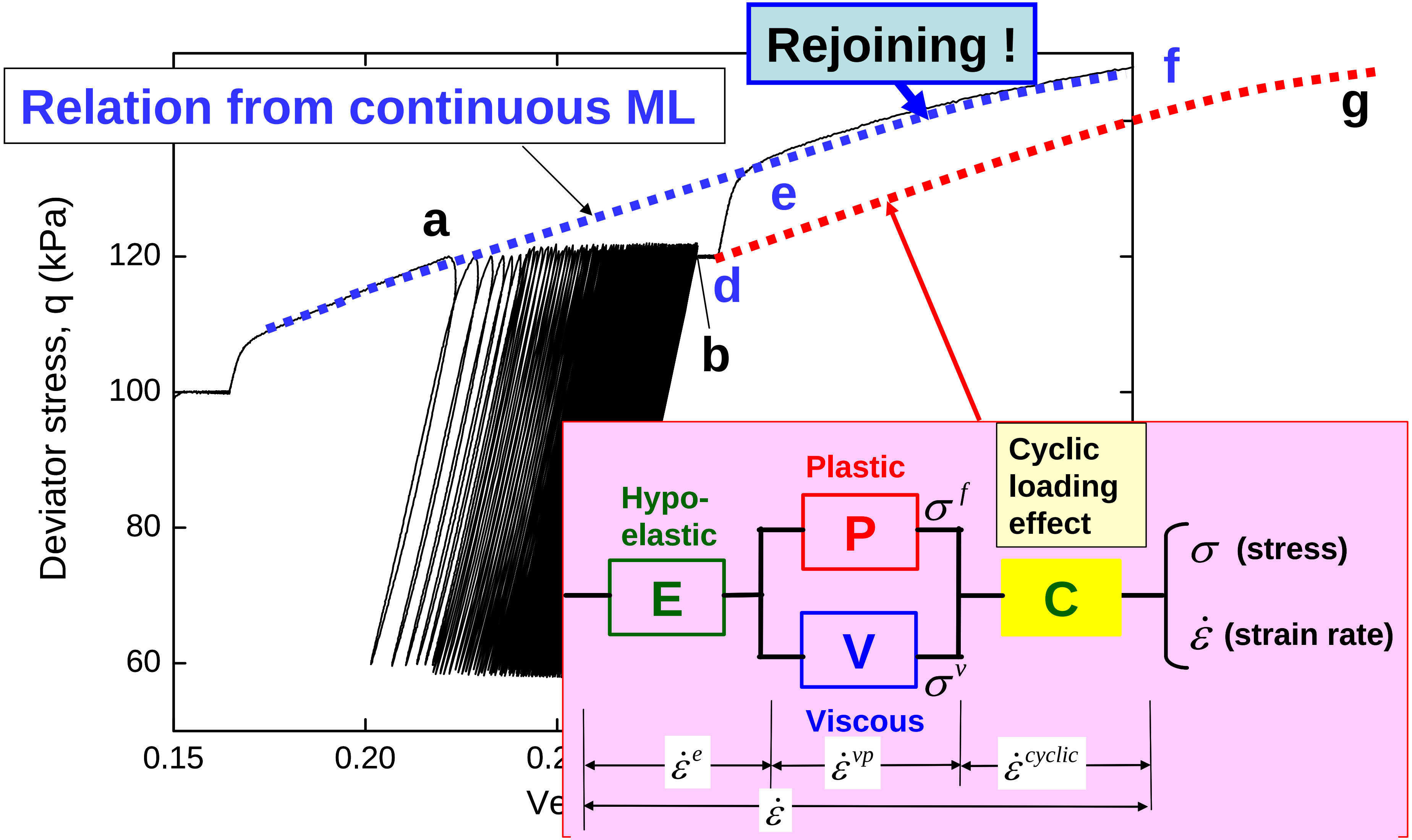




Hayashi et al. (2005)



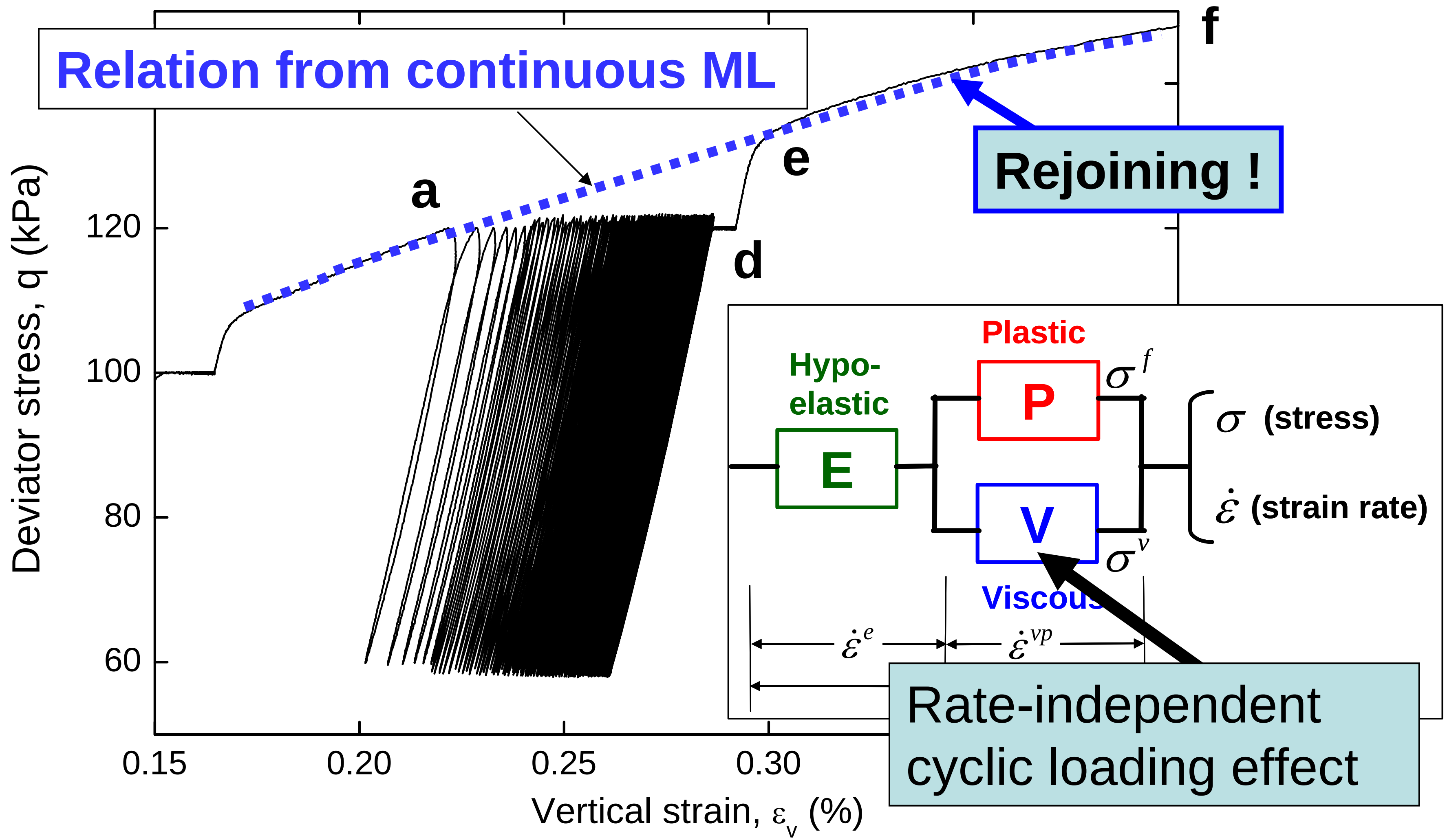
$\dot{\varepsilon}^{cyclic}$ and "$\dot{\varepsilon}^{vp}$ during sustained loading" are not independent.



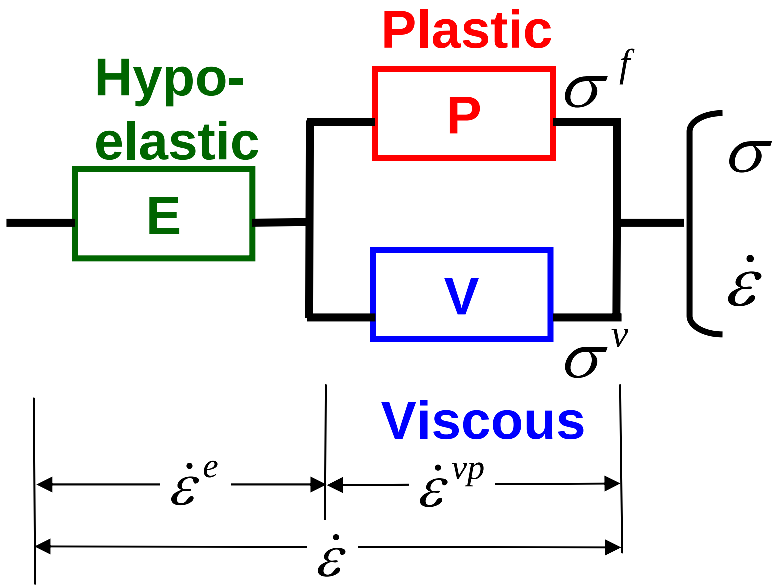
This model wrongly predicts d→g.

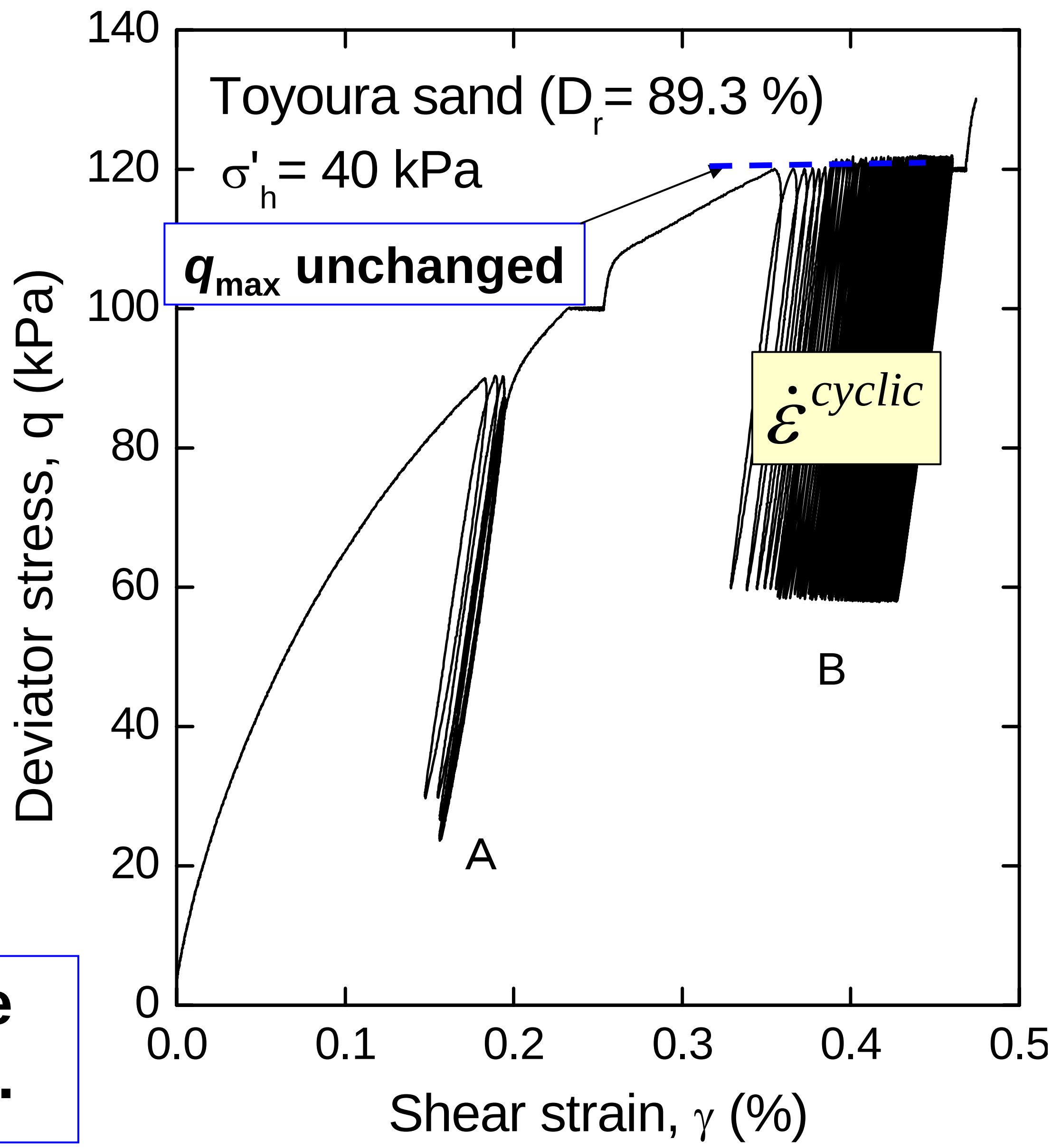
'Rejoining' means:

" $\dot{\varepsilon}^{cyclic}$ (a→b)" and " $\dot{\varepsilon}^{vp}$ during ML loading (a→e)" are not independent.



‘Rejoining’ means that major cyclic loading effects should be on V component.

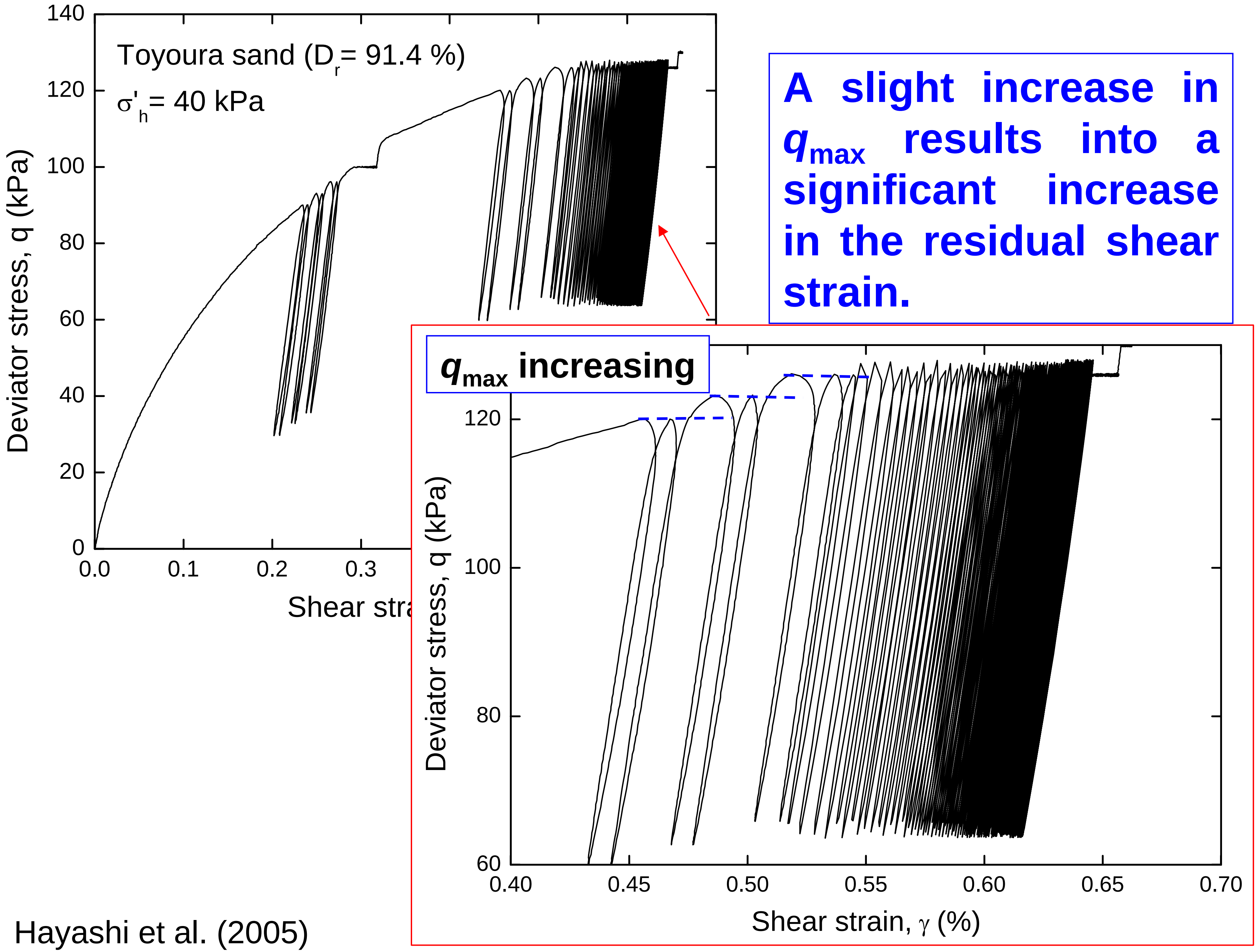




$\dot{\varepsilon}^{cyclic}$: included in $\dot{\varepsilon}^{vp}$, controlled by yielding of σ^f

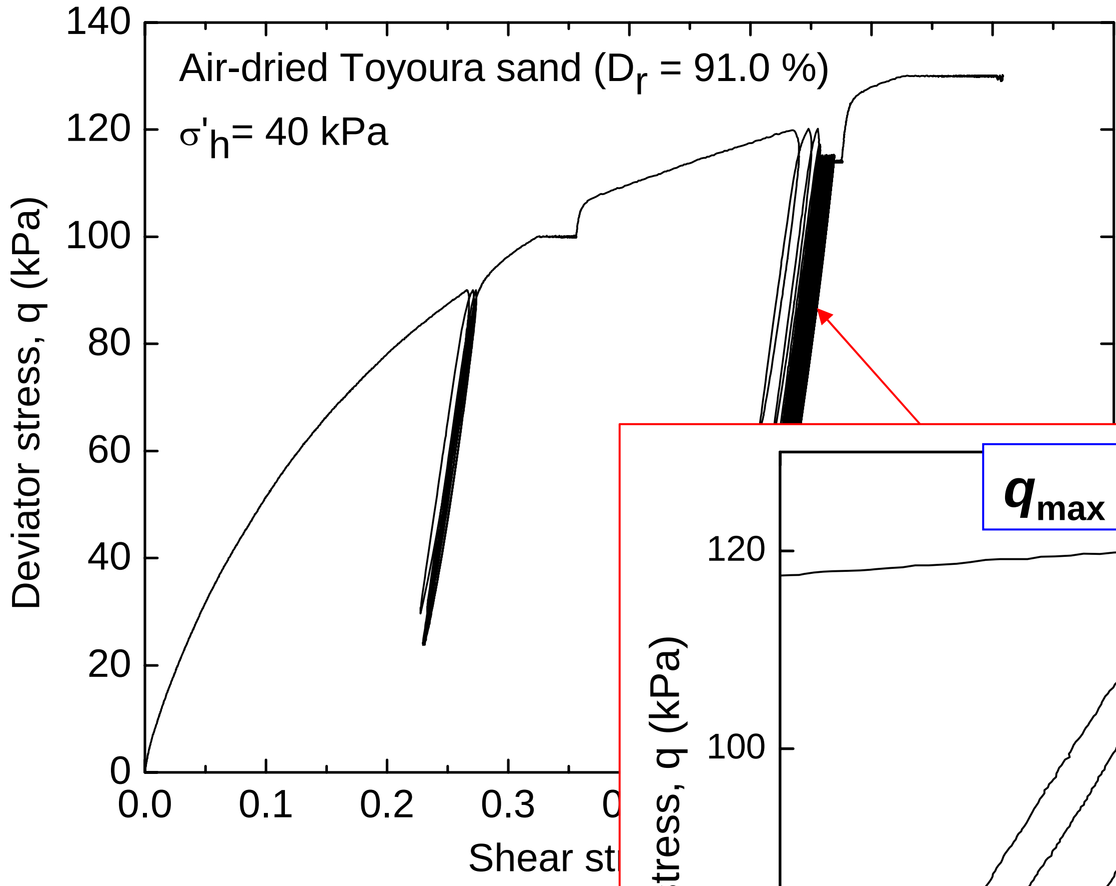
Change in q_{max} affects the yielding of σ^f, then $\dot{\varepsilon}^{cyclic}$.

Hayashi et al. (2005)

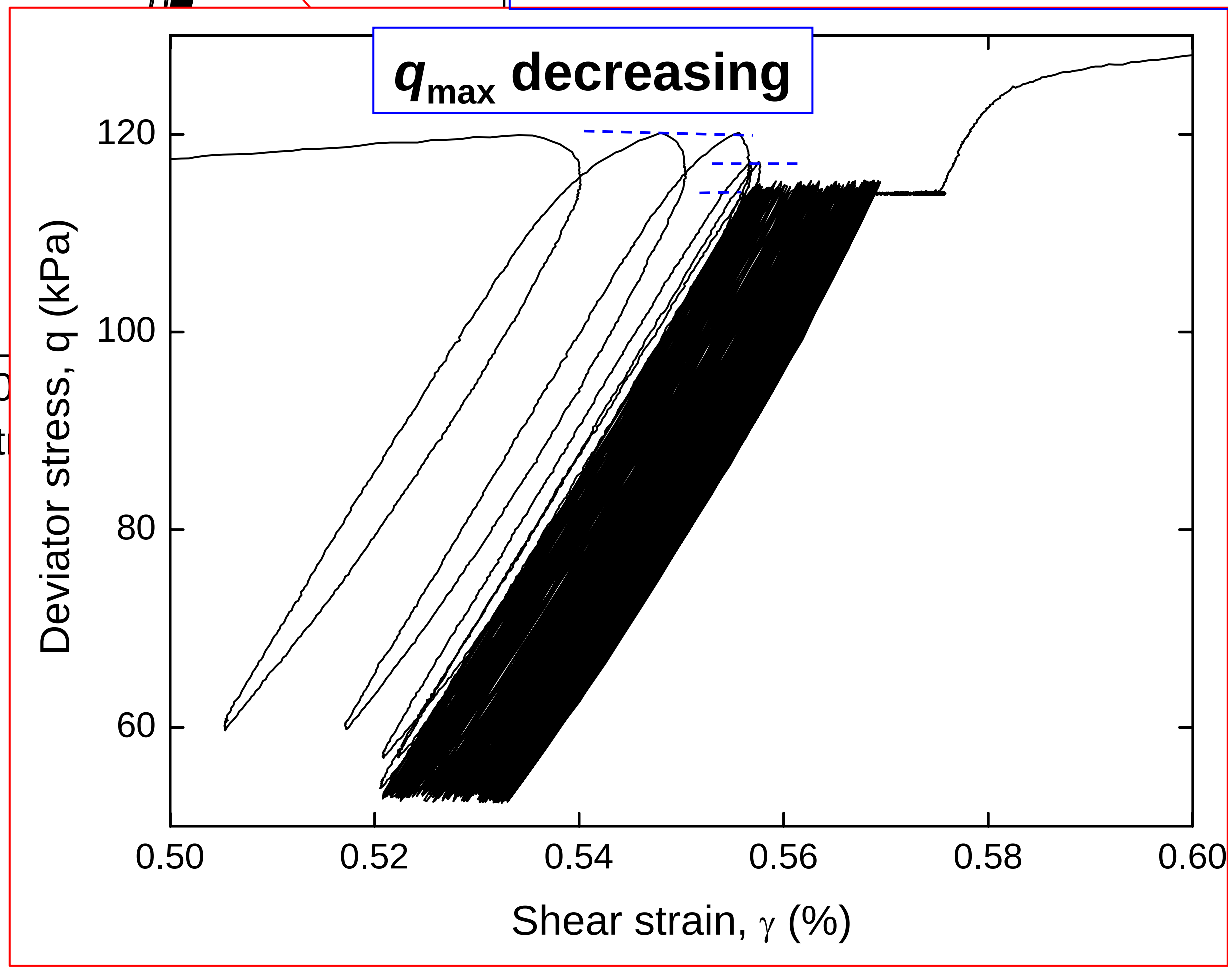


A slight increase in q_{max} results into a significant increase in the residual shear strain.

Hayashi et al. (2005)



A slight decrease in q_{max} results into a significant decrease in the residual shear strain.



