International Symposium on Deformation Characteristics of Geomaterials,
September 1~3, 2011, Seoul, Korea

Bishop Lecture

Professor Alan Bishop (1920-88)

Laboratory stress-strain tests for developments in geotechnical engineering research and practice

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Topics:

To illustrate significant roles of laboratory stress-strain tests of geomaterial for developments in geotechnical engineering research and practice,

several recent advances in our understanding of:

1) quasi-elastic stress-strain behaviour;

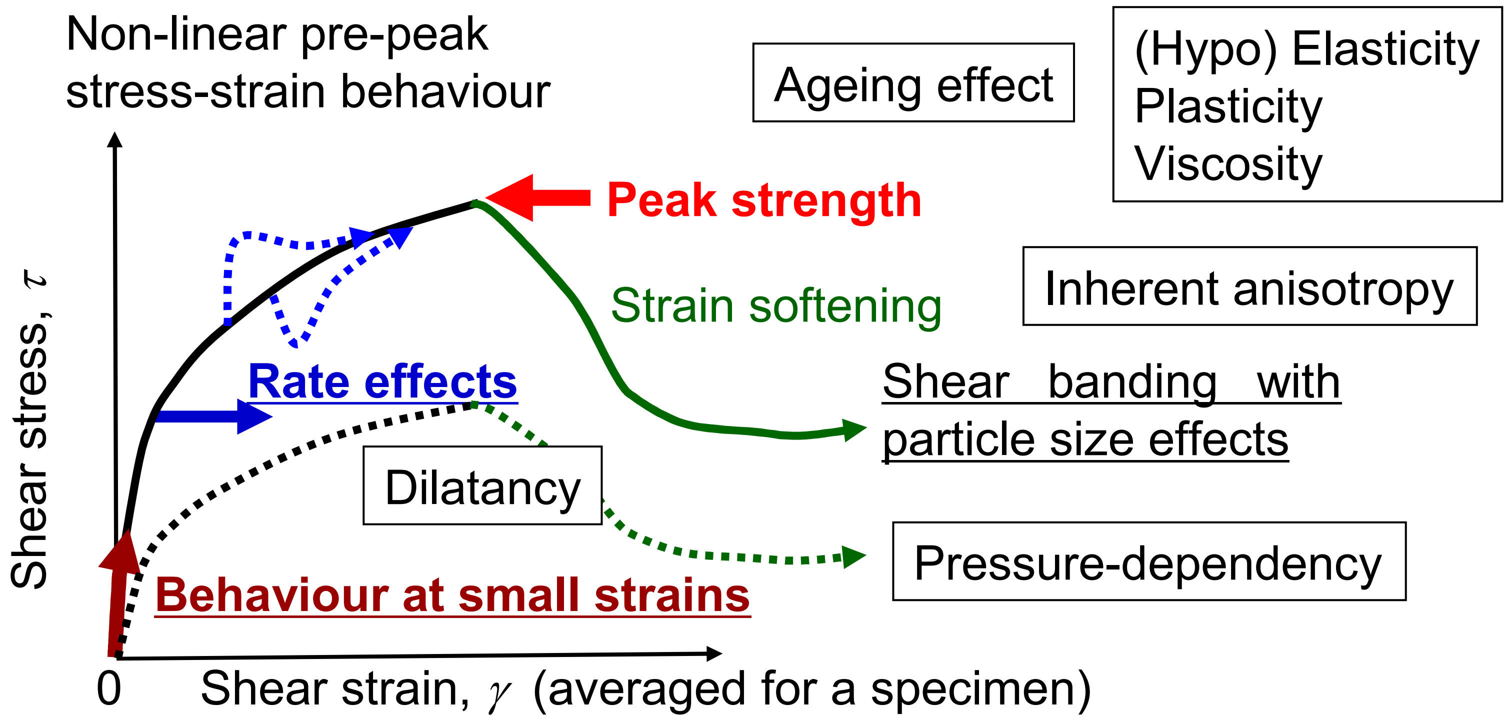
2) rate-dependent stress-strain behaviour; and

3) strength and stiffness of compacted soil related to field fill compaction control and design

are presented.