Hayashi et al. (2005)

Introduction: in-elastic strain by plasticity, viscosity and cyclic loading, all affected by ageing effect

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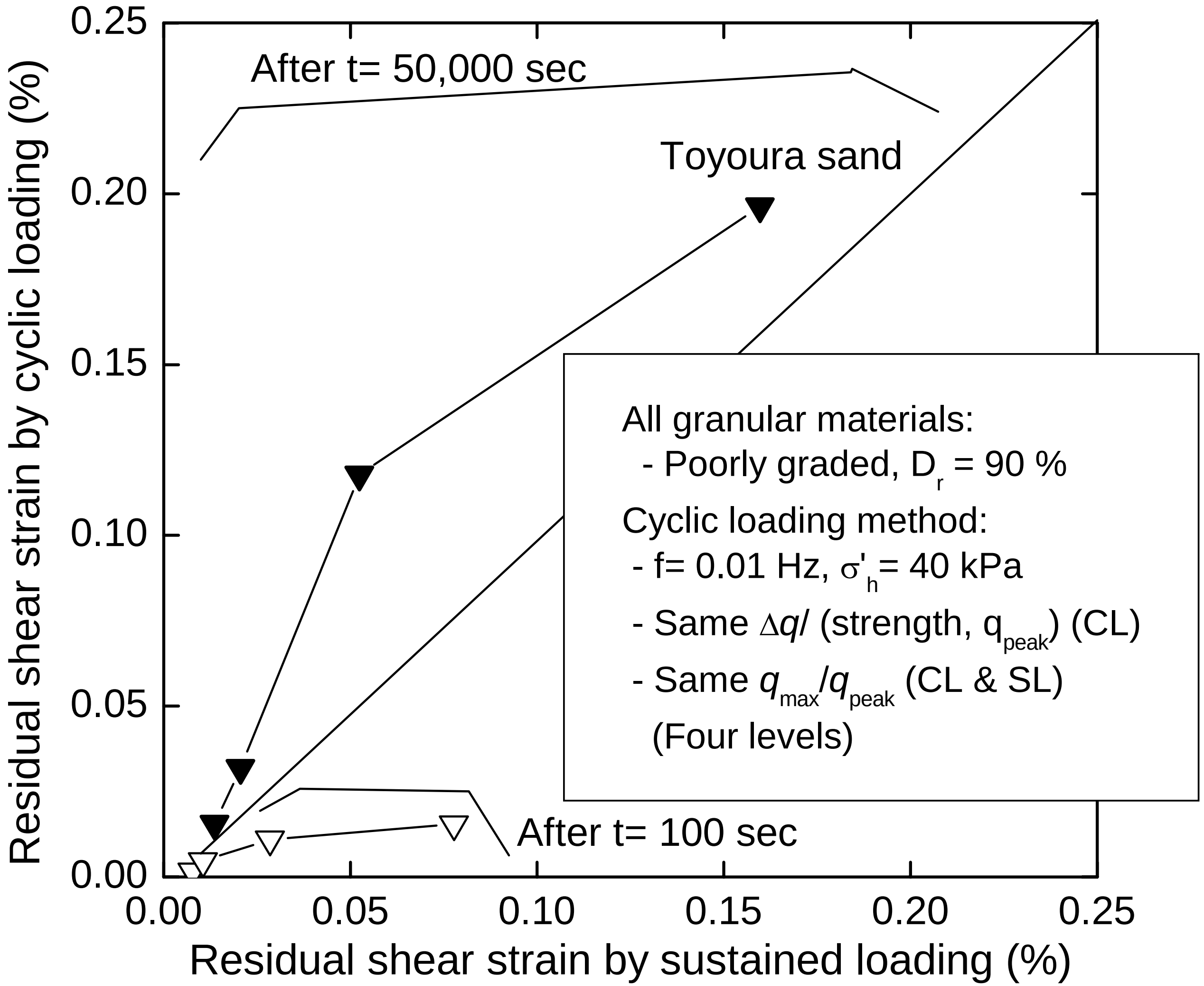
Viscosity: three types (*Isotach*, *TESRA* and *P&N*); and viscosity of other materials

Cyclic loading effect: interactions and particle shape effect

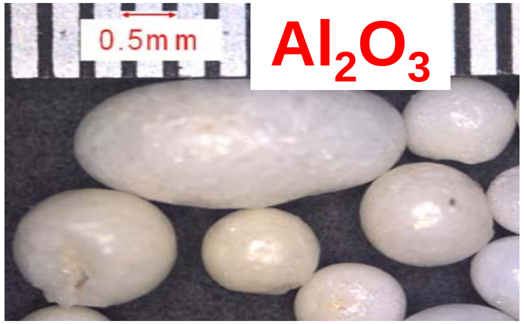
Ageing effect

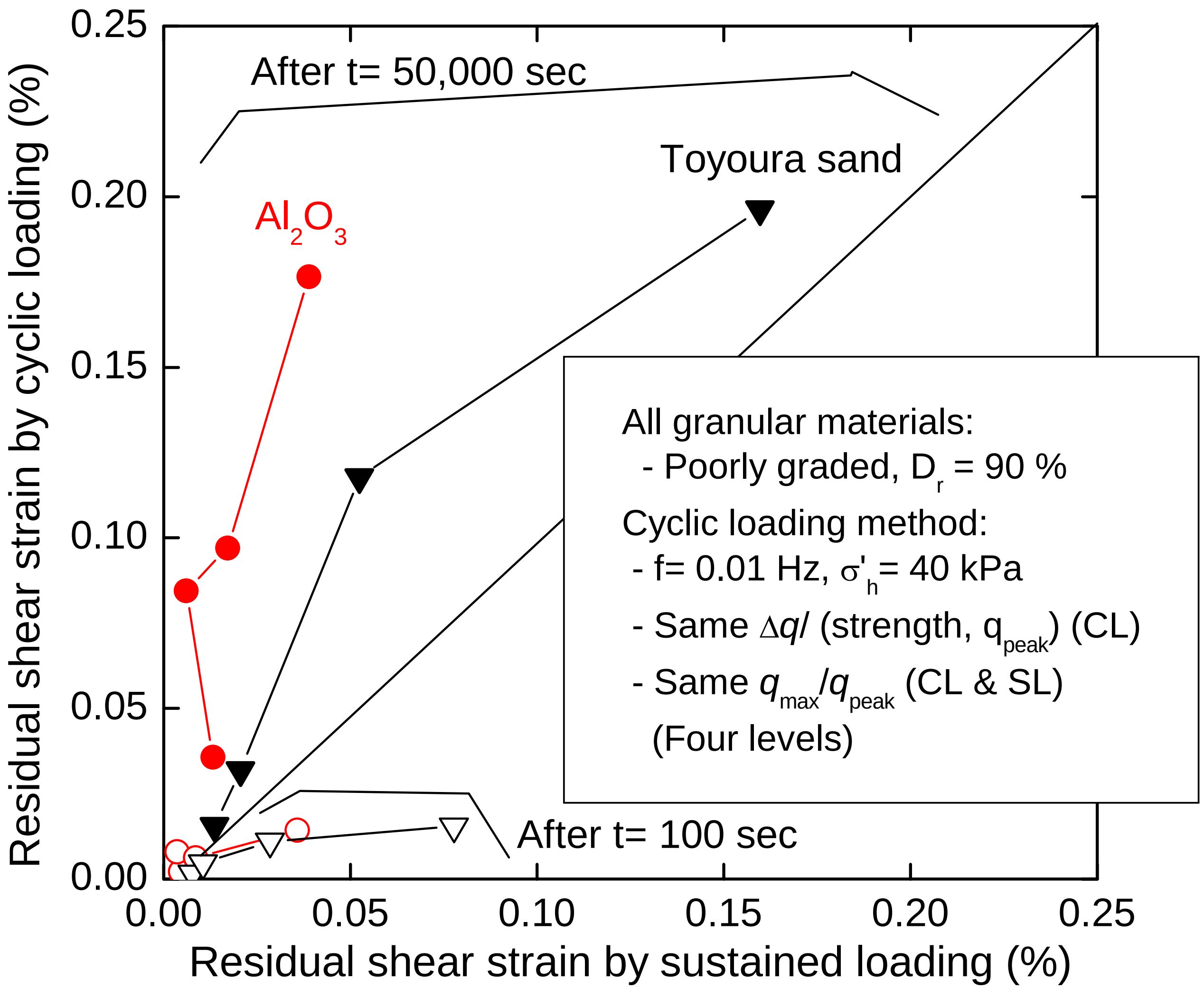
1D consolidation of clay

Summary

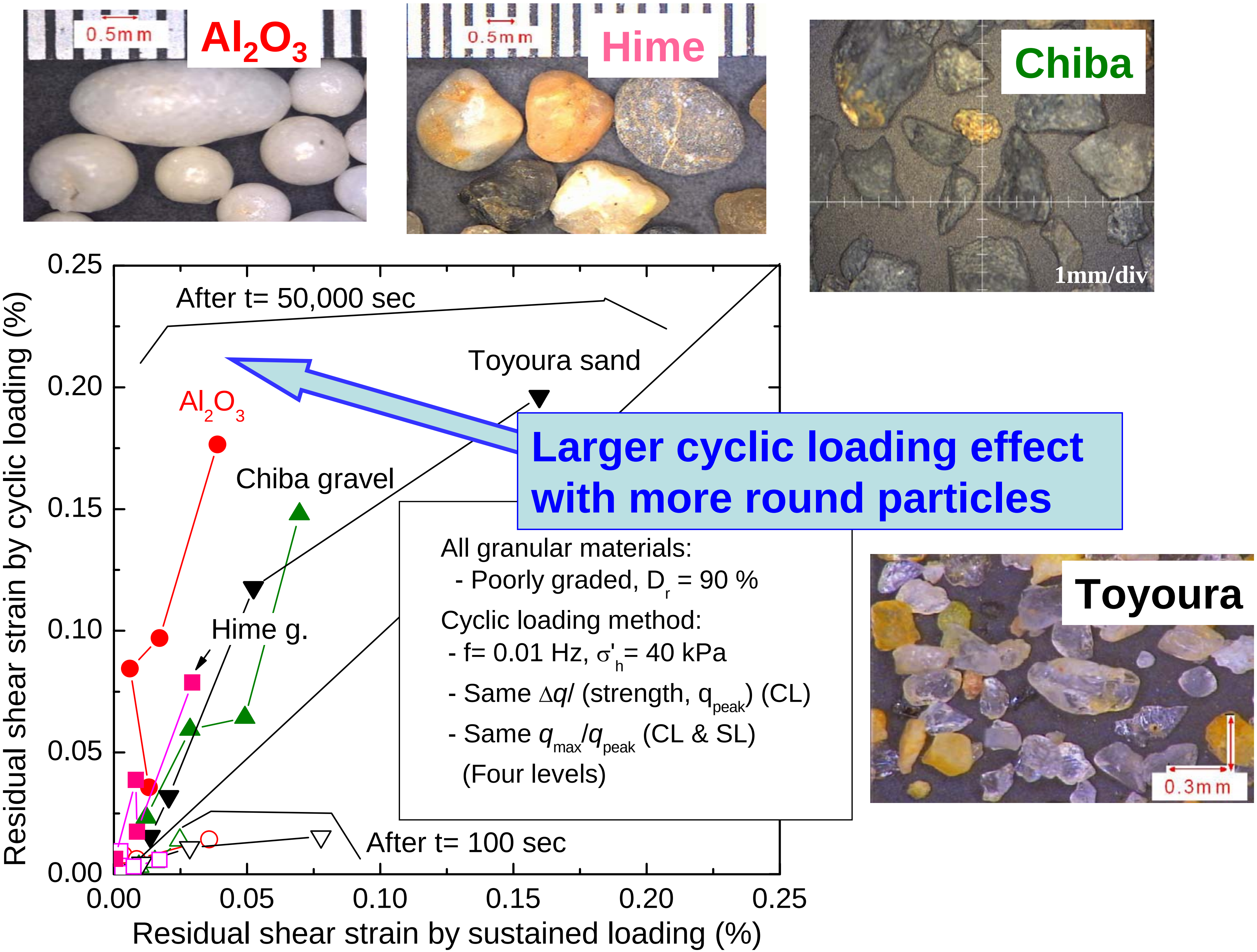


Hayashi et al. (2006)


0.5mm
Al2O3

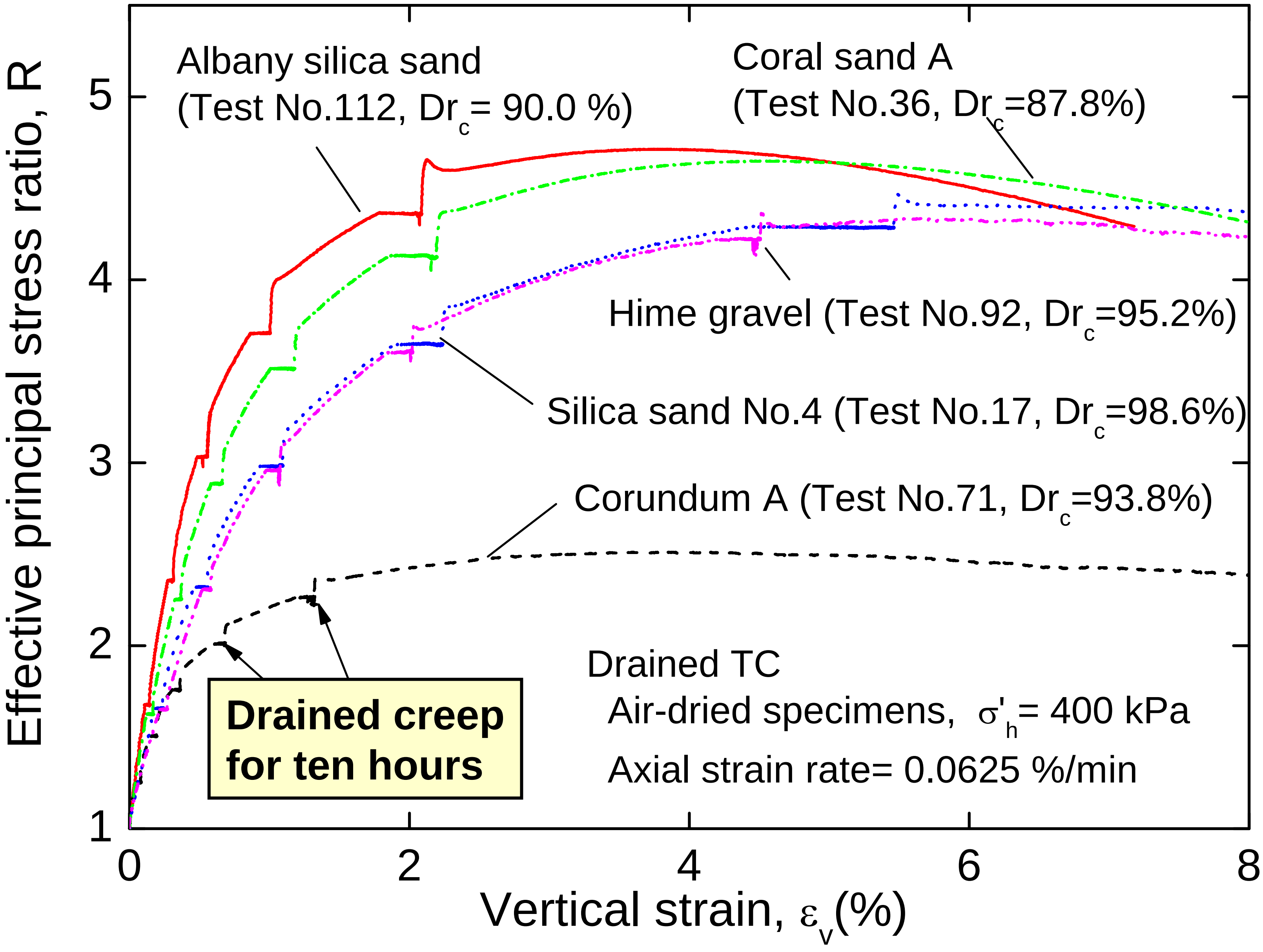

After t= 50,000 sec
Toyoura sand
Al2O3
All granular materials:
- Poorly graded, Dr = 90 %
Cyclic loading method:
- f= 0.01 Hz, σ'h= 40 kPa
- Same Δq/ (strength, qpeak) (CL)
- Same qmax/qpeak (CL & SL)
(Four levels)
After t= 100 sec
0.00
0.05
0.10
0.15
0.20
0.25
Residual shear strain by cyclic loading (%)
Residual shear strain by sustained loading (%)


Toyoura
0.3mm

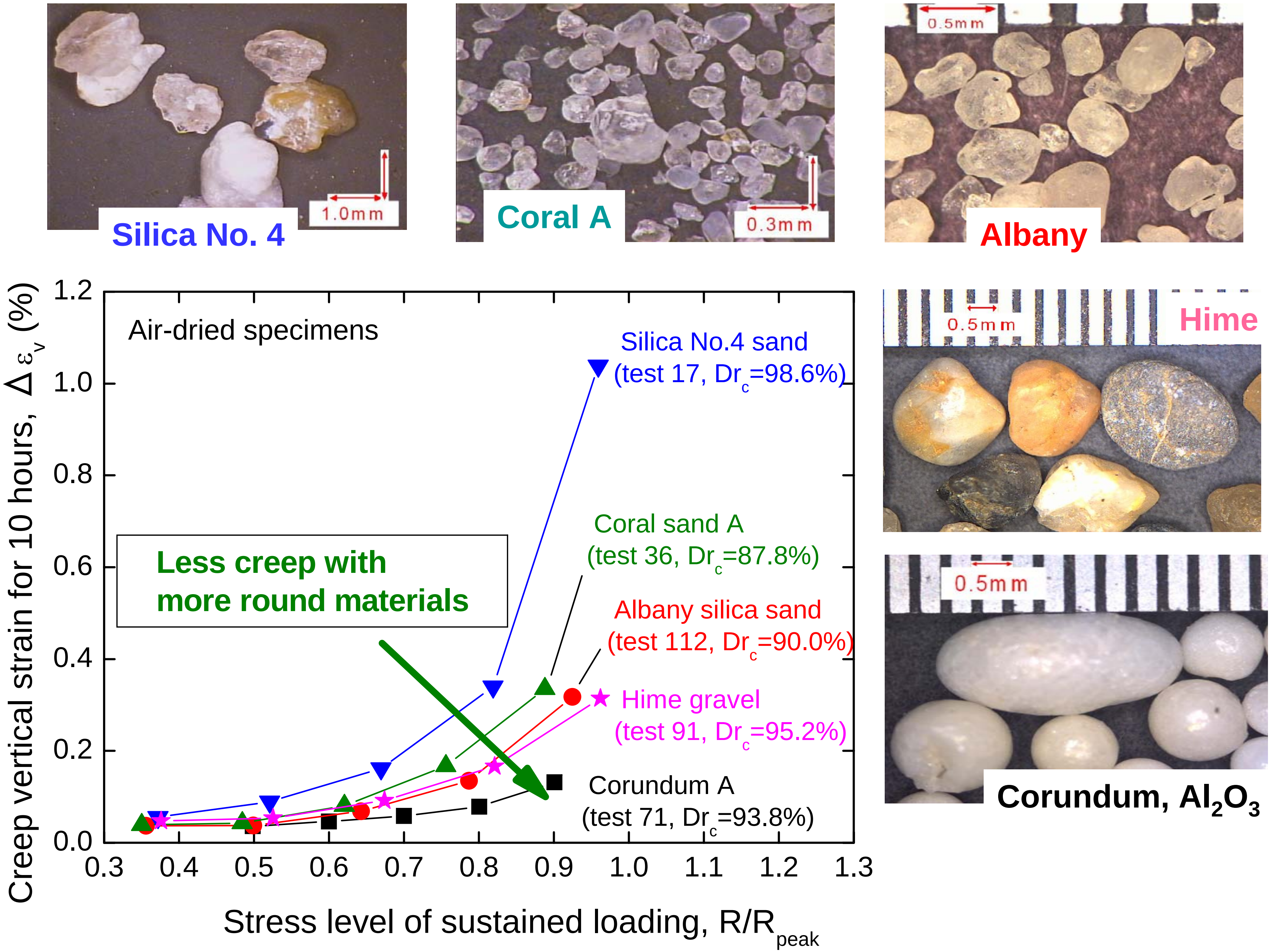


0.5mm
Al2O3
0.5mm
Hime
Chiba
1mm/div
Toyoura
0.3mm
Larger cyclic loading effect with more round particles
After t= 50,000 sec
Toyoura sand
Al2O3
Chiba gravel
Hime g.
After t= 100 sec
All granular materials:
- Poorly graded, Dr = 90 %
Cyclic loading method:
- f= 0.01 Hz, σ'h= 40 kPa
- Same Δq/ (strength, qpeak) (CL)
- Same qmax/qpeak (CL & SL)
(Four levels)
0.00
0.05
0.10
0.15
0.20
0.25
Residual shear strain by cyclic loading (%)
Residual shear strain by sustained loading (%)

All dense poorly graded granular materials



Enomoto et al. (2006a), *Roma*



Silica No. 4
1.0mm
Coral A
0.3mm
0.5mm
Albany
0.5mm
Hime
0.5mm
Corundum, Al2O3
Air-dried specimens
Silica No.4 sand
(test 17, Drc=98.6%)
Coral sand A
(test 36, Drc=87.8%)
Albany silica sand
(test 112, Drc=90.0%)
Hime gravel
(test 91, Drc=95.2%)
Corundum A
(test 71, Drc=93.8%)
Less creep with
more round materials
Creep vertical strain for 10 hours, Δεv (%)
Stress level of sustained loading, R/Rpeak
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3

Viscosity type (θ) / Influencing factors	Isotach (θ =1) → TESRA (θ =0) → Positive & negative (θ <0)
Particle shape (stiff particles)	**More angular → More round**
Grading characteristics	**Less uniformly graded → More poorly graded**
Particle size (if saturated)	**Smaller (*clay*) → Larger (*sand/gravel*)**
Particle crushability	**More crushable ?? → Less crushable ??**
Inter-particle bonding	**Stronger → Weaker → Null** ***ock/cement-mixed soil*) (*unbound granular materials*)**
Strain level	**Smaller strain → Larger strain (in particular, post-peak)**
Inter-particle contact point	**More stable (more cohesive & larger co-ordination numbers) → Less stable (less cohesive & smaller co-ordination number)**
- Deformation by cyclic loading	***Smaller → Larger***
- Creep deformation	***Larger → Smaller***

Some link !

Introduction: in-elastic strain by plasticity, viscosity and cyclic loading, all affected by ageing effect

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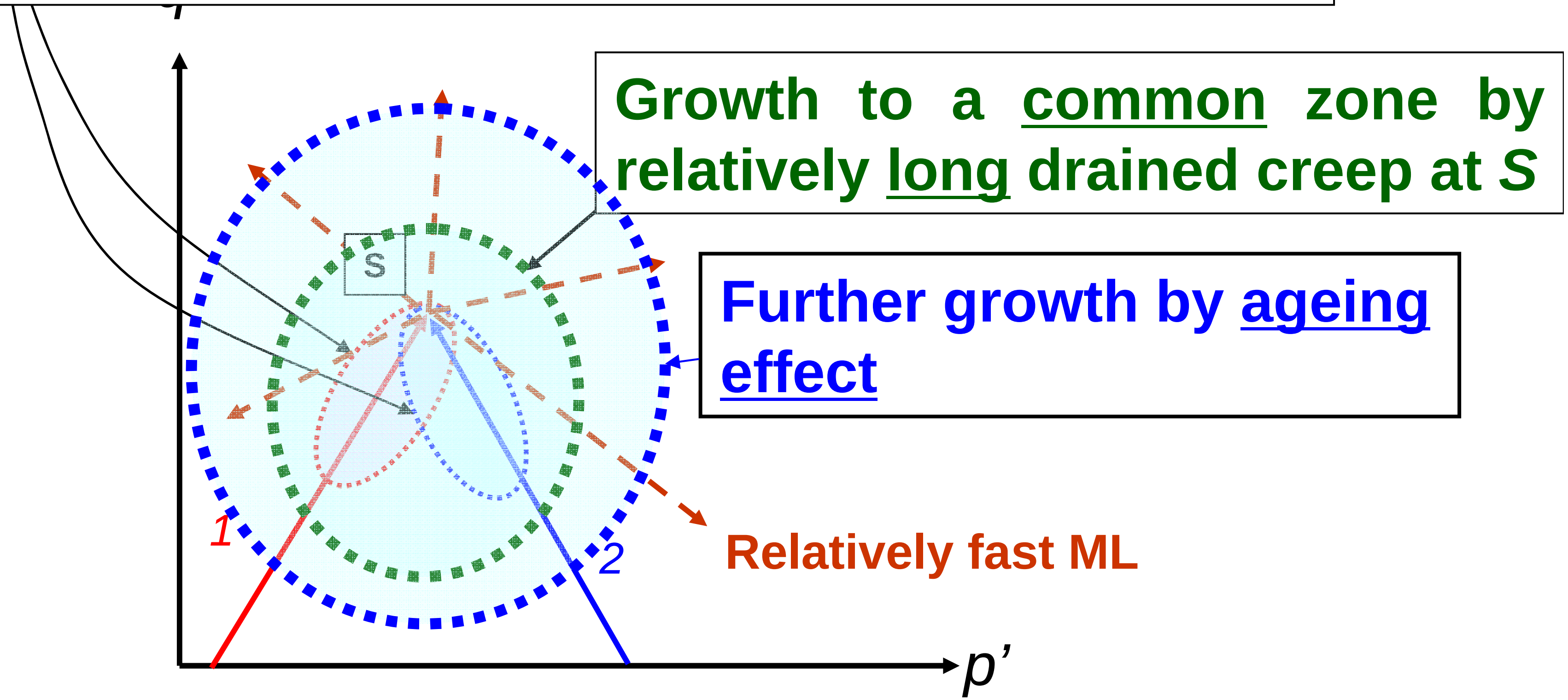
Summary

With ageing effect (changes in the stress-strain properties with time) ……

- **Relatively fast ML along stress paths *1* & *2***
- **Relatively short drained creep at stress point *S***
- **Relatively fast ML**

Then, different high stiffness zones



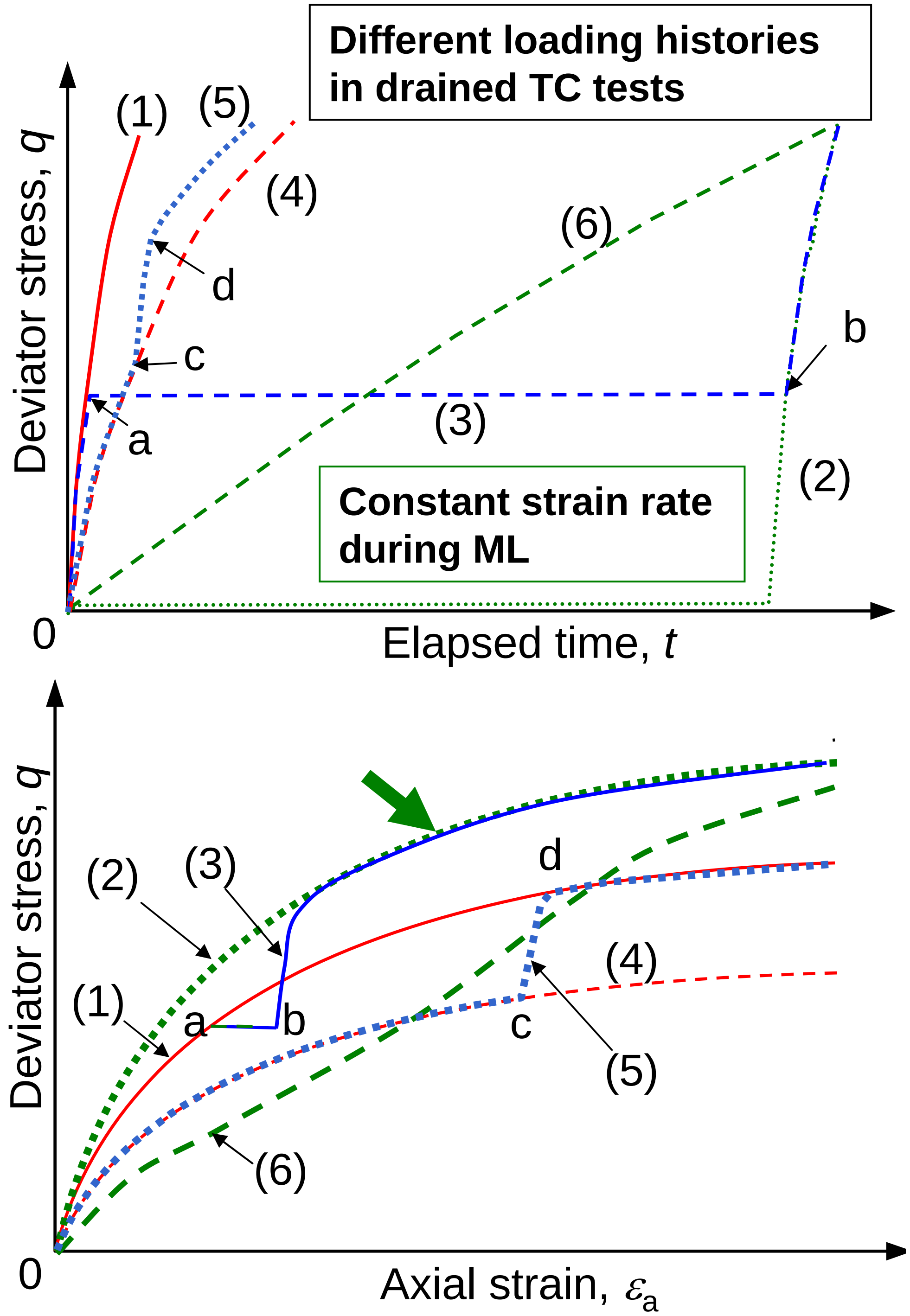
Tatsuoka et al. (1999a) *Hamburg*

Elasto-viscoplastic
with ageing effect:
- no interaction between viscosity and ageing effect

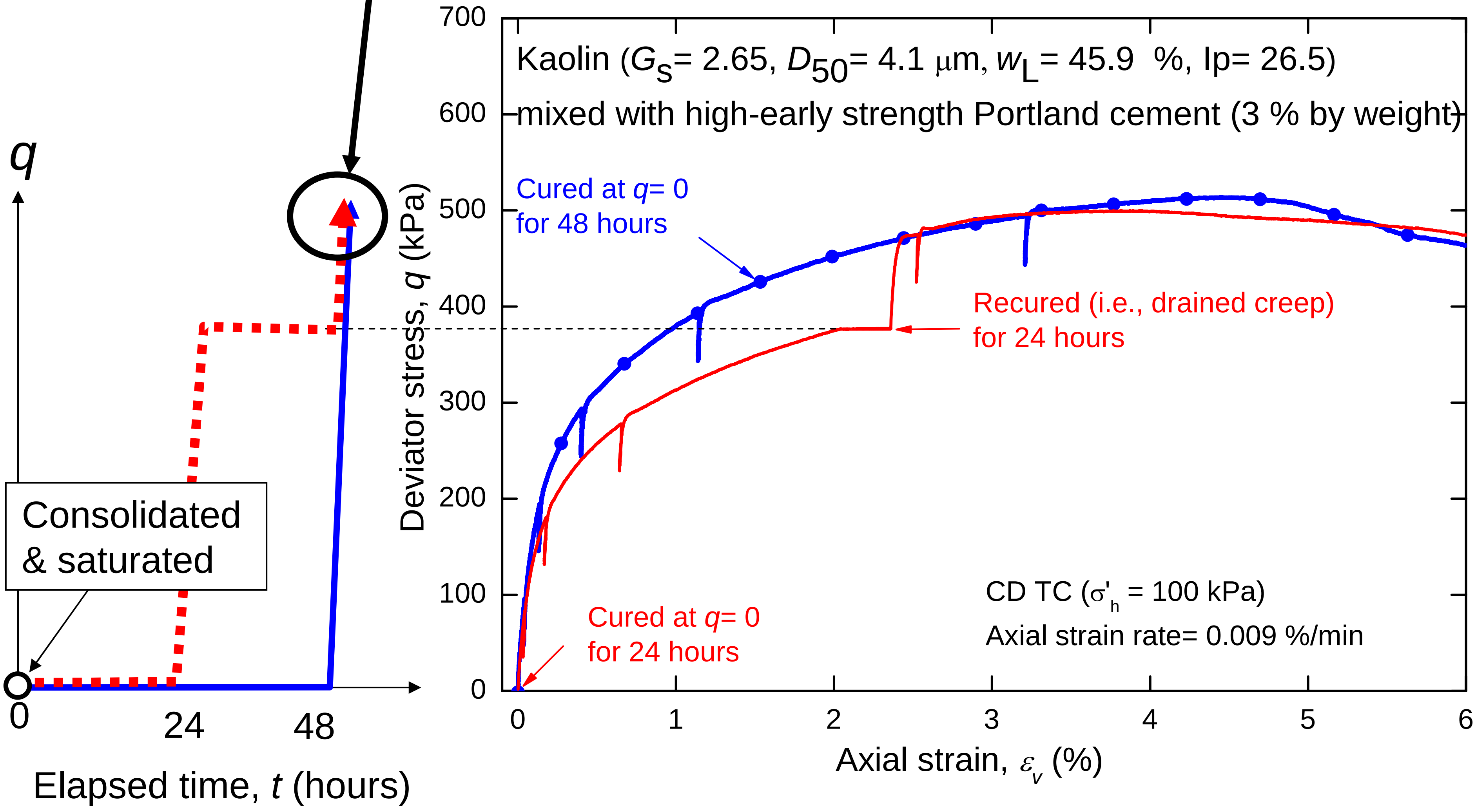
Different stress-strain curves between tests 1 & 2 due to ageing effect

A large high-stiffness zone from point b in test 3

The same behaviour for the same strain rate and the same ageing period in tests 2 & 3.

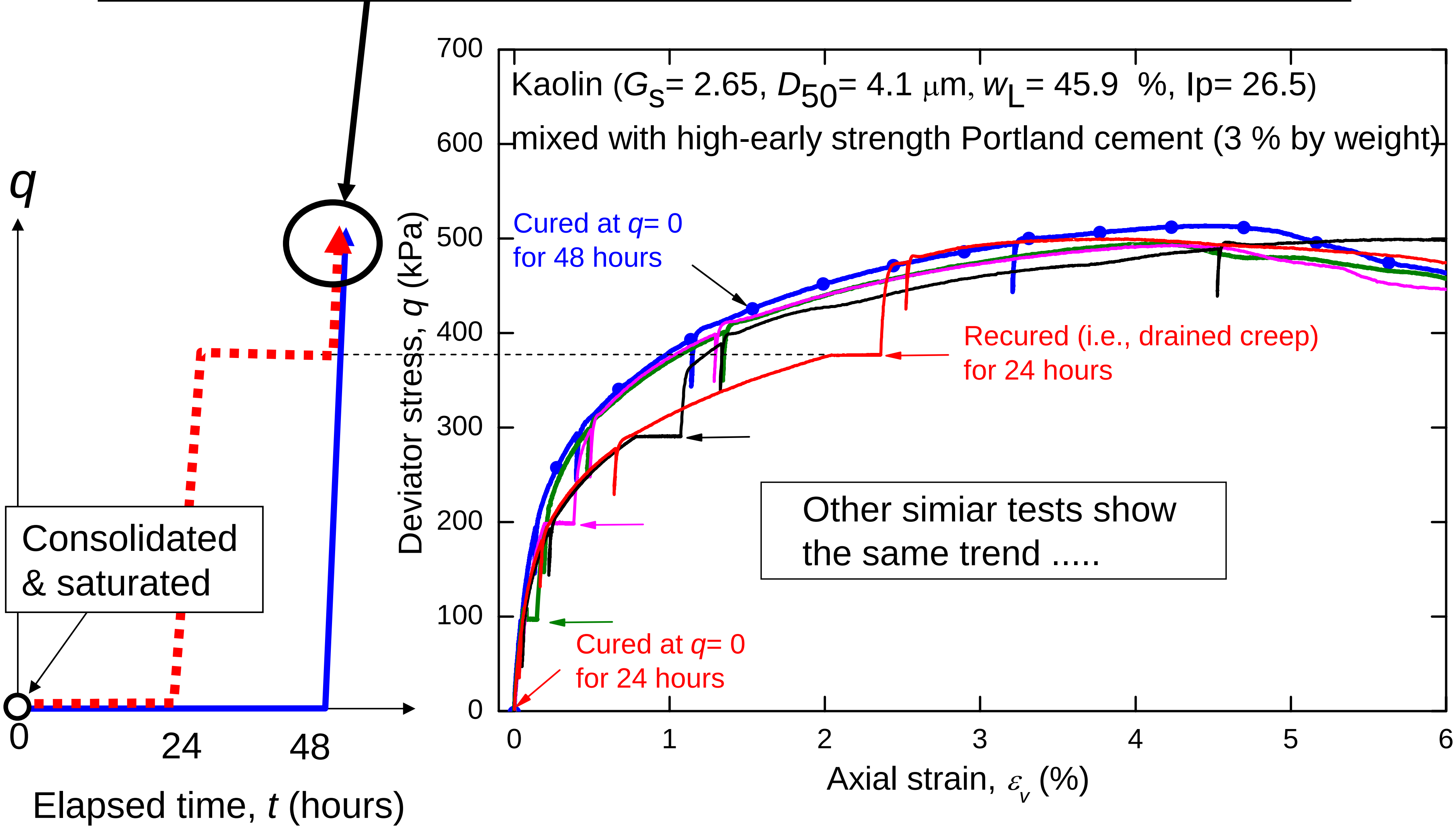


Nearly the same peak strength, showing negligible interaction between viscosity and ageing effect



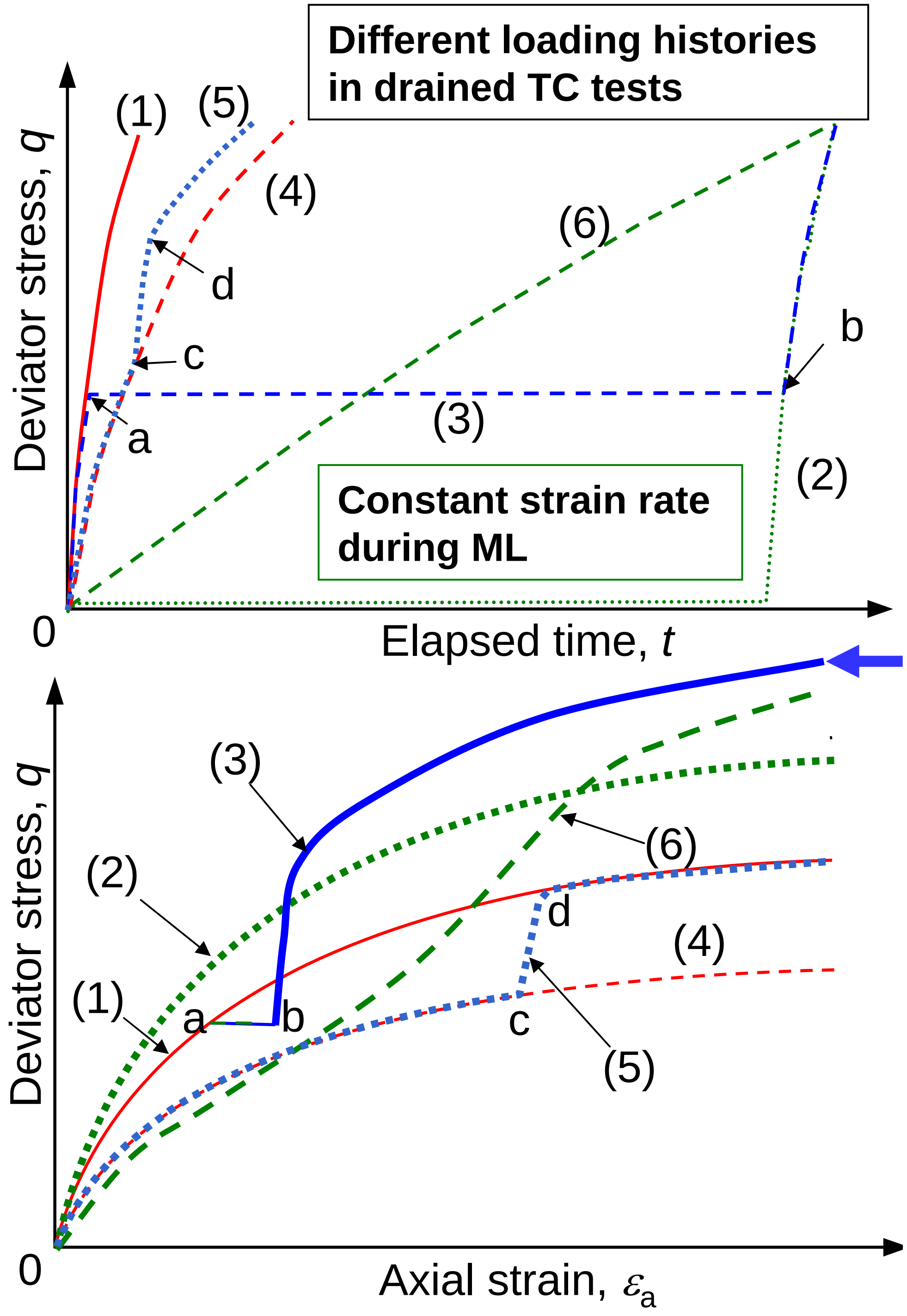
Komoto et al. (2004)

Nearly the same peak strength, showing negligible interaction between viscosity and ageing effect



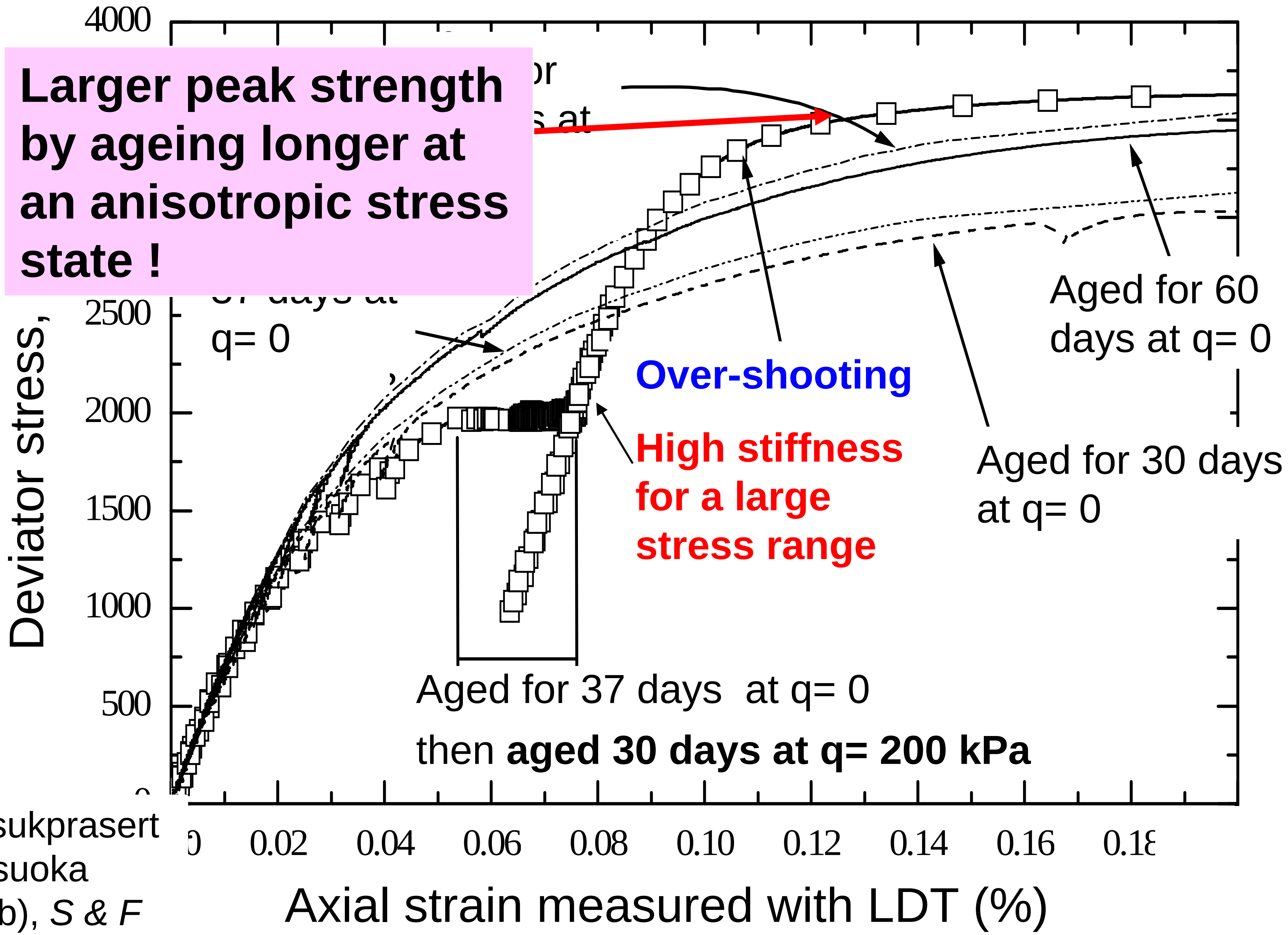
Komoto et al. (2004)

Elasto-viscoplastic with ageing effects:
- positive interaction between viscosity & ageing



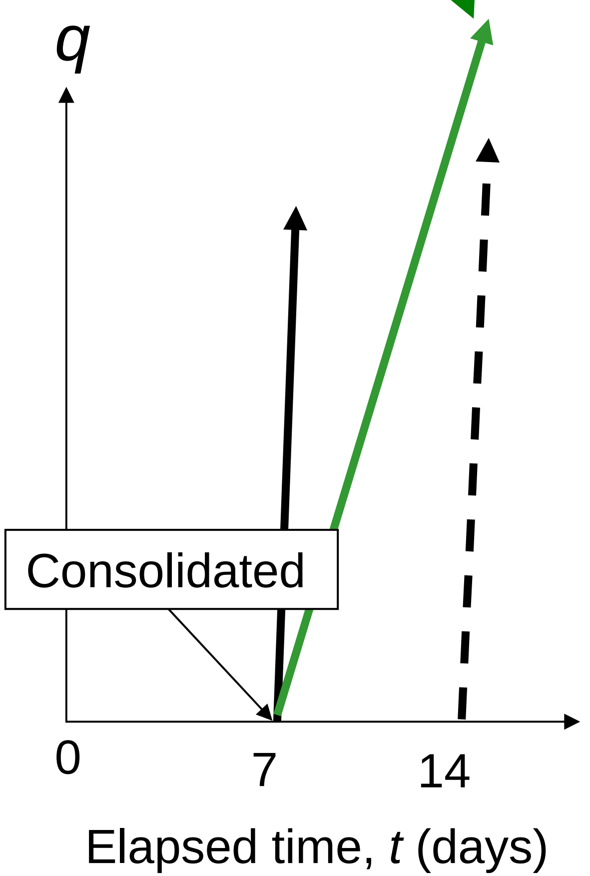
For the same strain rate and the same ageing period, <u>stronger in test 3 than in test 2</u> due to ageing longer at a higher deviator stress in test 3.