1) quasi-elastic stress-strain behaviour;
2) rate-dependent stress-strain behaviour; and
3) strength and stiffness of compacted soil related to field fill compaction control and design;

among other many important topics.



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2) rate-dependent stress-strain behaviour; and

3) strength and stiffness of compacted soil related to field fill compaction control and design;

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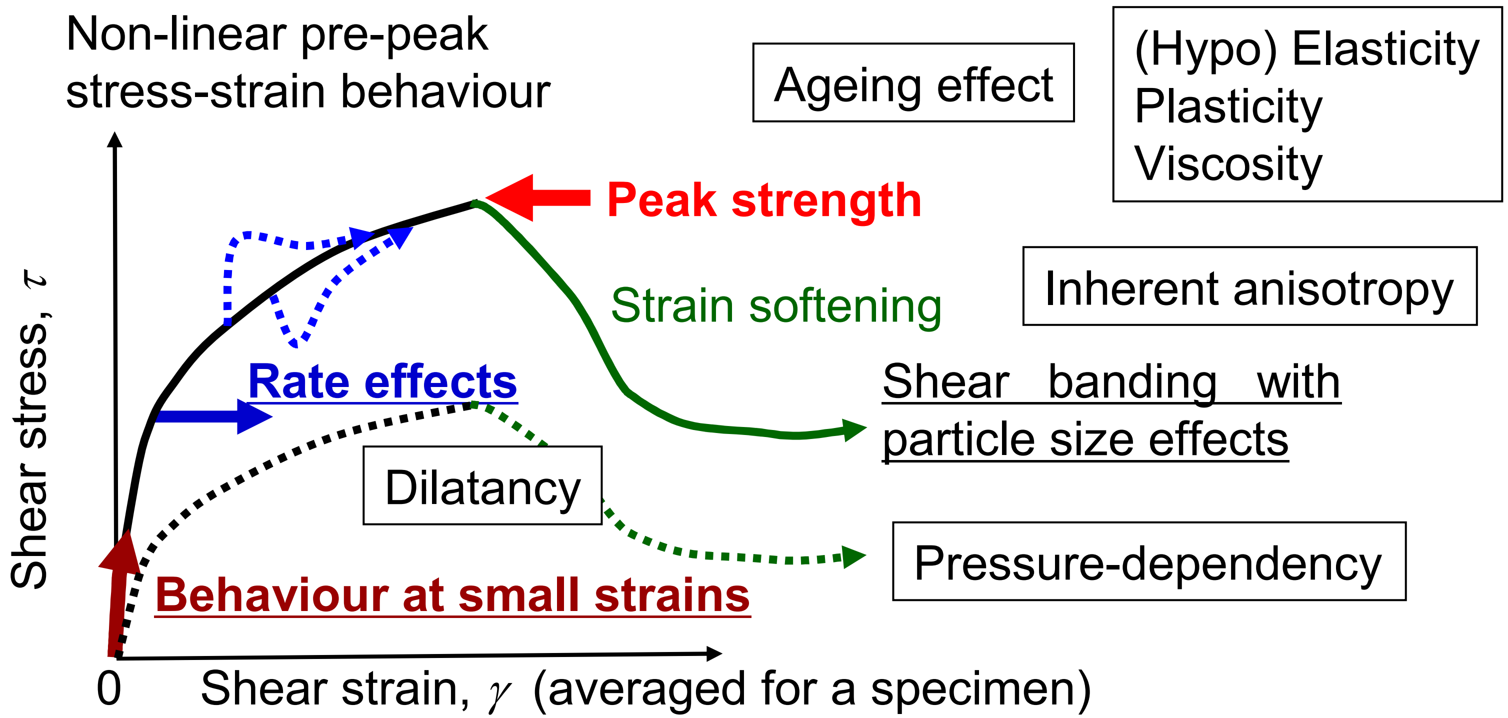
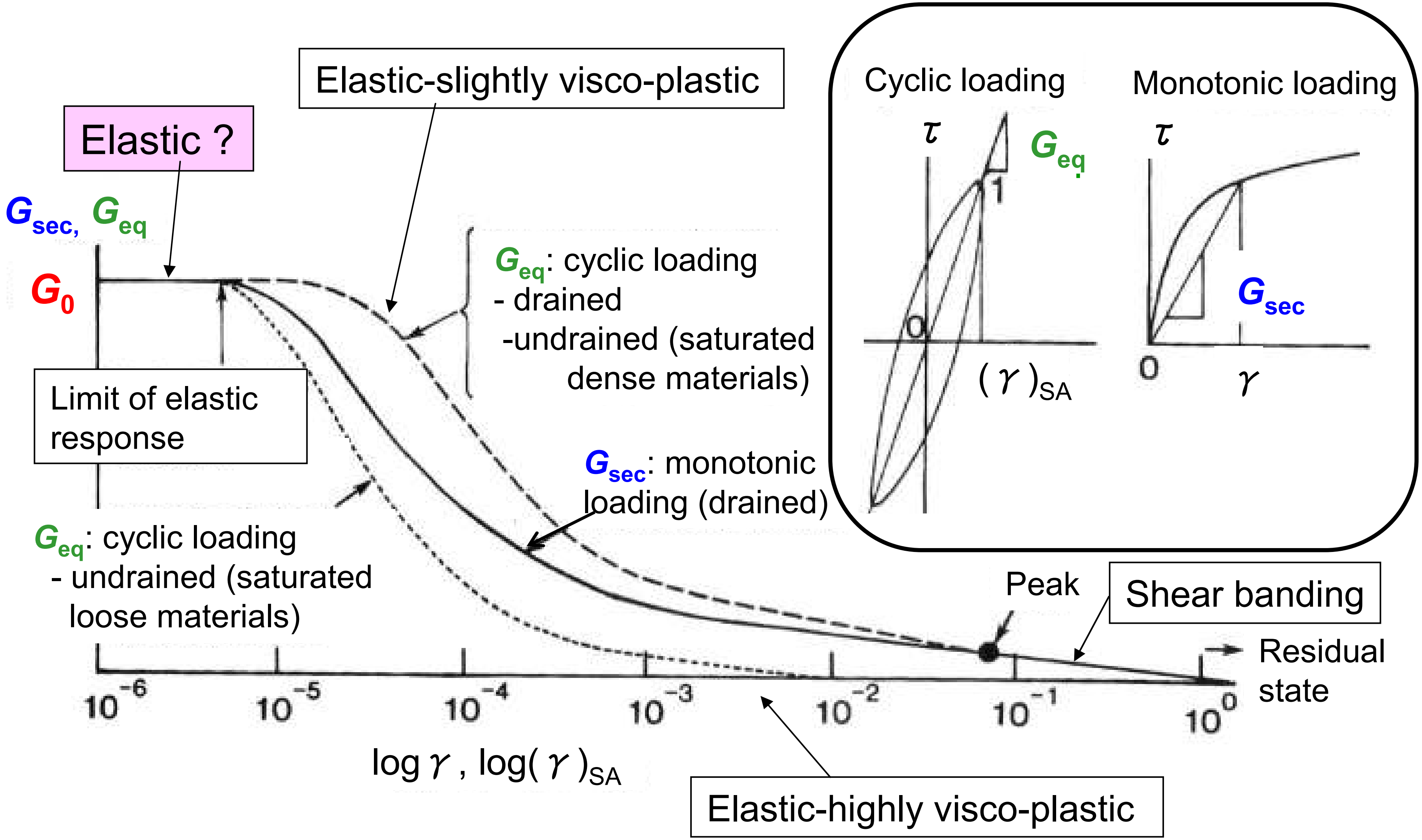


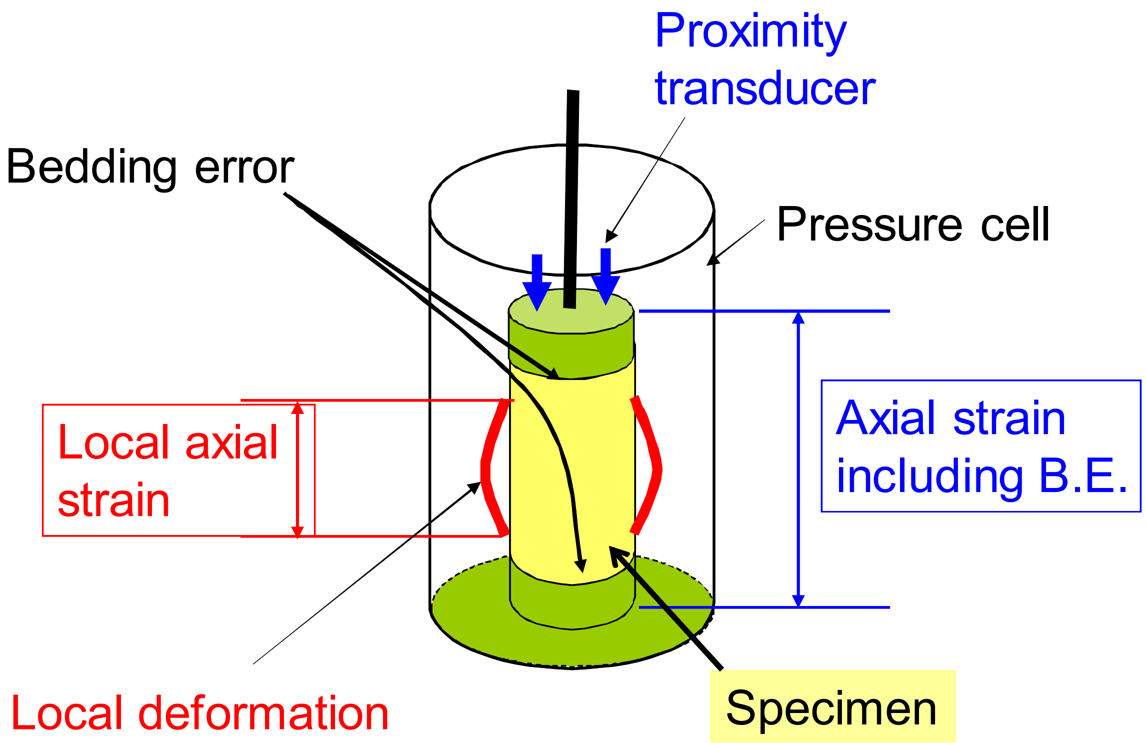
Can we observe "rate-independent and reversible (i.e., elastic) behaviour" at very small strains?