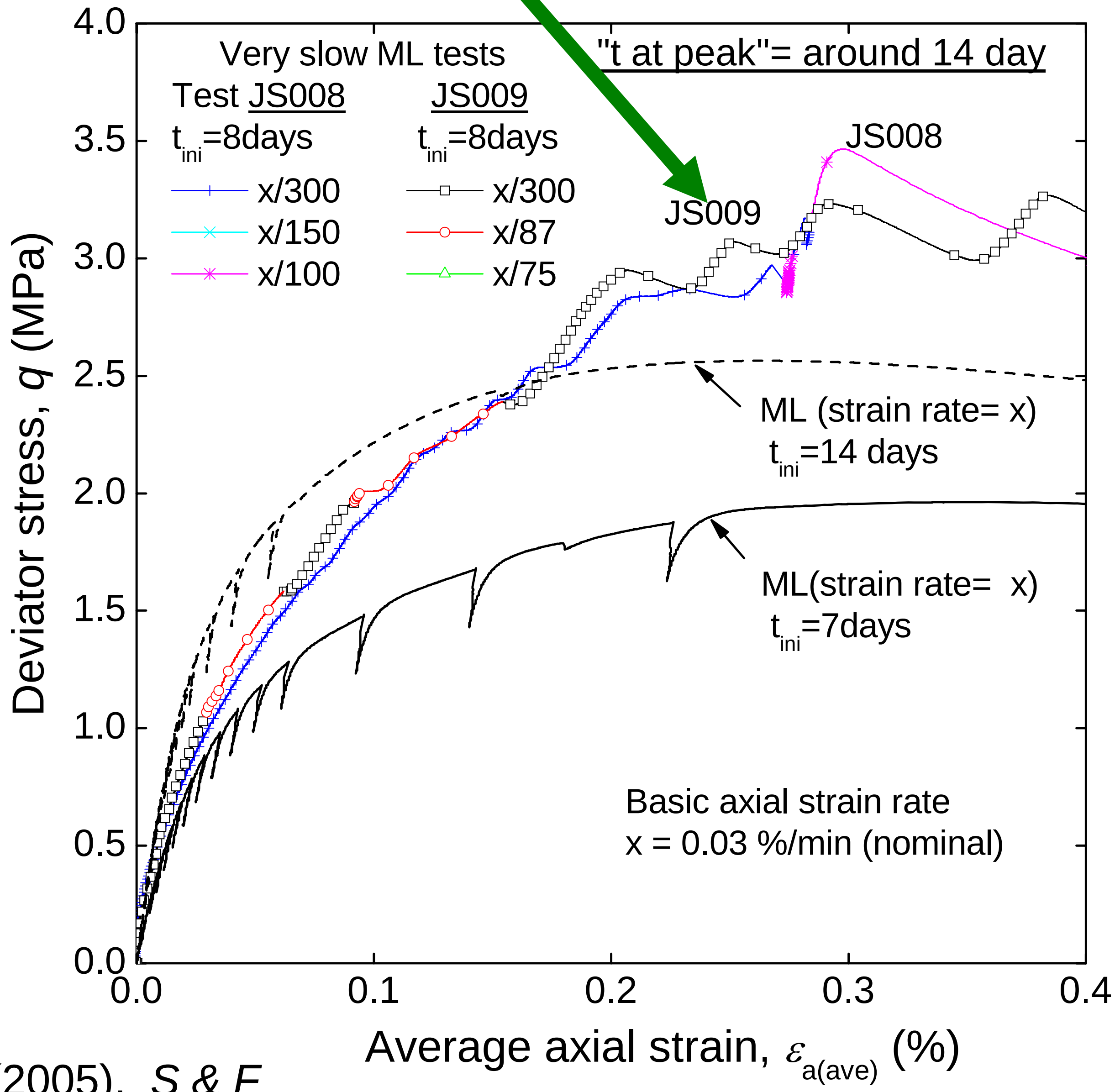
Compacted moist cement-mixed gravel in drained TC (σ'_h= 19.7 kPa and an axial strain rate of 0.03 %/min)



Kongsukprasert & Tatsuoka (2005b), *S & F*

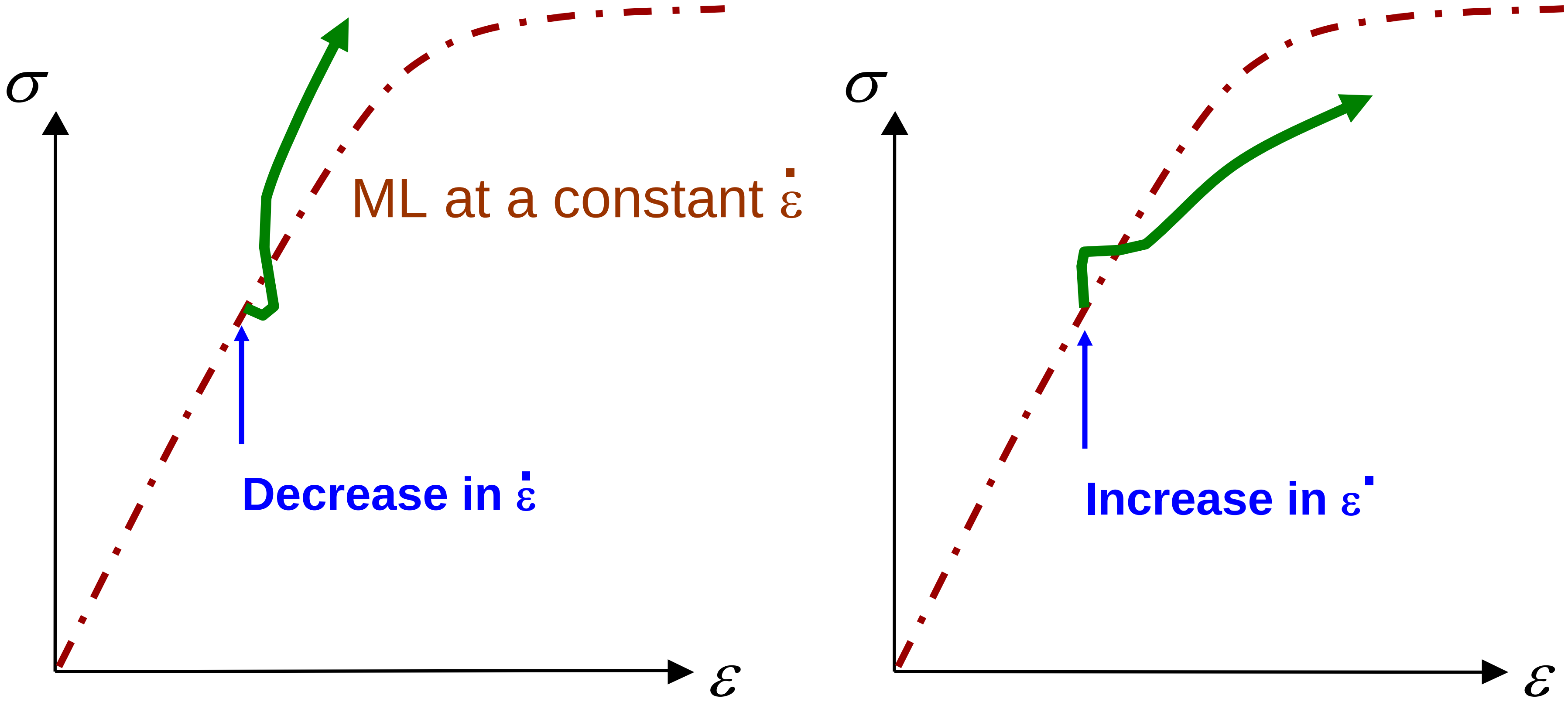
By continuing ageing effect during very slow loading, the tangent stiffness & peak strength increase.

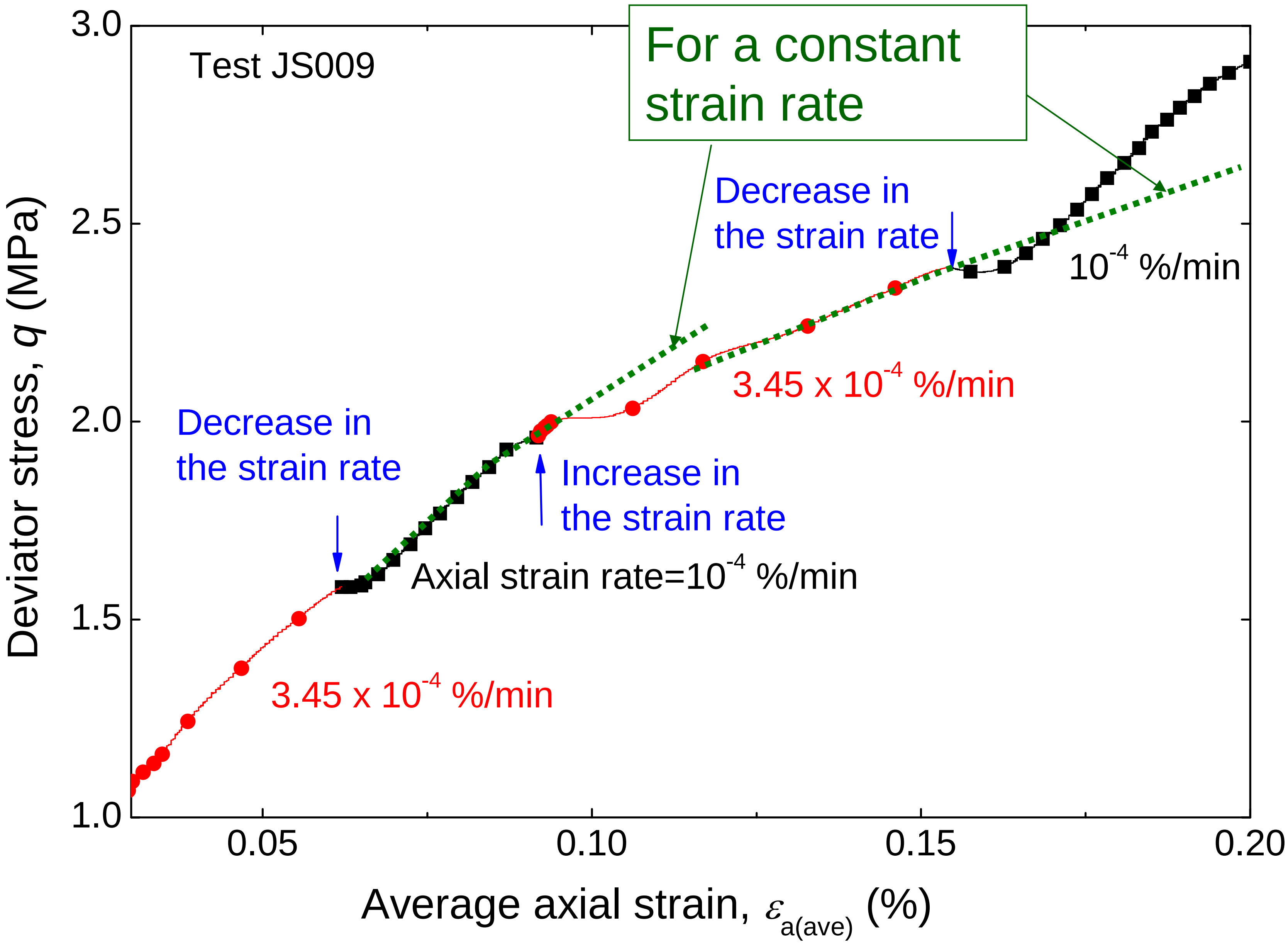




Kongsukprasert & Tatsuoka (2005), *S & F*

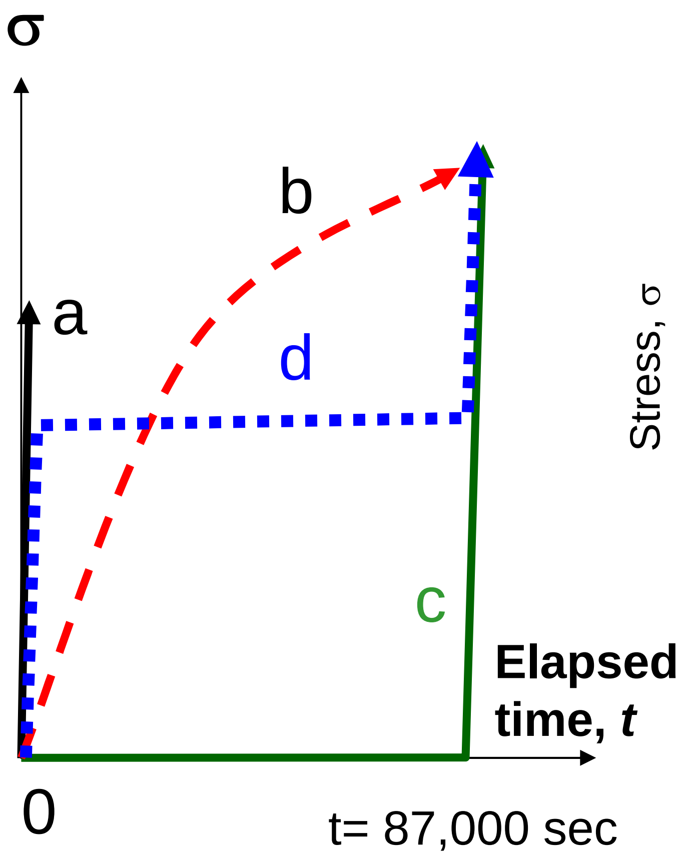
Peculiar behaviour due to continuing ageing effect

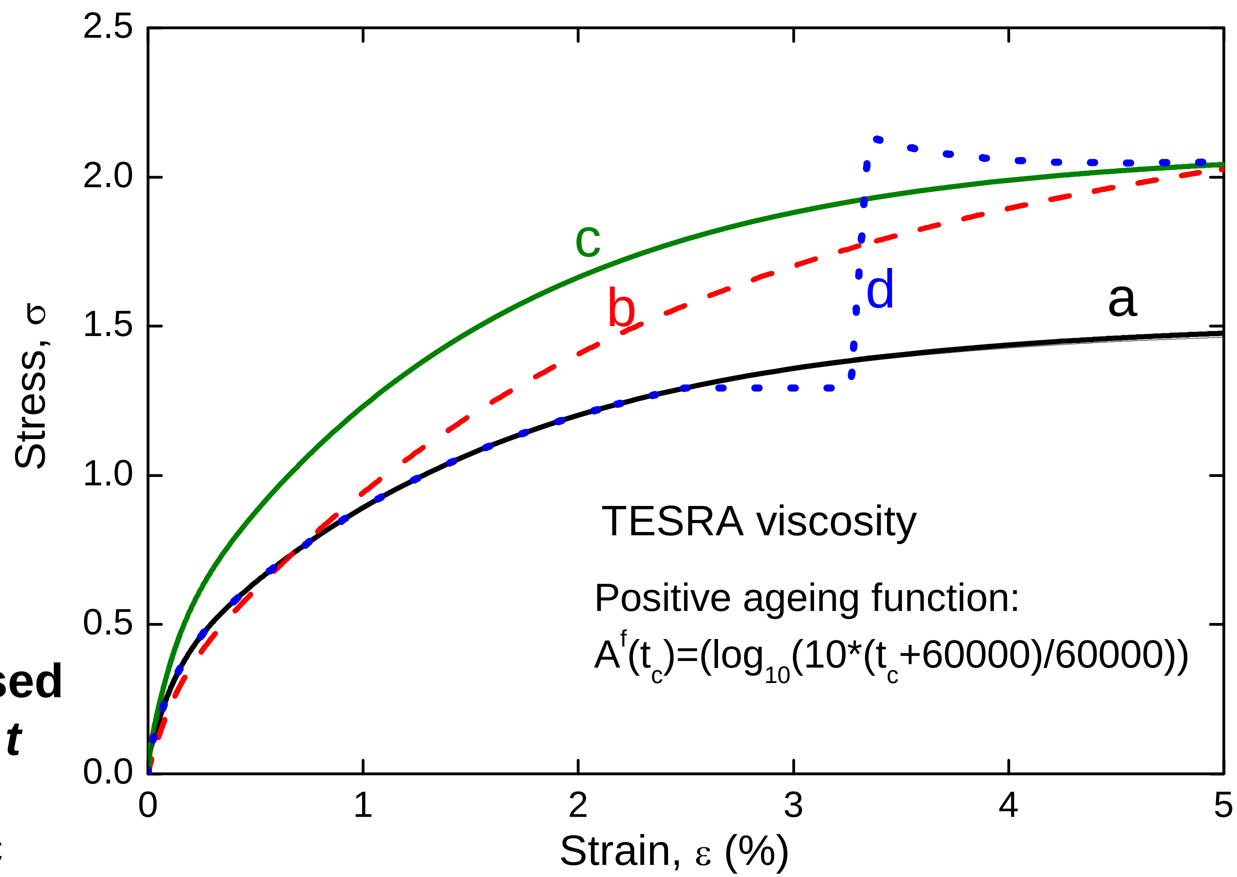




Kongsukprasert
& Tatsuoka (2005),
S & F

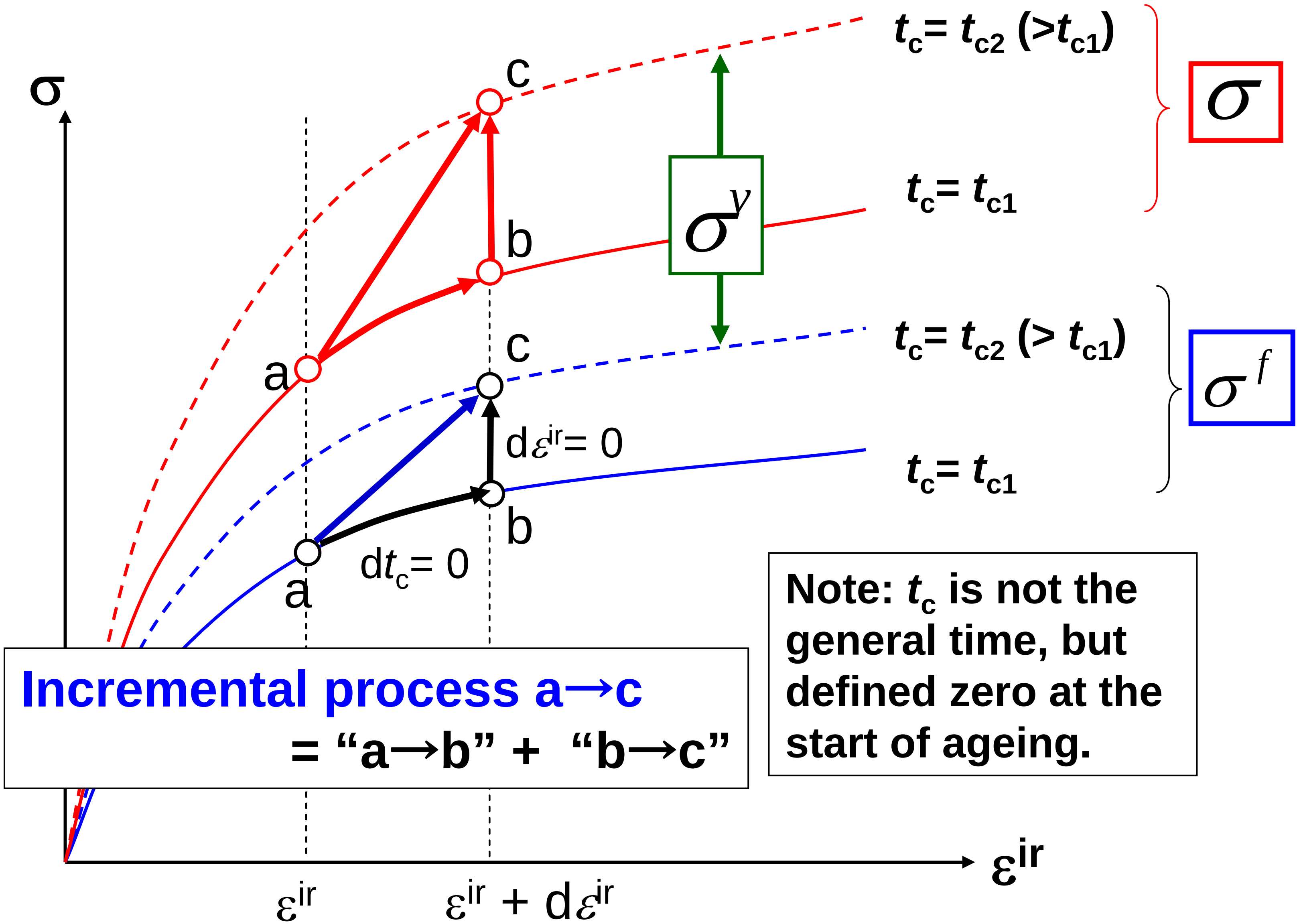
Simulation of positive ageing effects (no interaction with viscosity)





Tatsuoka et al. (2003), *Lyon*

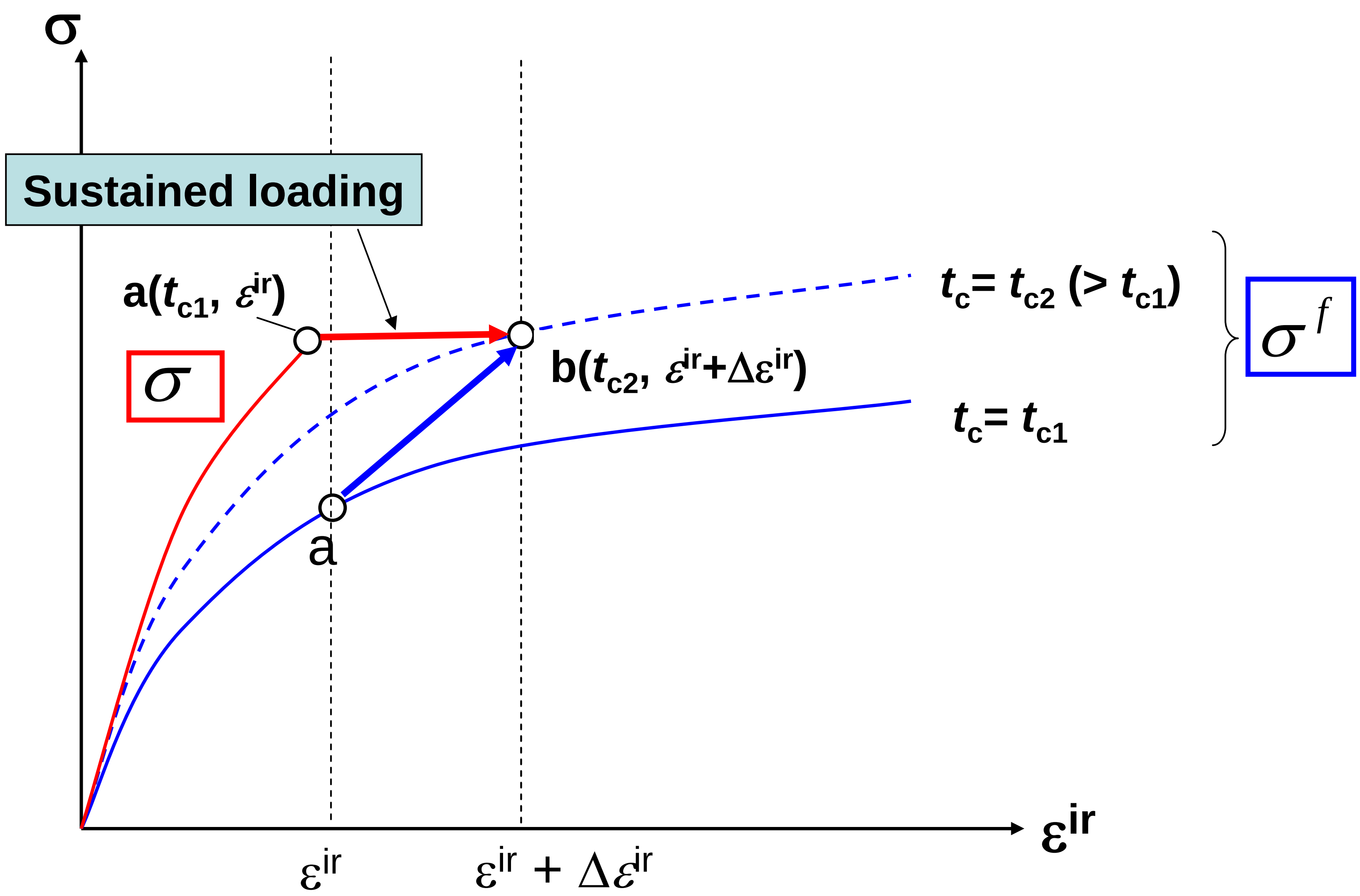
Essence of the simulation
(no interaction with viscosity)



Note: t_c is not the general time, but defined zero at the start of ageing.