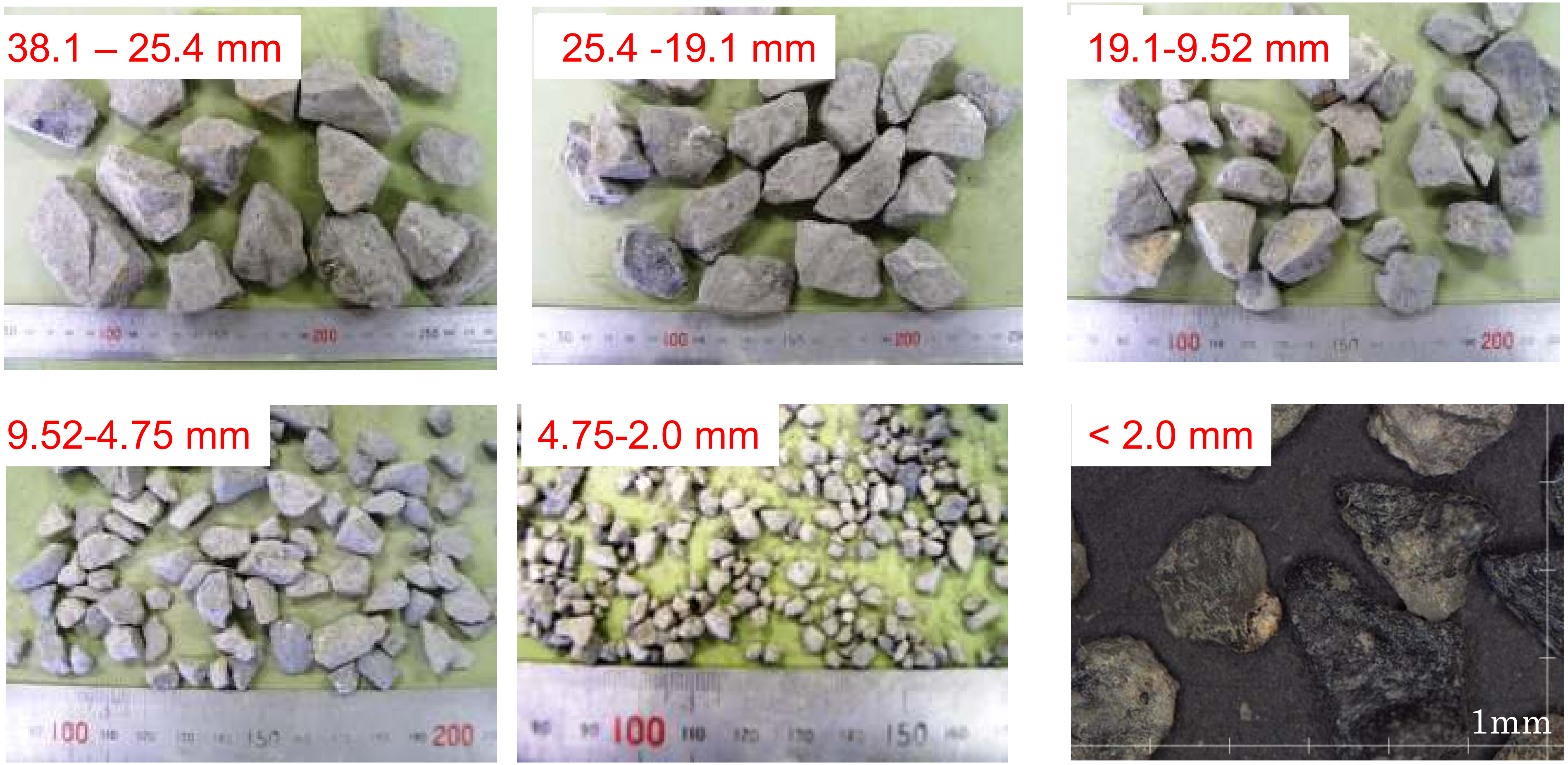
(Tatsuoka & Shibuya, 1991)

Triaxial test:

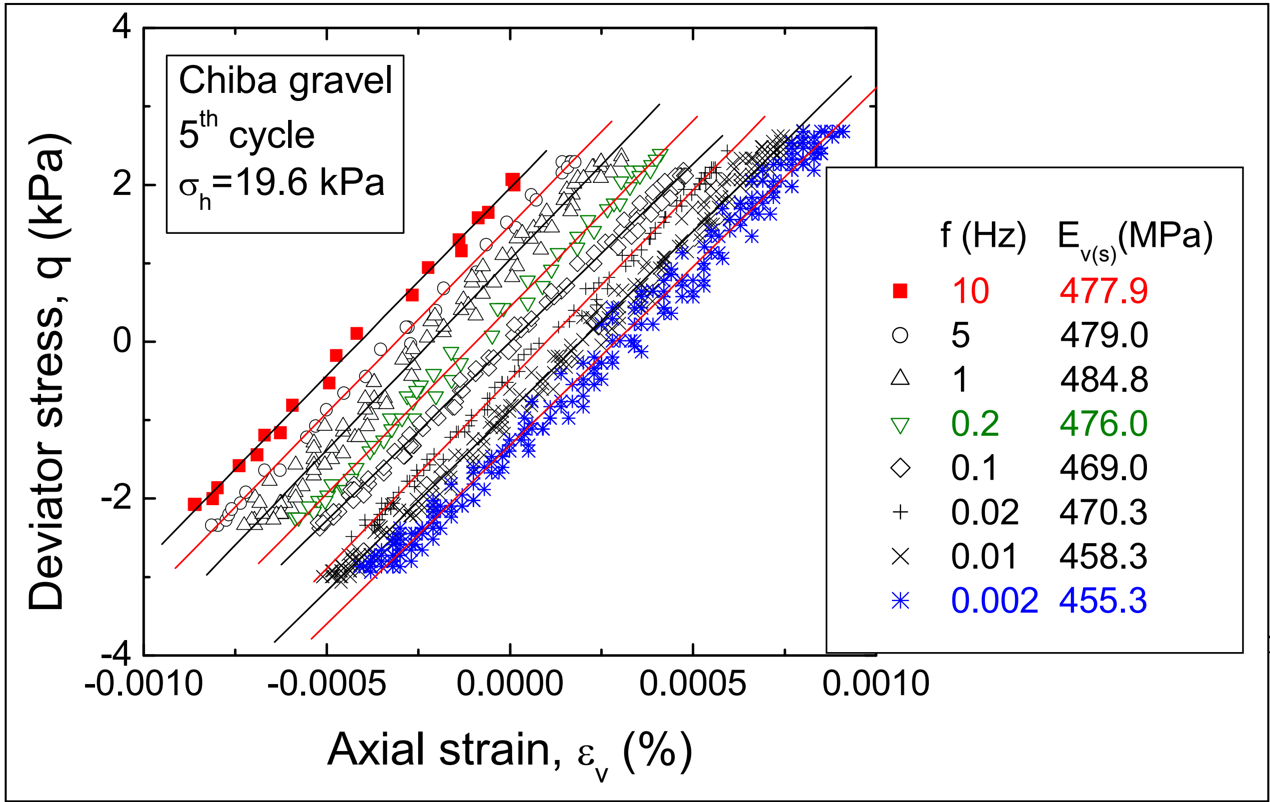
Specimen (30 cm-dia. & 60 cm-high)