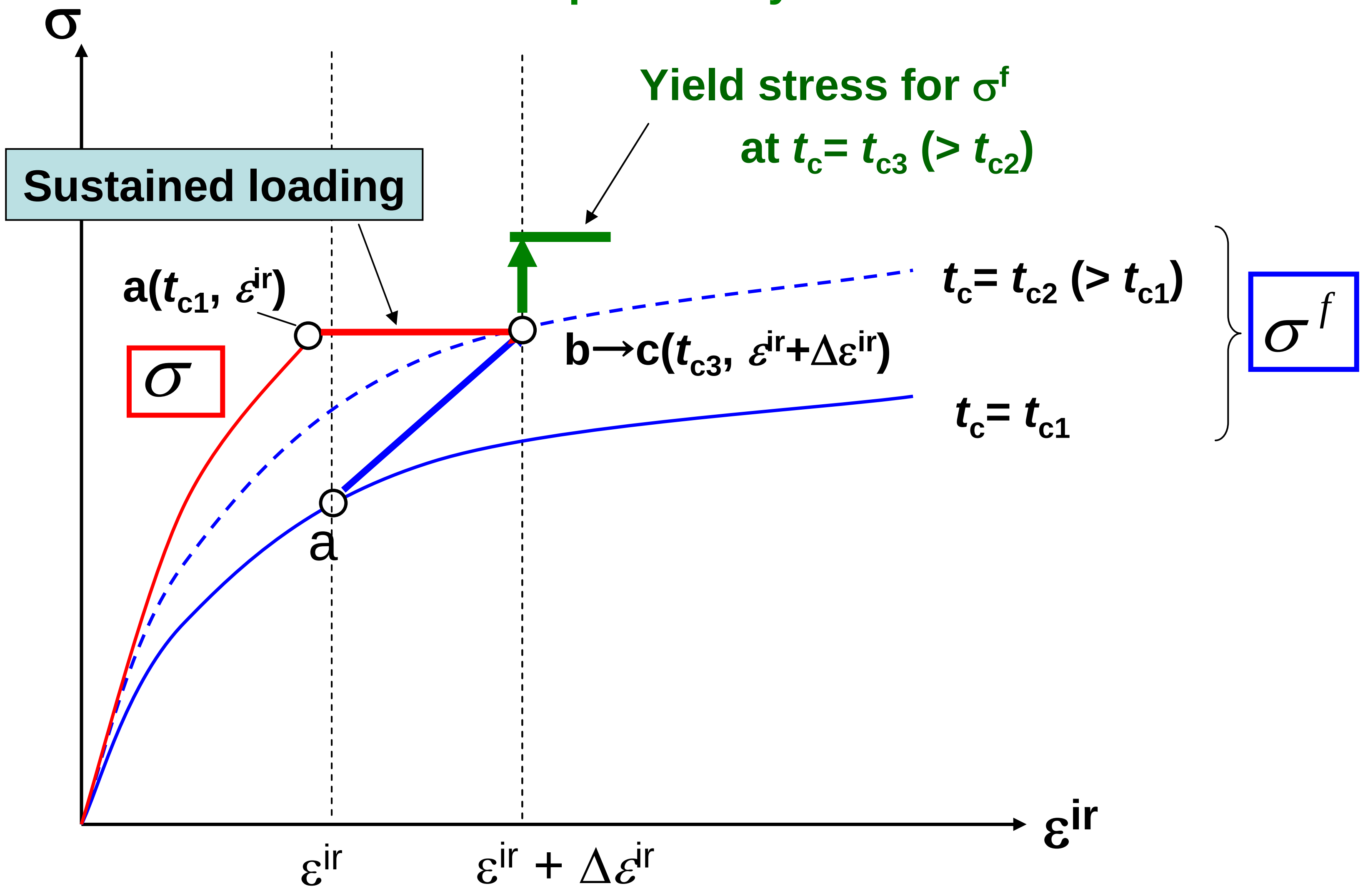
Tatsuoka et al. (2003), *Lyon*

a→b: development of creep strain
b: cease of creep strain development

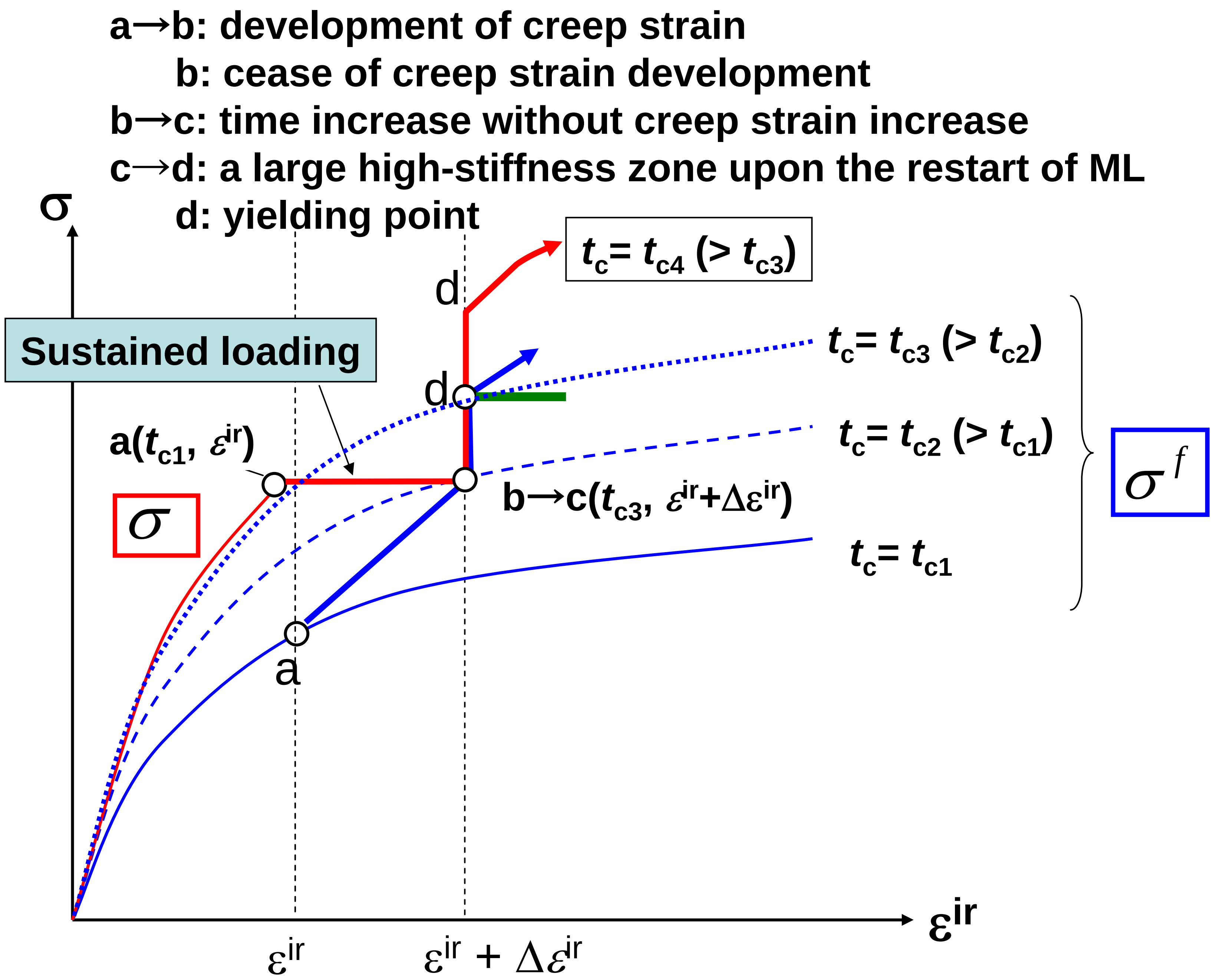


Tatsuoka et al. (2003), *Lyon*

a→b: development of creep strain
b: cease of creep strain development
b→c: time increase without creep strain increase
but with development of yield stress for σ^f

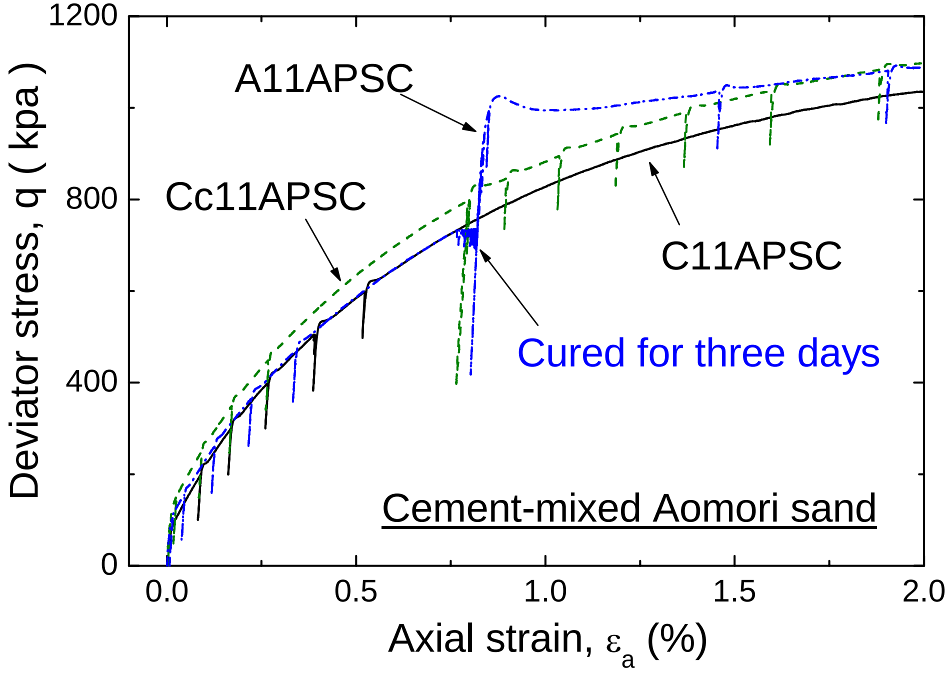


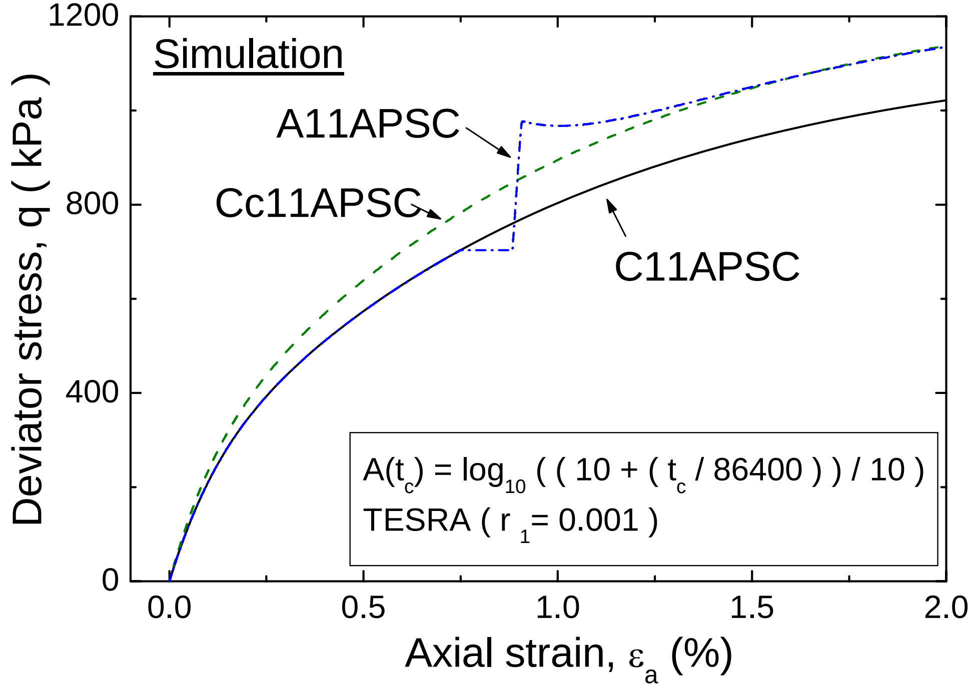
Tatsuoka et al. (2003), *Lyon*



Tatsuoka et al. (2003), *Lyon*

Simulation of drained TC tests





Two ML tests
with and w/o curing for 3 days
at *q*= 0.

The other test:
w/o curing at *q*= 0
cured for 3 days with *q*.

The model (TESRA viscosity) works !

Tatsuoka et al. (2003), *Lyon*

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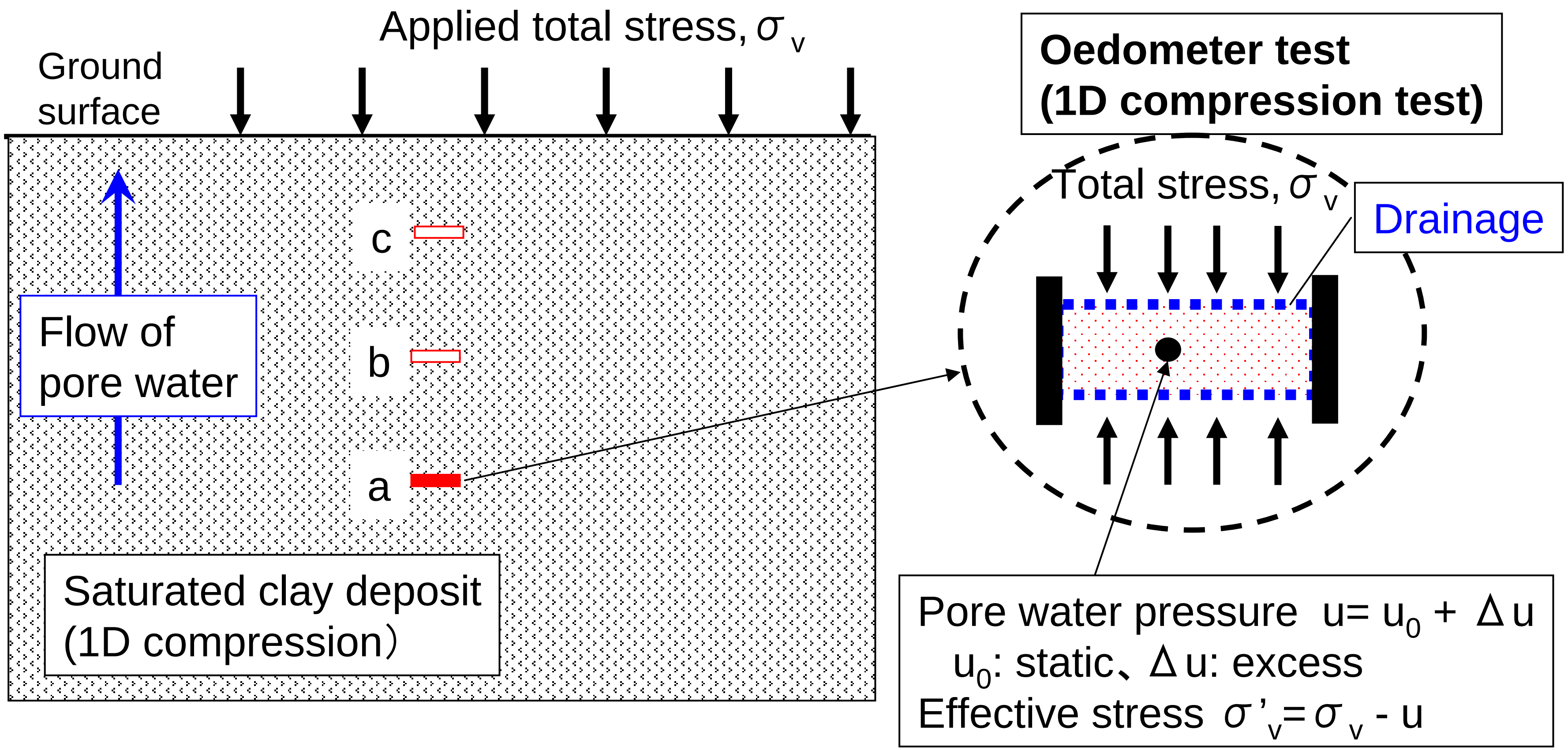
1D consolidation of clay

Summary

Some fundamental issues of 1D clay consolidation:

largely owing to
Late Prof. IMAI, Goro,
Yokohama National University

1D consolidation of soft clay:



A long history of research !

due to very complicated interactions among
three different 'time'-dependent factors …..

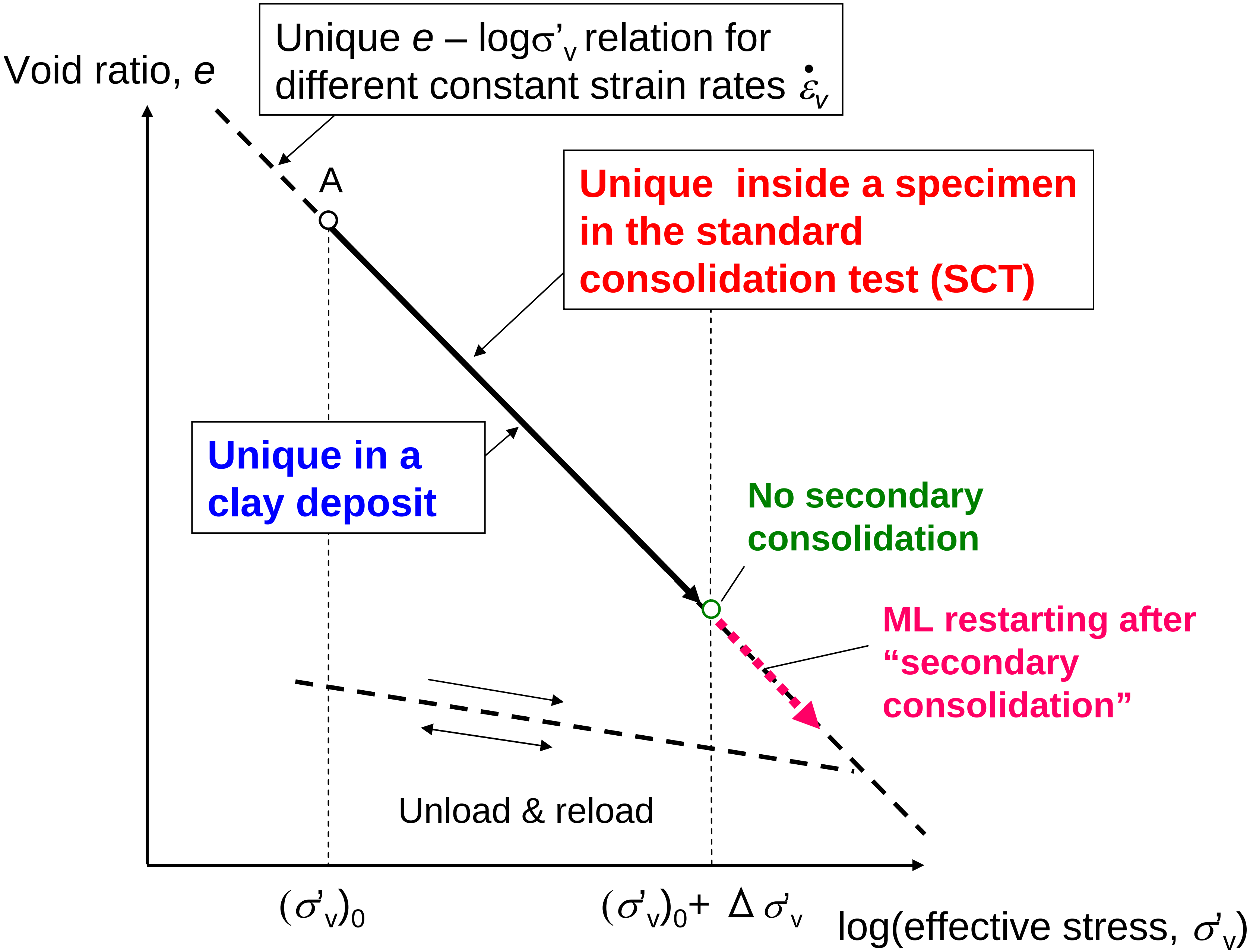
Three 'time'-dependent factors in clay consolidation

'Time'-dependent factor	Basic mechanism	Parameter for modelling
1. Delayed dissipation of Δu	Flow of pore water and compression of clay	Time (t^*) defined zero at the start of dissipation of Δu; $T=c_v t^*/H^2$ in the Terzaghi theory
2. Rate-dependent behaviour	Material viscosity	$\dot{\varepsilon}^{ir}$
3. Ageing effect	Time-dependent change in strength, stiffness …	Time (t_c) defined zero at the start of ageing

We need three sub-constitutive models

Different combinations of three factors

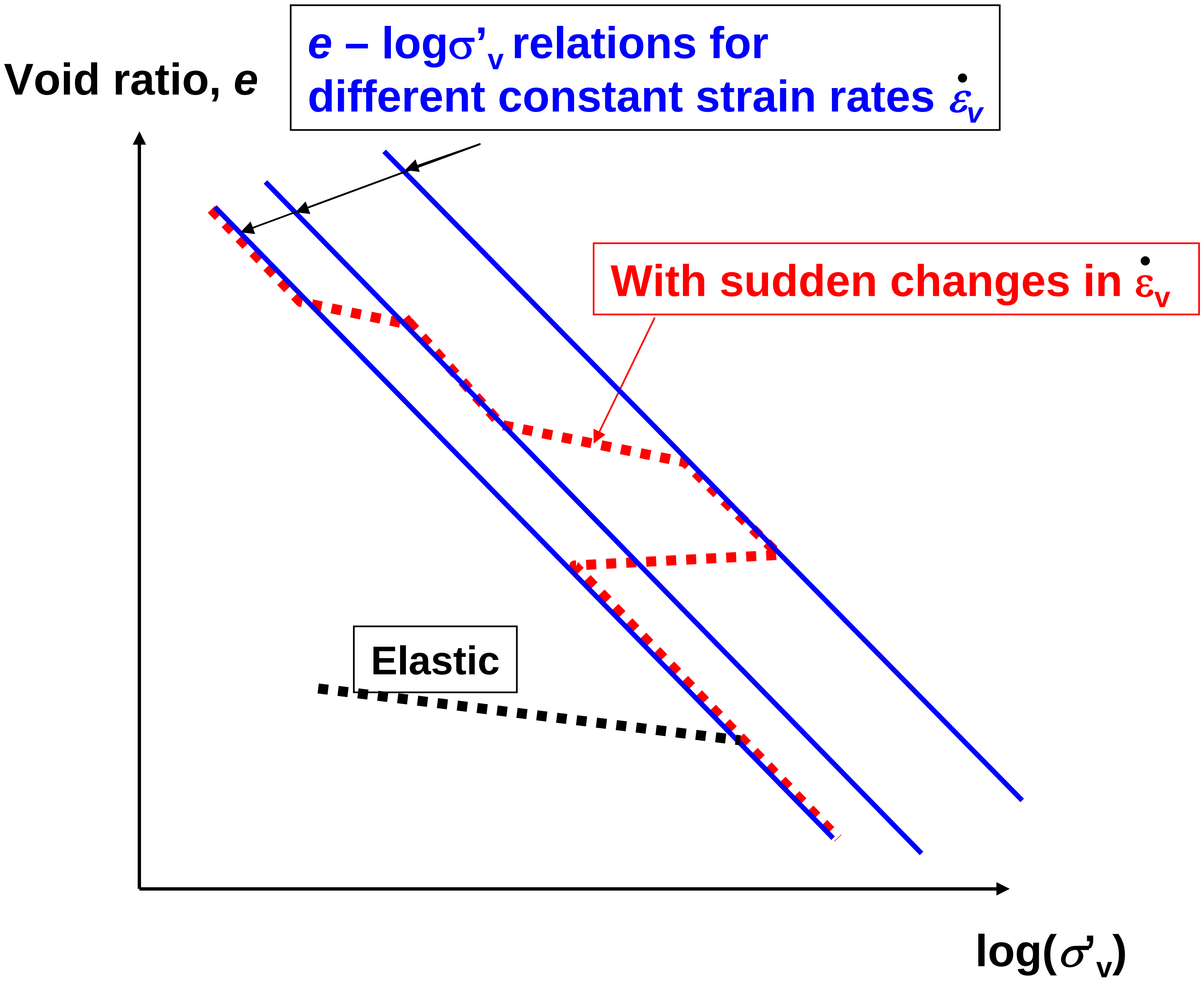
	e – logσ'_v behaviour	Delayed dissipation of Δu	Ageing effect	Note
1	No definitions of elasticity, plasticity and so on	No	No	
		Yes	No	
2	Elasto-plastic	No	No	
		Yes	No	Terzaghi theory
3	Elasto-visco-plastic	No	No	
		Yes	No	- Consolidation of a clay deposit for a relatively short period
4	Elasto-visco-plastic	No	Yes	
		Yes	Yes	- Long-term sedimentationt - Consolidation of young cement-mixed soil