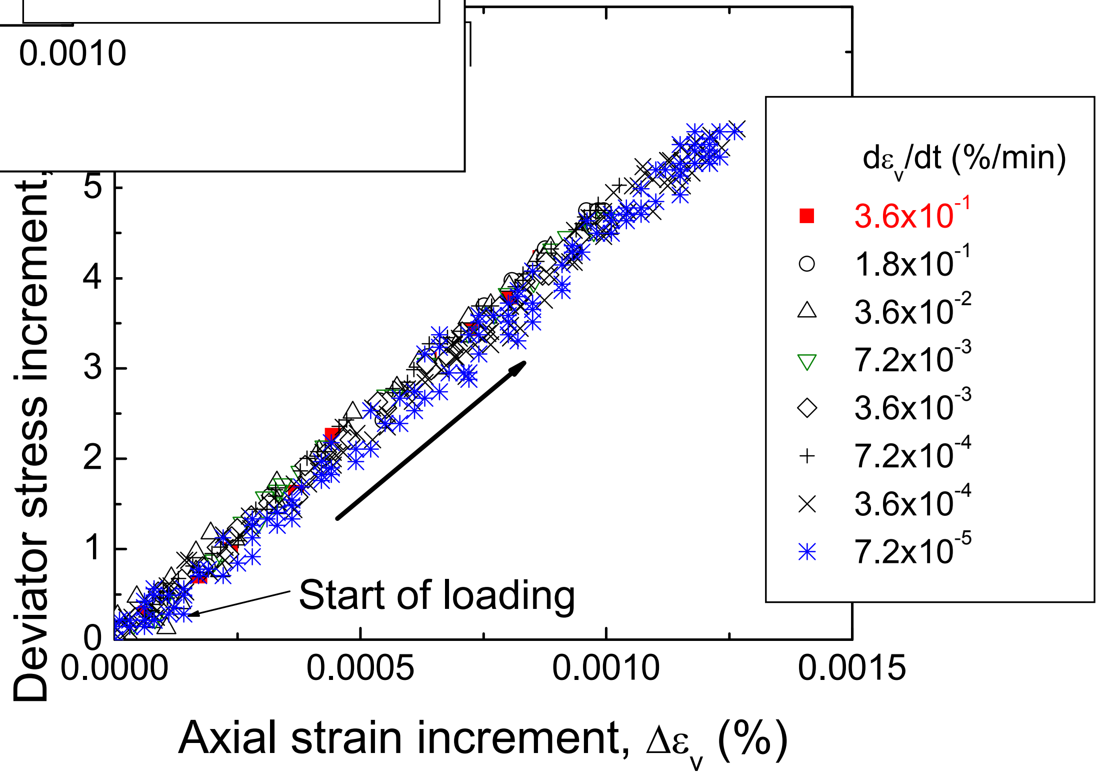


Well-compacted air-dried Chiba gravel (crushed well-graded angular sandstone from a quarry); D_{max}= 38 mm, D_{50}= 3.5 mm & U_c= 12.75



- Cyclic triaxial tests; a very small axial strain amplitude (about 0.001 %)