Void ratio, e
Unique e – logσ'v relation for different constant strain rates ε̇v
A
Unique inside a specimen in the standard consolidation test (SCT)
Unique in a clay deposit
No secondary consolidation
ML restarting after "secondary consolidation"
Unload & reload
(σ'v)0
(σ'v)0+ Δ σ'v
log(effective stress, σ'v)

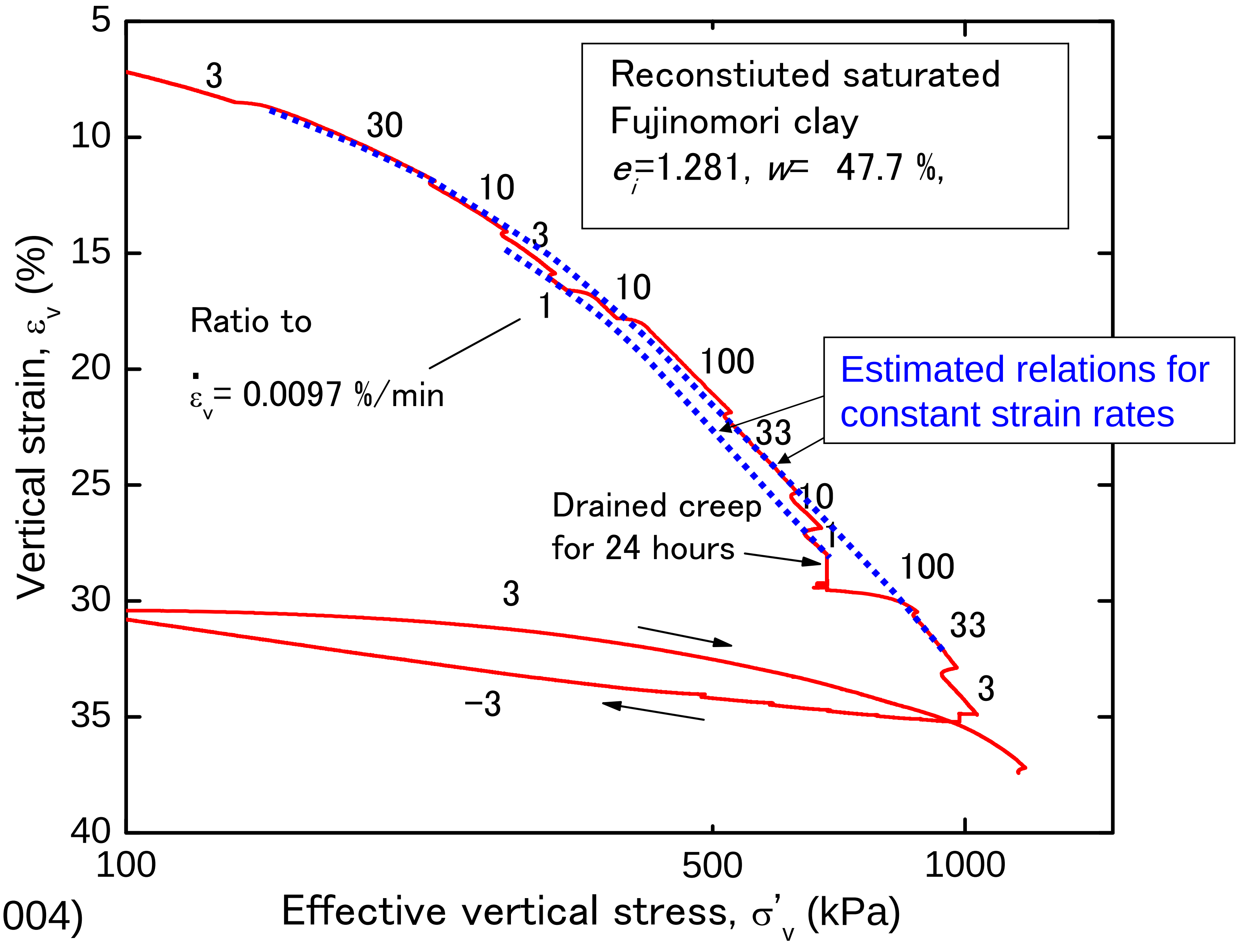
Different combinations of three factors

	e – logσ'_v behaviour	Delayed dissipation of Δu	Ageing effect	Note
1	No definitions of elasticity, plasticity and so on)	No	No	
		Yes	No	
2	Elasto-plastic	No	No	
		Yes	No	Terzaghi theory
3	Elasto-visco-plastic	No	No	
		Yes	No	- Consolidation of a clay deposit for a relatively short period
4	Elasto-visco-plastic	No	Yes	- Long-term sedimentation forming a clay deposit - Consolidation of young cement-mixed soil
		Yes	Yes	

Isotach viscosity in 1D compression of clay

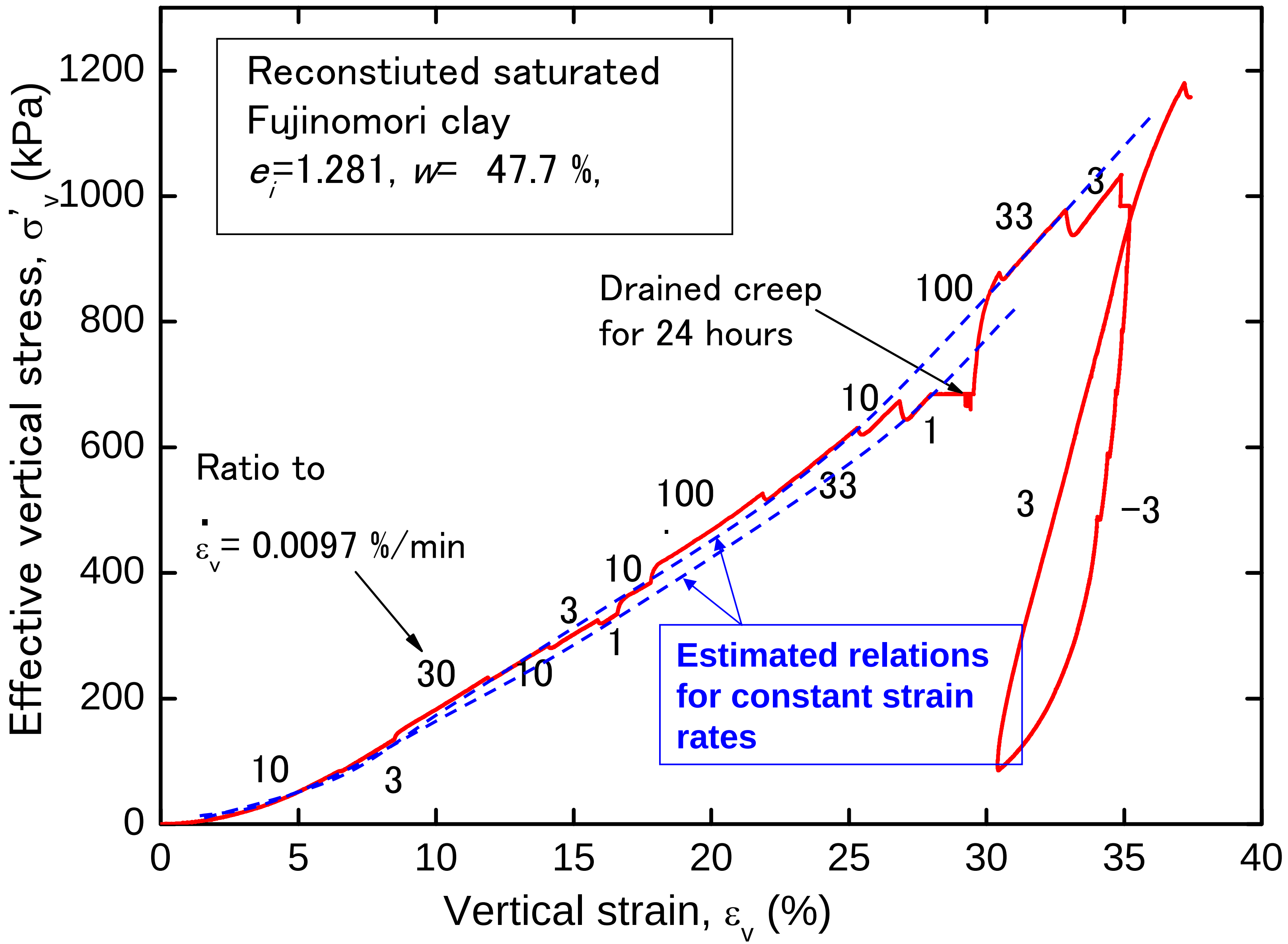


Isotach viscosity in a CRS test on saturated clay, similar to the test results by Leroueil & Marques (1996)



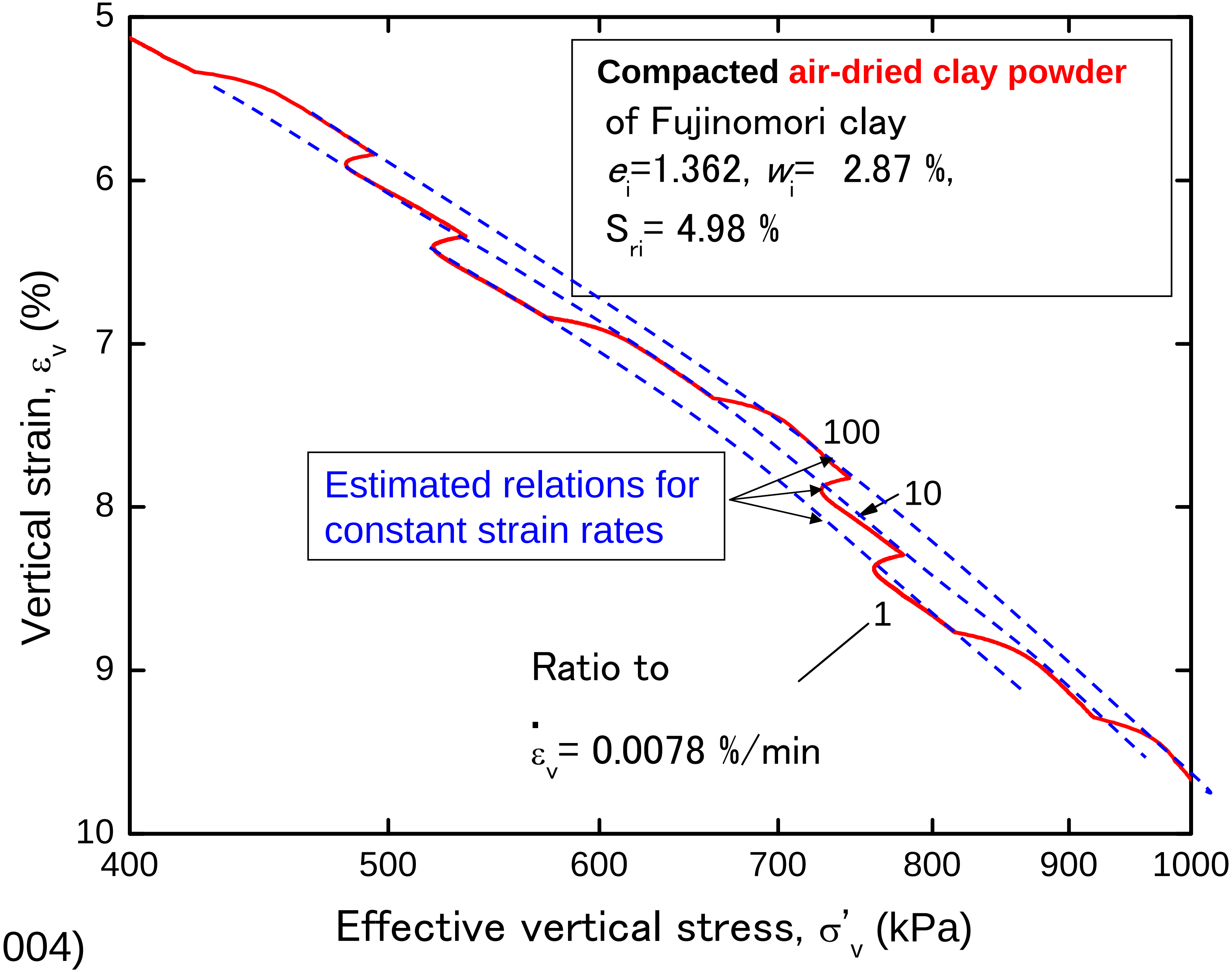
Li et al. (2004)

Isotach viscosity in 1D compression, similar to the one in TC & PSC tests



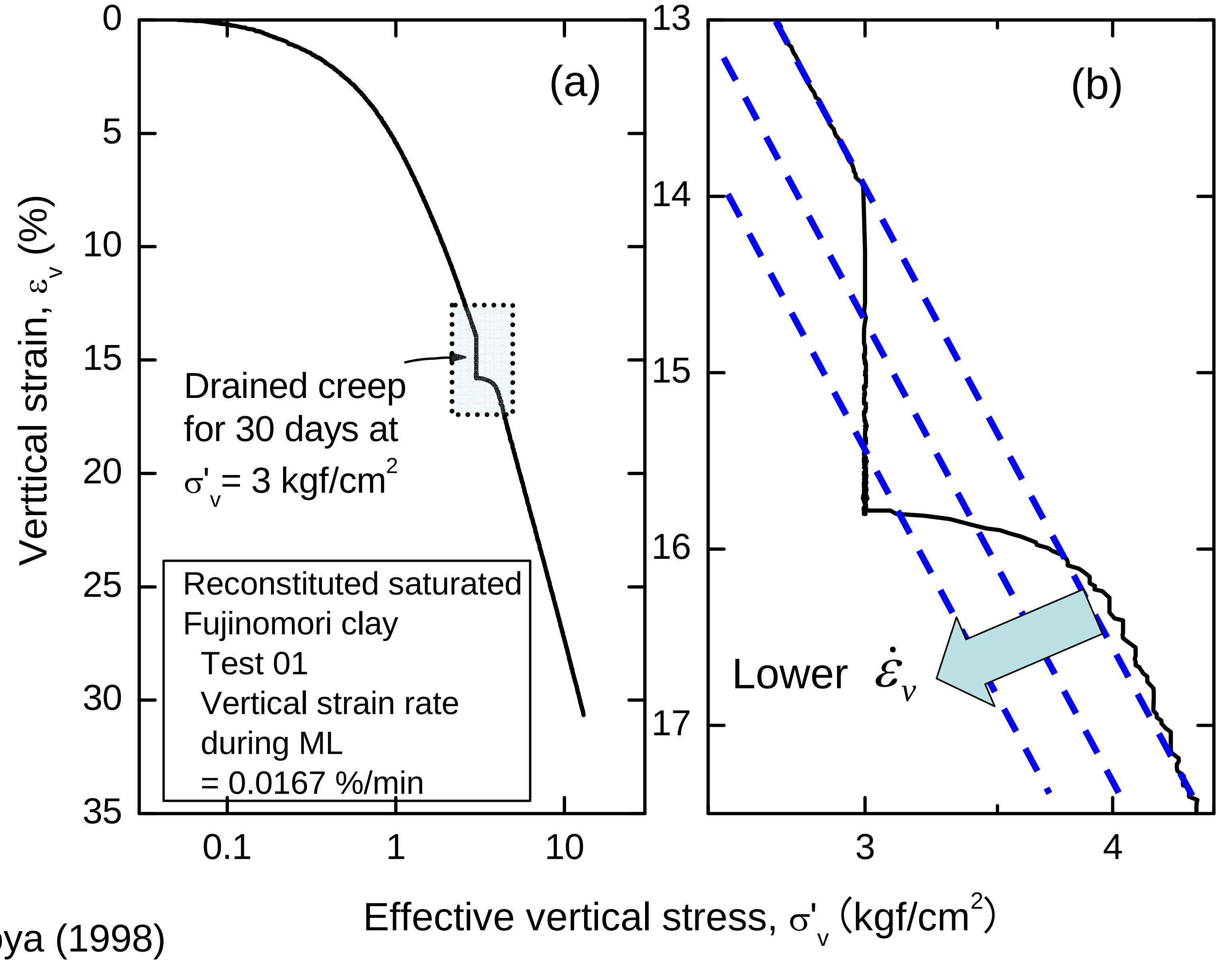
Li et al. (2004); Acosta-Martínez et al. (2005)

Compacted air-dried clay powder also exhibits Isotach viscosity → Clay has viscosity as sand and gravel.



Li et al. (2004)

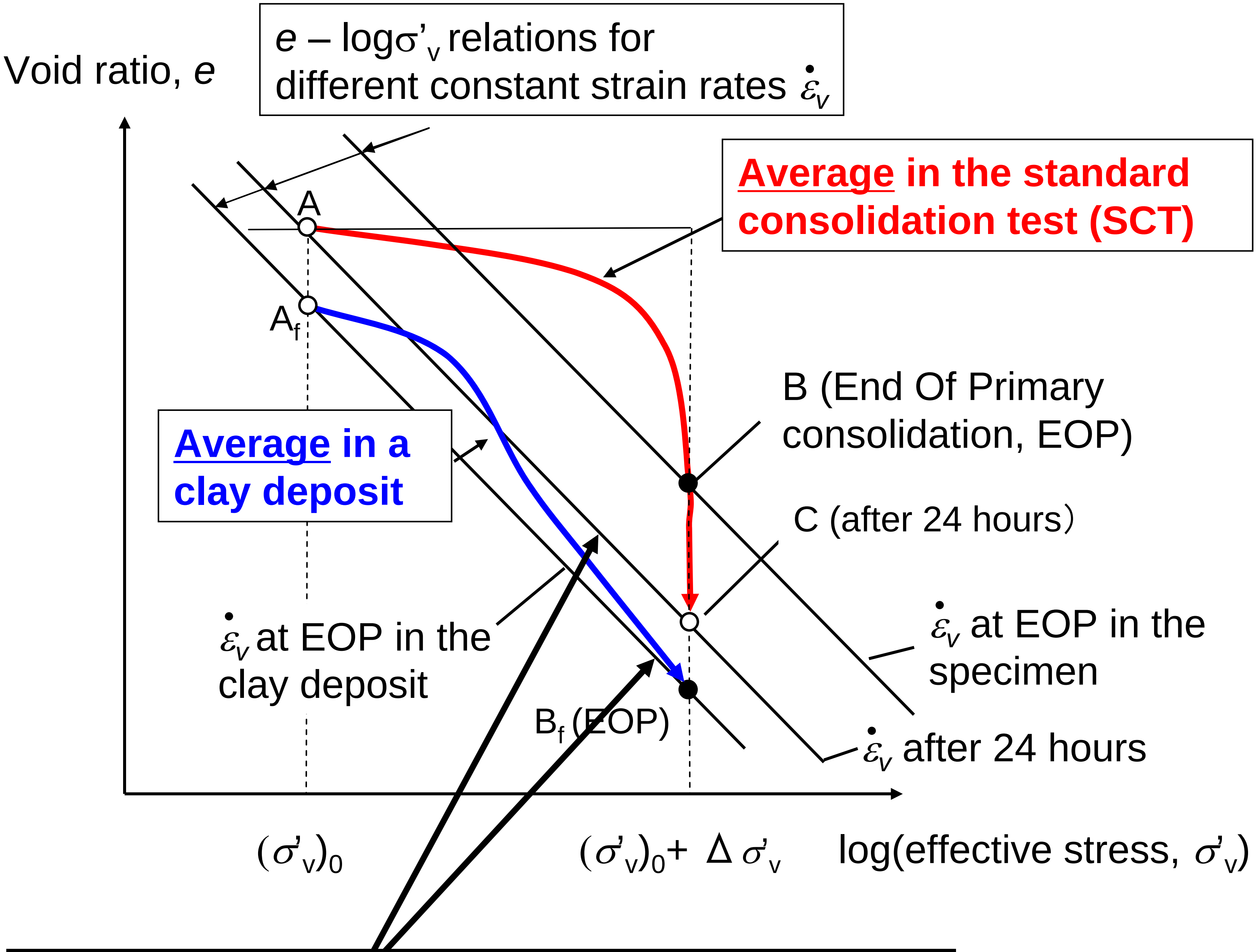
Creep is a viscous response, controlled by isotaches, not by isochrones !



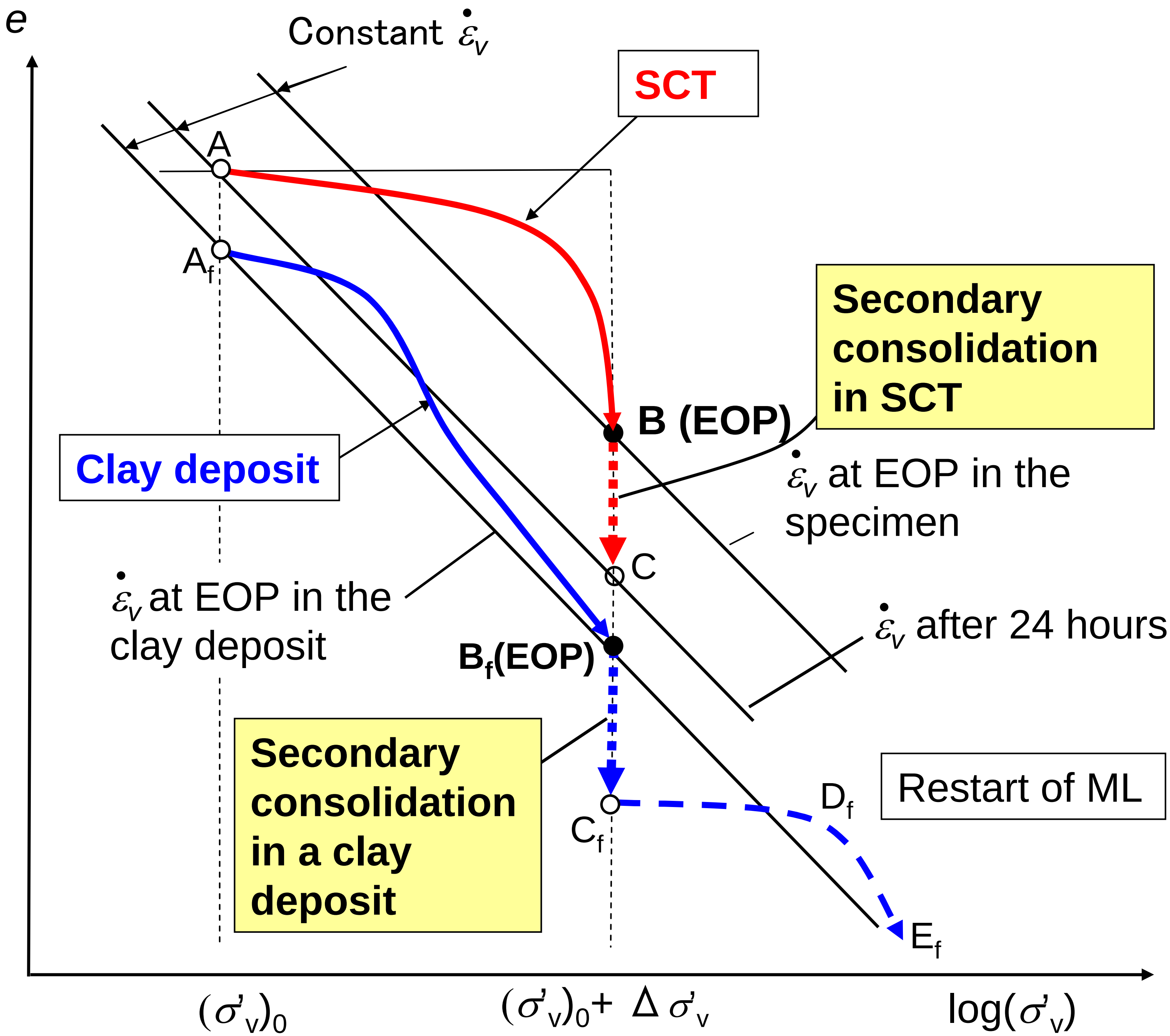
Momoya (1998)

Different combinations of three factors

	e – logσ'_v behaviour	Delayed dissipation of Δu	Ageing effect	Note
1	No definitions of elasticity, plasticity and so on)	No	No	
		Yes	No	
2	Elasto-plastic	No	No	
		Yes	No	Terzaghi theory
3	Elasto-<u>visco</u>-plastic	No	No	
		Yes	No	- Consolidation of a clay deposit for a relatively short period
4	Elasto-<u>visco</u>-plastic	No	Yes	- Long-term sedimentation forming a clay deposit - Consolidation of young cement-mixed soil
		Yes	Yes	

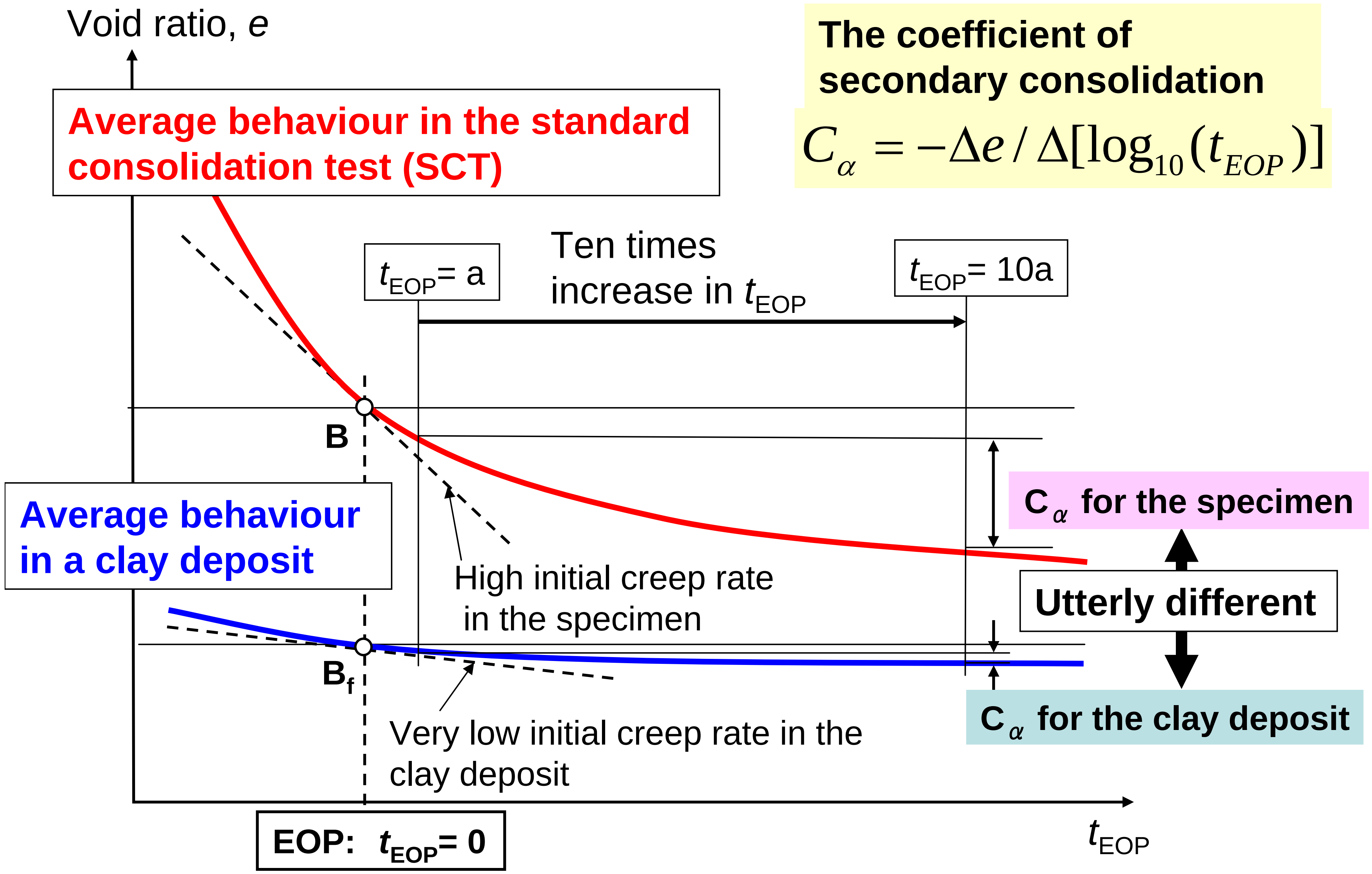


Slopes A- C & A_f – B_f may agree co-incidentally.



e
Constant $\dot{\varepsilon}_v$
SCT
A
A_f
Secondary consolidation in SCT
B (EOP)
Clay deposit
$\dot{\varepsilon}_v$ at EOP in the specimen
C
$\dot{\varepsilon}_v$ at EOP in the clay deposit
$\dot{\varepsilon}_v$ after 24 hours
B_f(EOP)
Secondary consolidation in a clay deposit
D_f
Restart of ML
C_f
E_f
$(\sigma'_v)_0$
$(\sigma'_v)_0 + \Delta\sigma'_v$
$\log(\sigma'_v)$

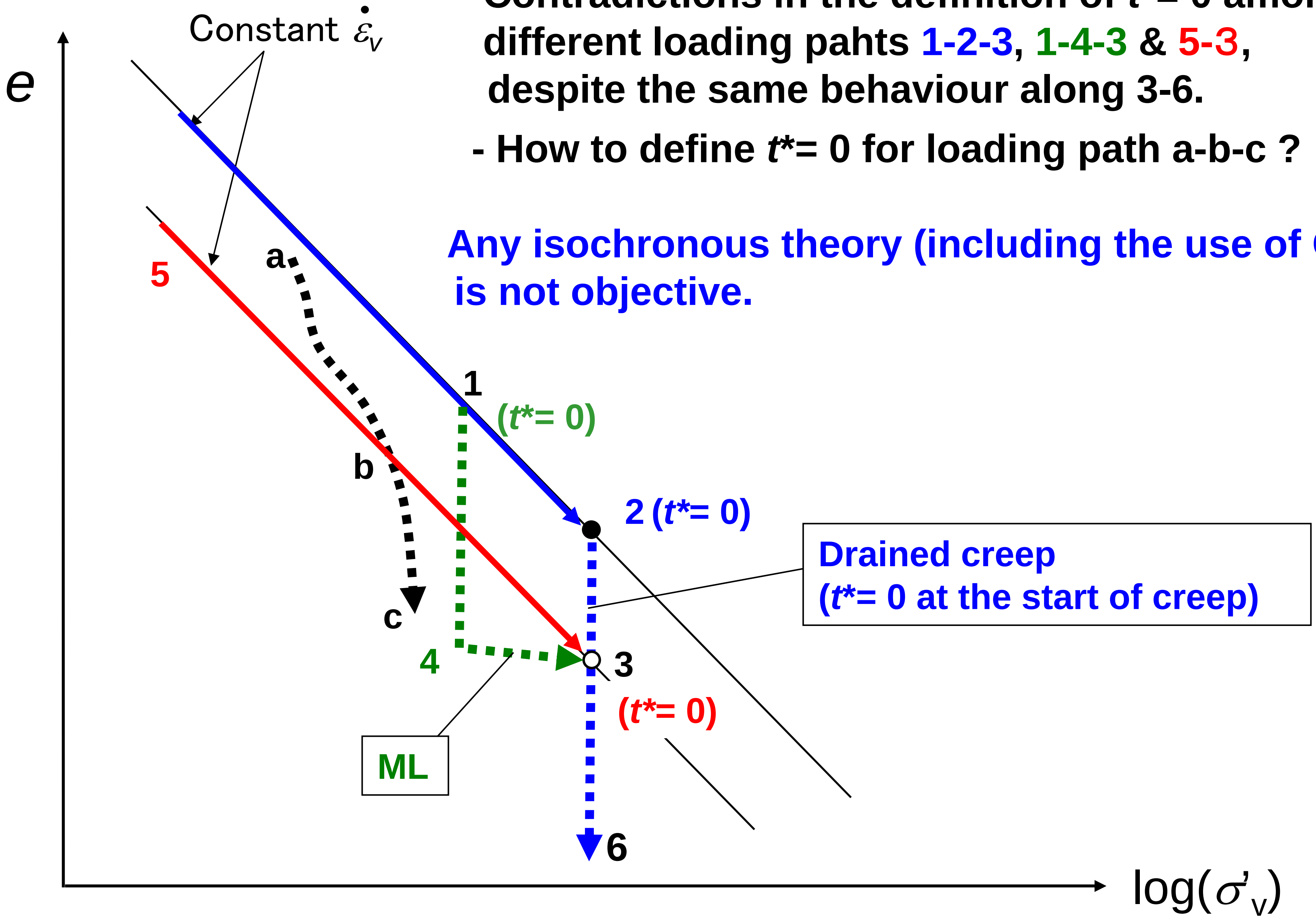
C_α is not fixed material properties, but affected by the initial strain rate.



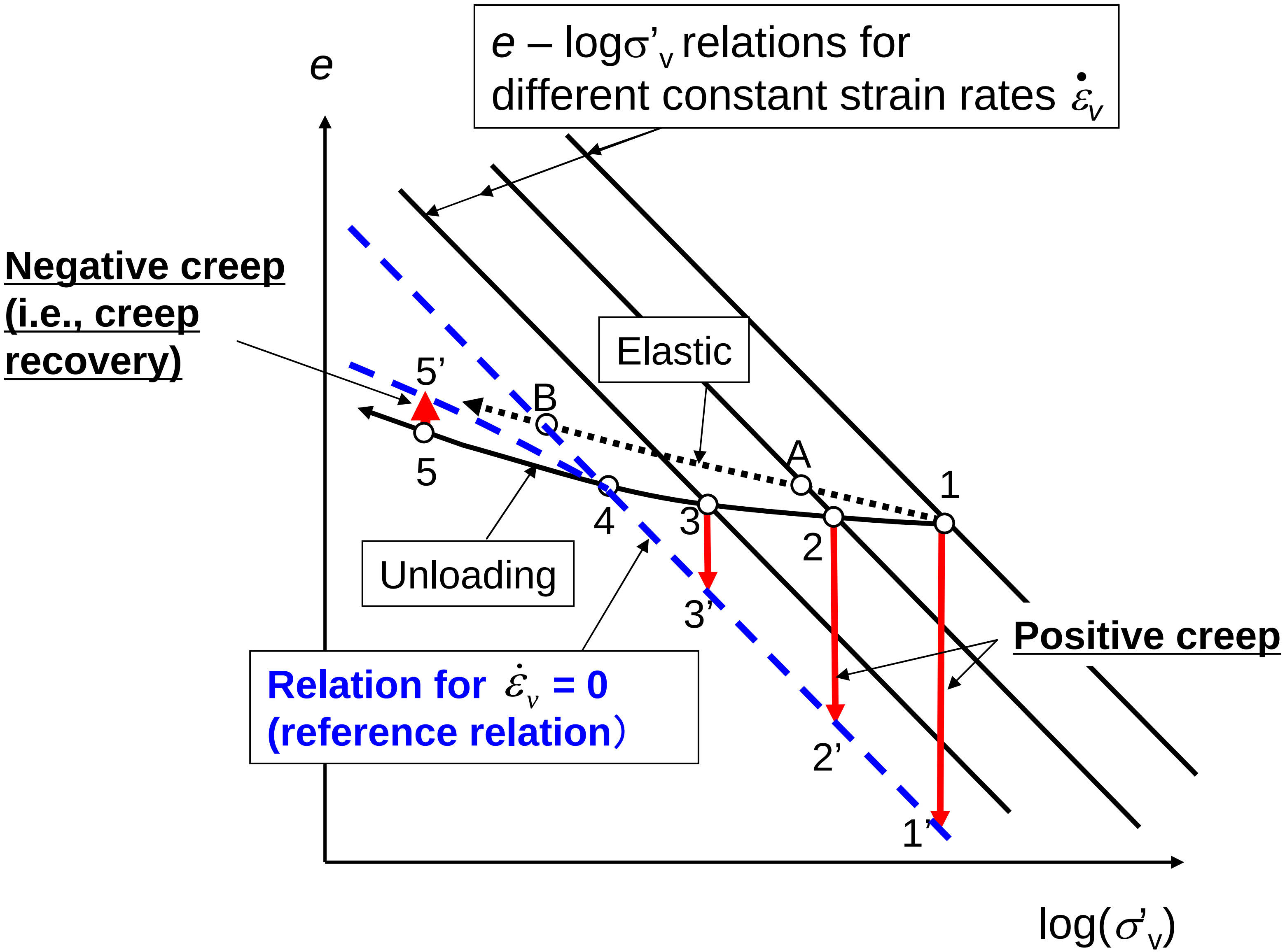
'Time' is the problem:

- Contradictions in the definition of $t^*= 0$ among different loading pahts 1-2-3, 1-4-3 & 5-3, despite the same behaviour along 3-6.
- How to define $t^*= 0$ for loading path a-b-c ?

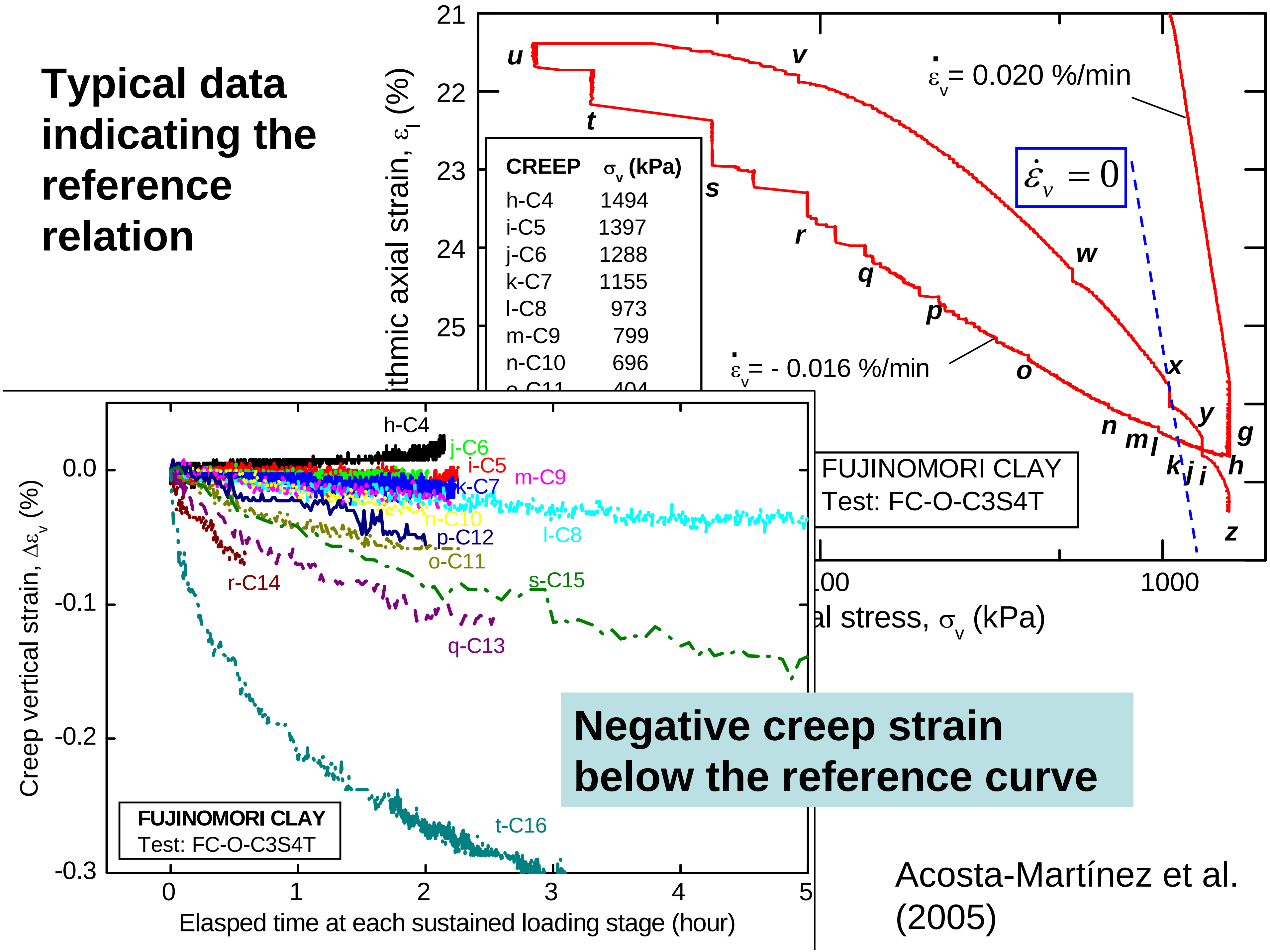
Any isochronous theory (including the use of C_{α}) is not objective.



Isotach for $\dot{\varepsilon}_v$ = 0 (the reference curve) is necessary.



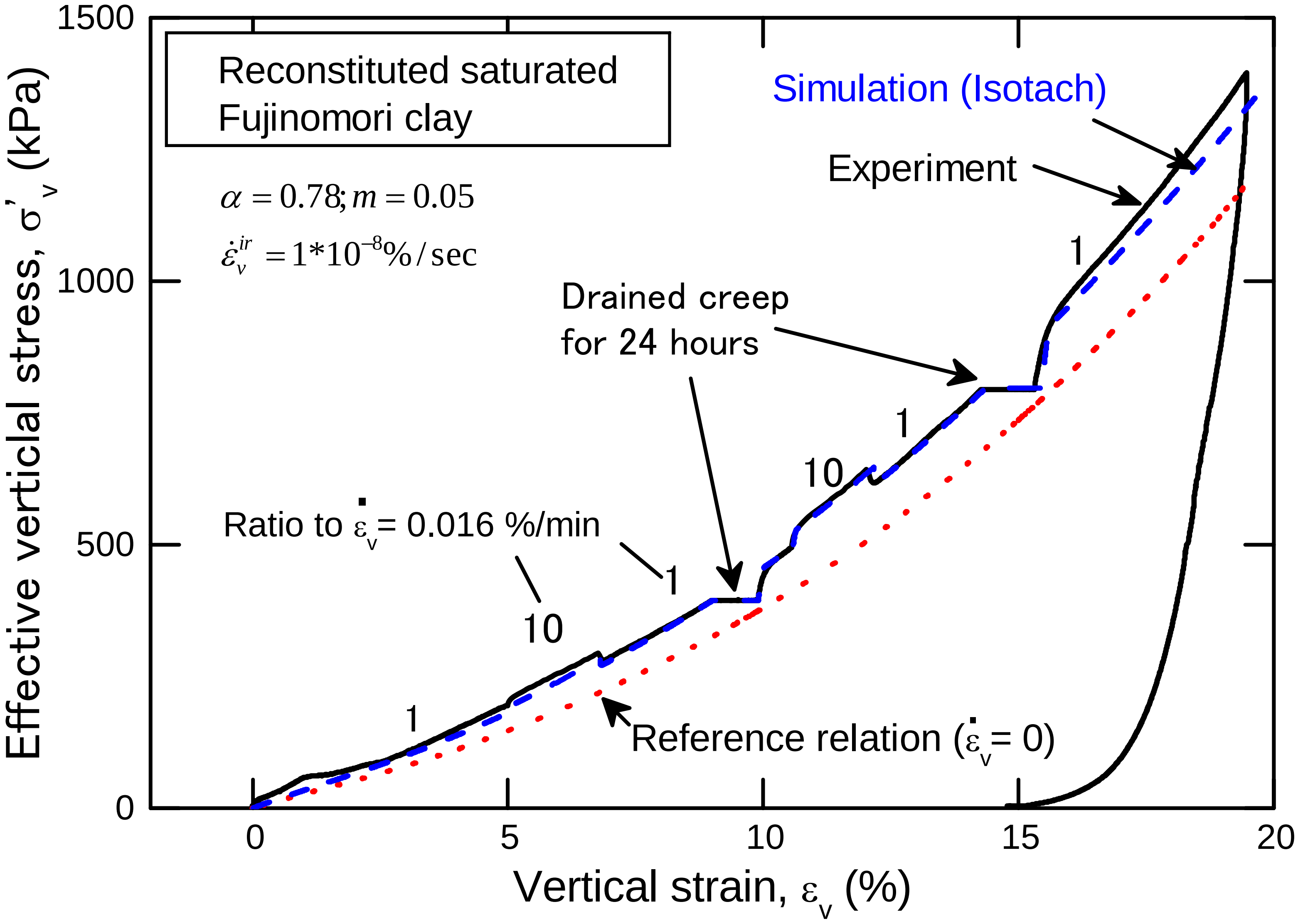
Typical data indicating the reference relation



Negative creep strain below the reference curve

Acosta-Martínez et al. (2005)

Introduction of the reference relation leads to a three-component model (i.e., an isotach model)….



Acosta-Martínez et al. (2005)

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		Yes	No	Terzaghi theory
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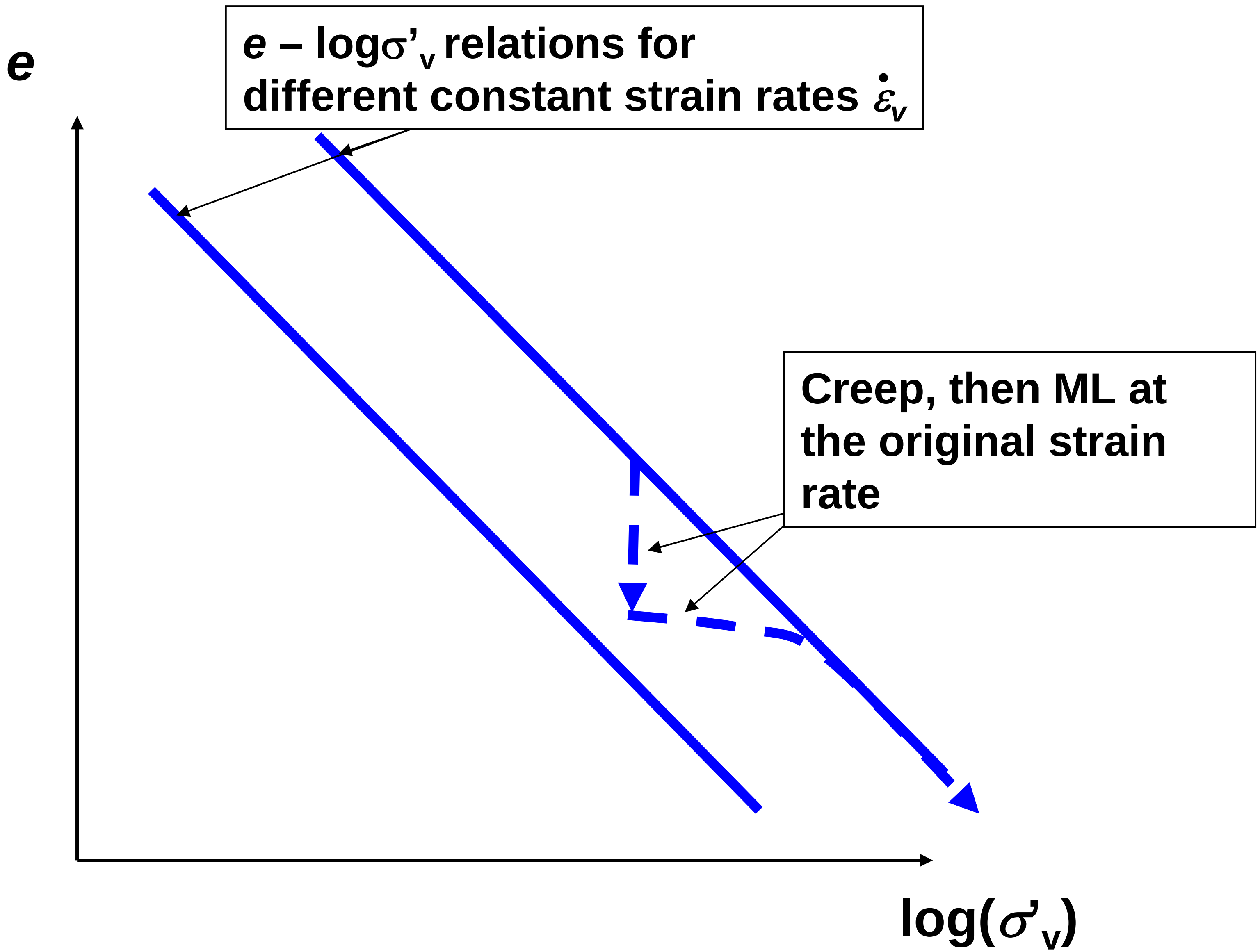
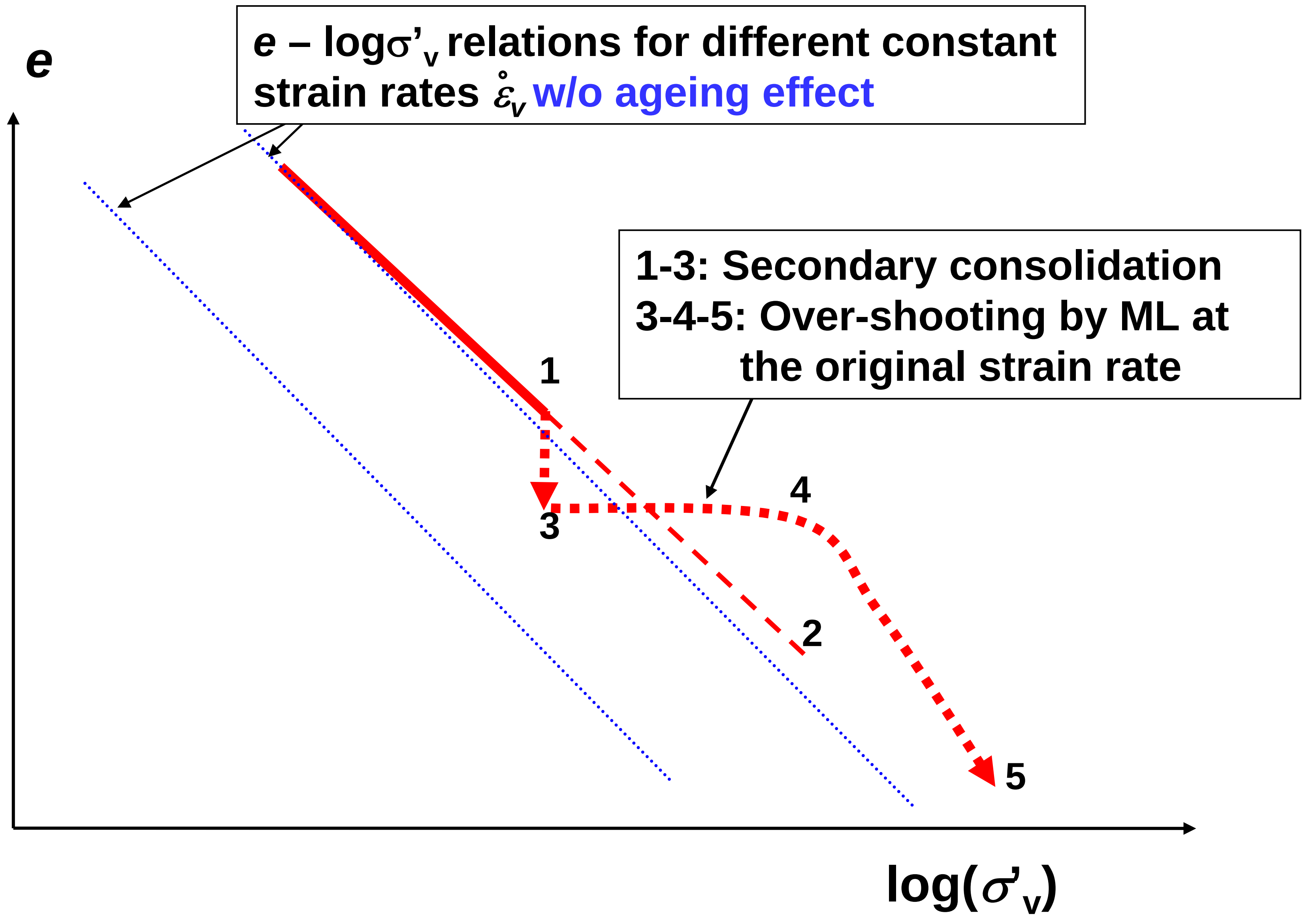
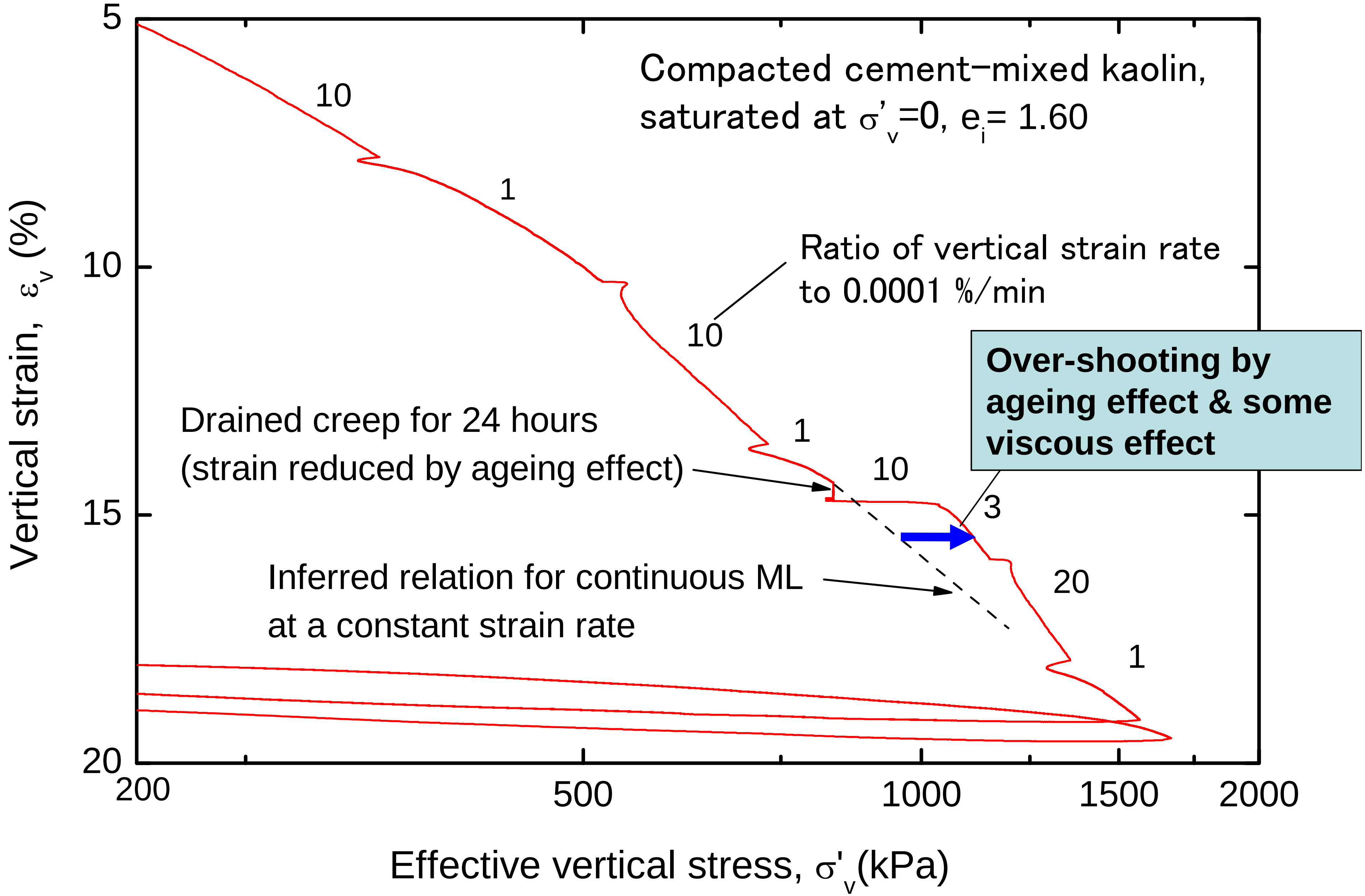


Simplified behaviour without ageing effect



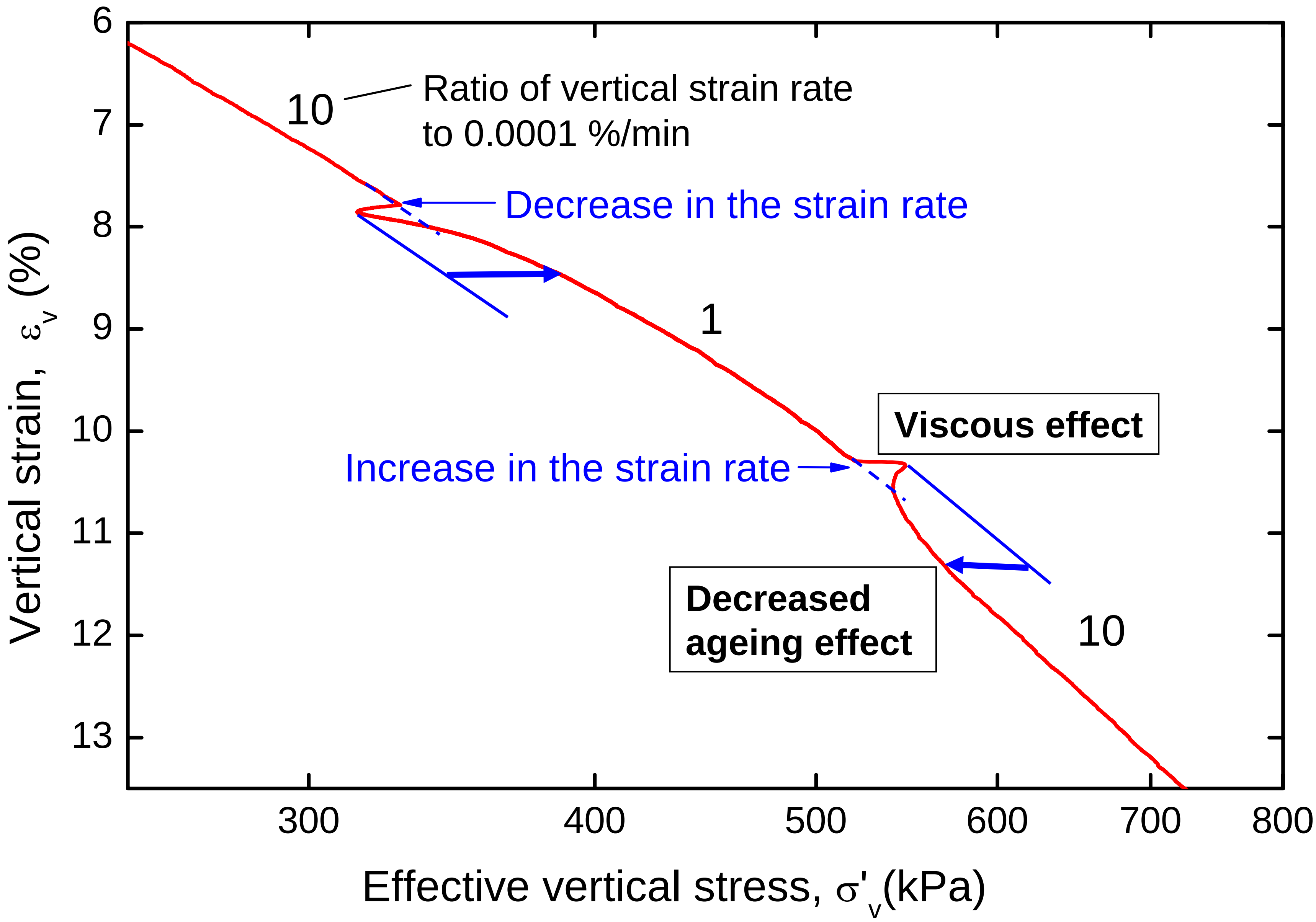
Simplified behaviour with ageing effect

1D compression of clay with continuing ageing effects



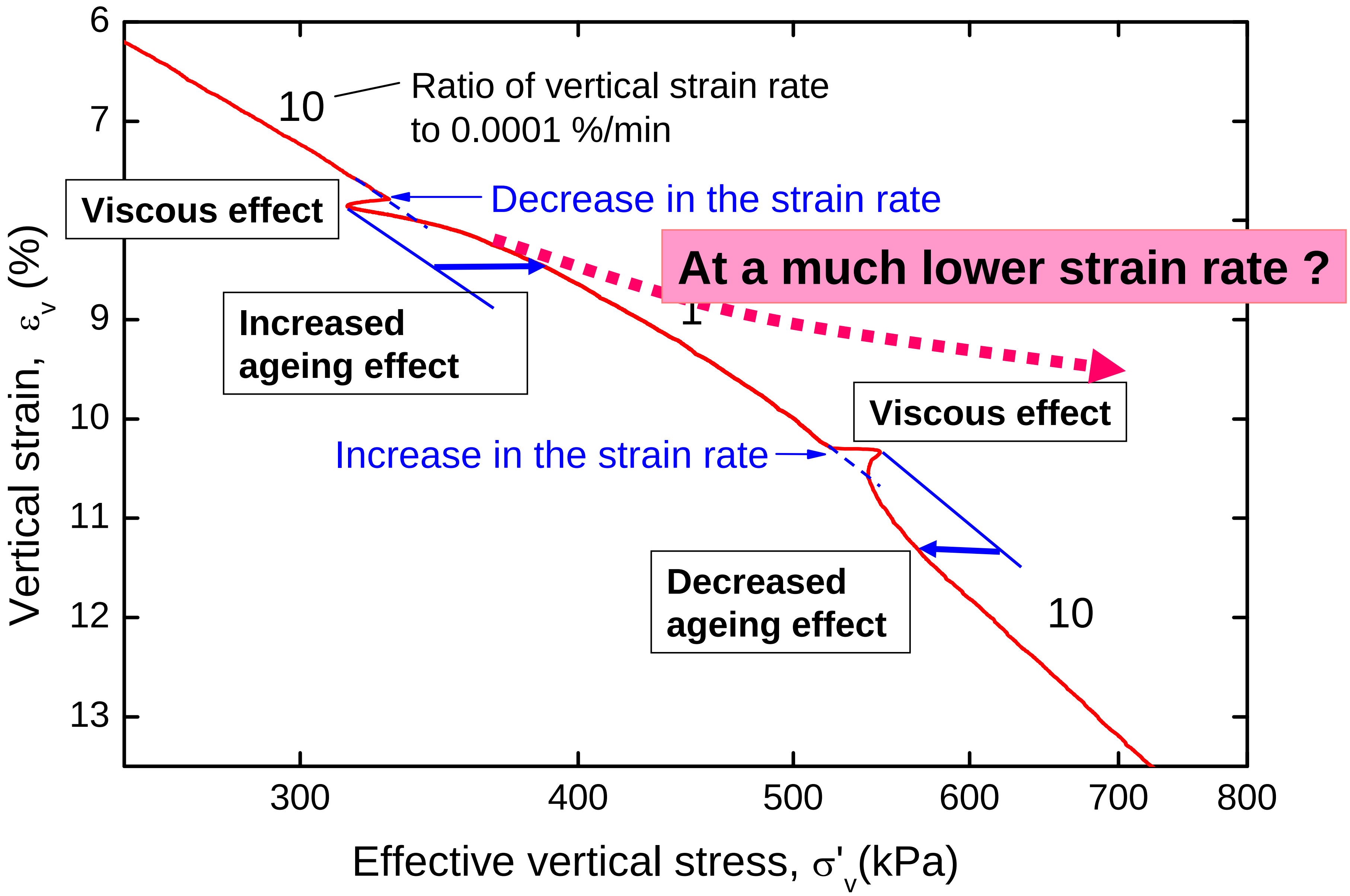
Deng & Tatsuoka (2005)

Continuing ageing effects in 1D compression of clay

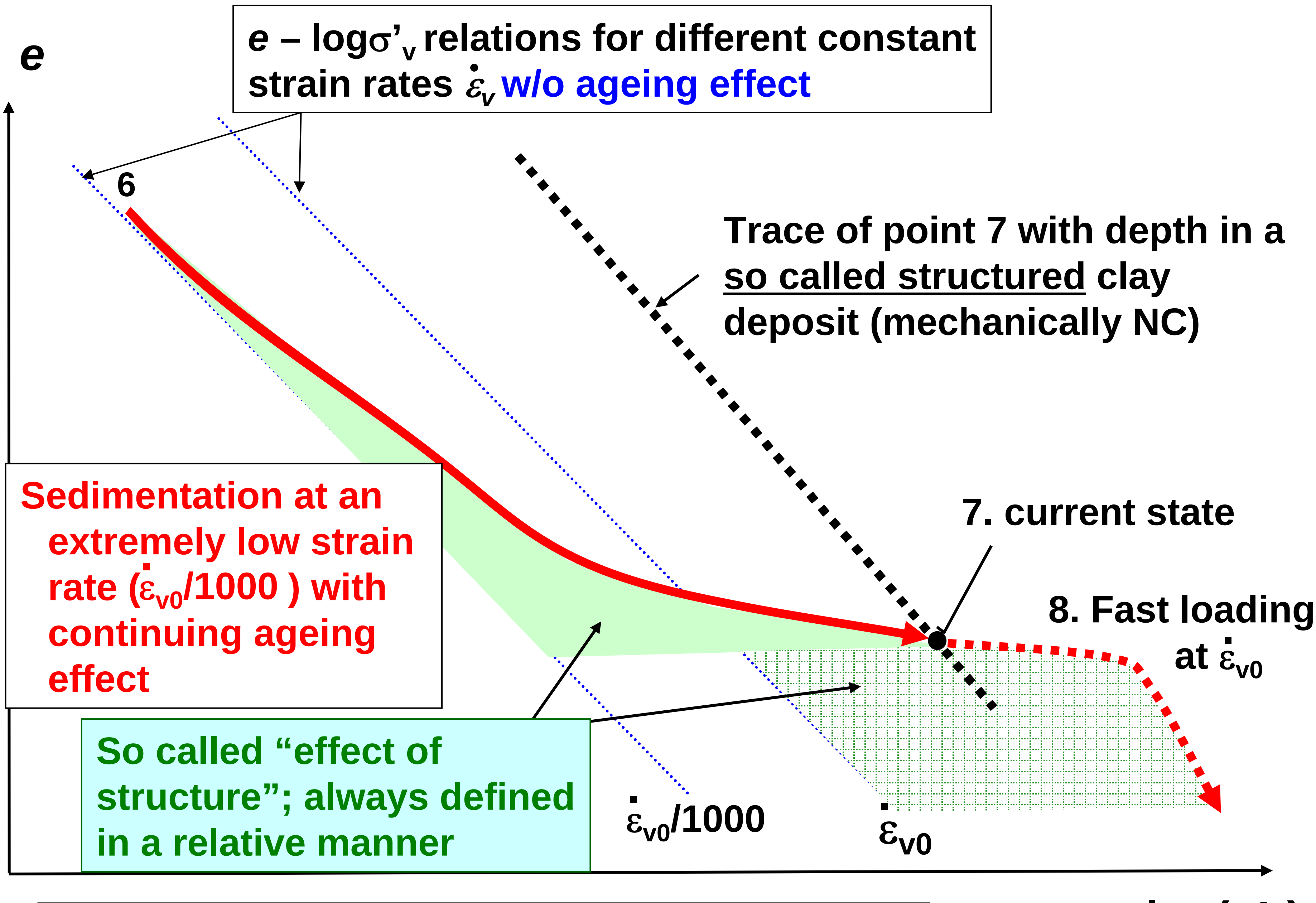


Deng & Tatsuoka (2005)

Continuing ageing effects in 1D compression of clay

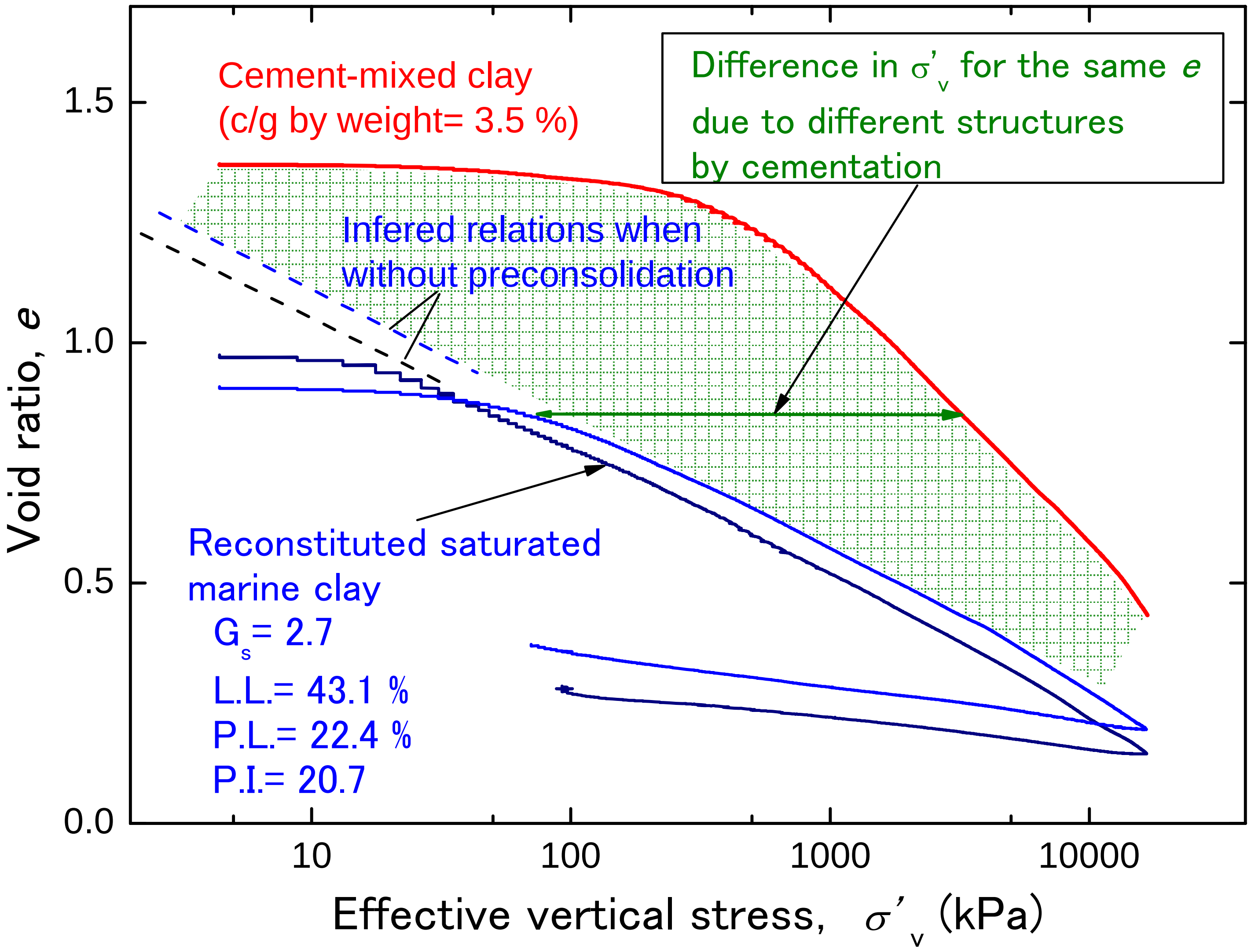


Deng & Tatsuoka (2005)



Simplified behaviour with ageing effect

Effects of a given structure and its degrading by straining are important. But, viscosity and ageing process are also important and usually cannot be ignored.



Sugai & Tatsuoka (2003), *Lyon*

Summary

1. In-elastic strain develops due to plasticity, viscosity and cyclic loading effect, all affected by ageing effect. But, any strain-additive model for these factors is not relevant.

2. The plastic yielding consists of shear and volumetric yielding mechanisms.

3. Three basic types of viscosity, *Isotach*, *TESRA* and *P&N*, have been observed. A general expression to describe these and others as well as their transformation is suggested.

(to continue)

Summary (continued)

4. **A non-linear three-component model, described in terms of strain rate, is relevant. Any isochronous model, described in term of general time, is not objective.**

5. **Cyclic loading effect could be significant. In taking into account this factor, any strain-additive model is not relevant. The three-component model should be modified.**

(to continue)

Summary (continued)

6. **Particle shape** has systematic effects on viscosity and cyclic loading effect.

7. **Ageing effect** is different from viscosity. A method to incorporate ageing effect in a constitutive model is suggested.

8. To properly understand the **1D consolidation of clay**, both viscosity and ageing effect are essential in addition to excess pore water dissipation. Changes in the structural effect with strain is another factor.

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