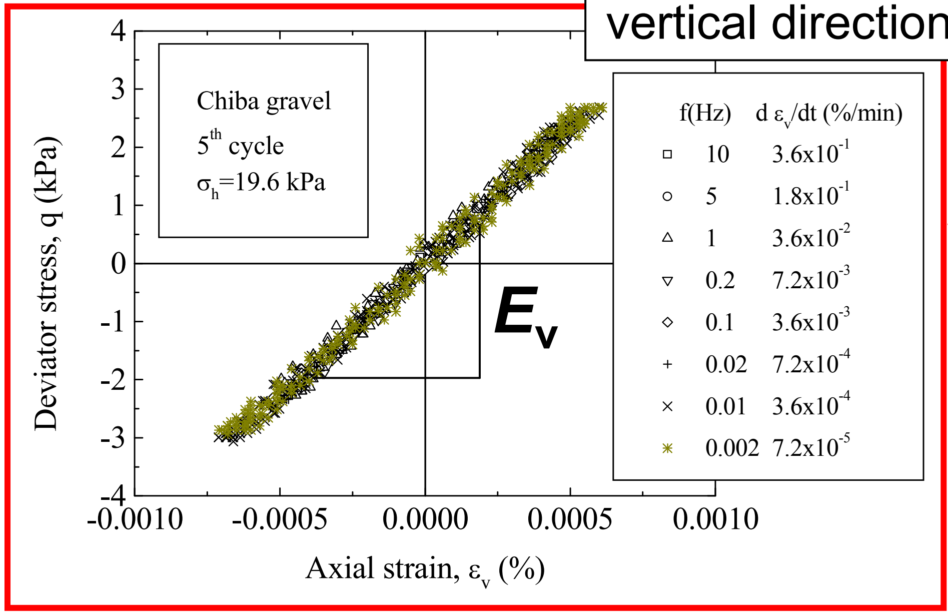


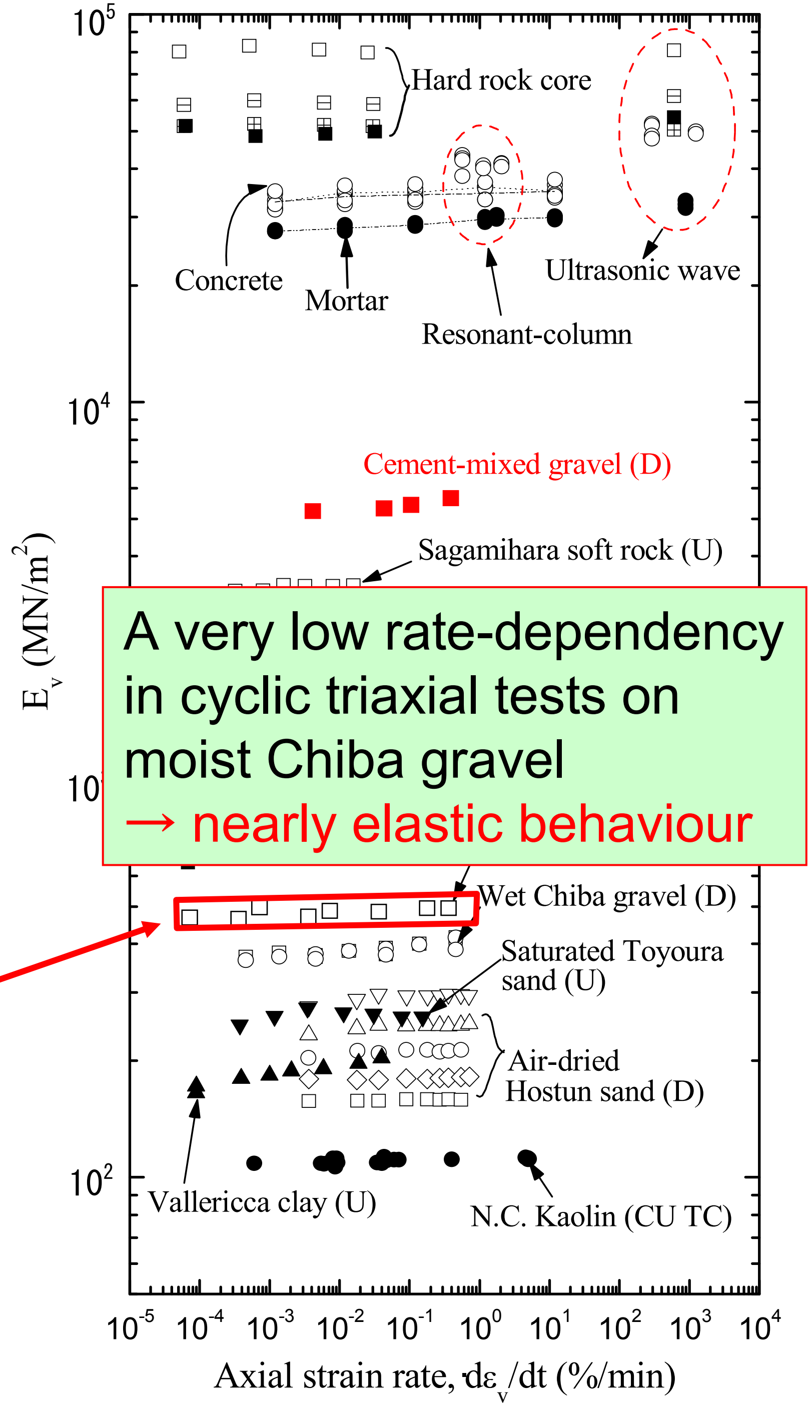
Nearly no rate effects for largely different loading frequencies (by a factor up to 5,000 times)

- Relationships between E_v at strain of 0.001 % or less and axial strain rate of hardrock cores; mortar & concrete; sedimentary softrock; cement-mixed gravel; gravel; sand; & clay by static tests (mostly) & dynamic tests (partly)

→Generally very small rate-dependency, but some details …….

E_v= "E_0 in the vertical direction"

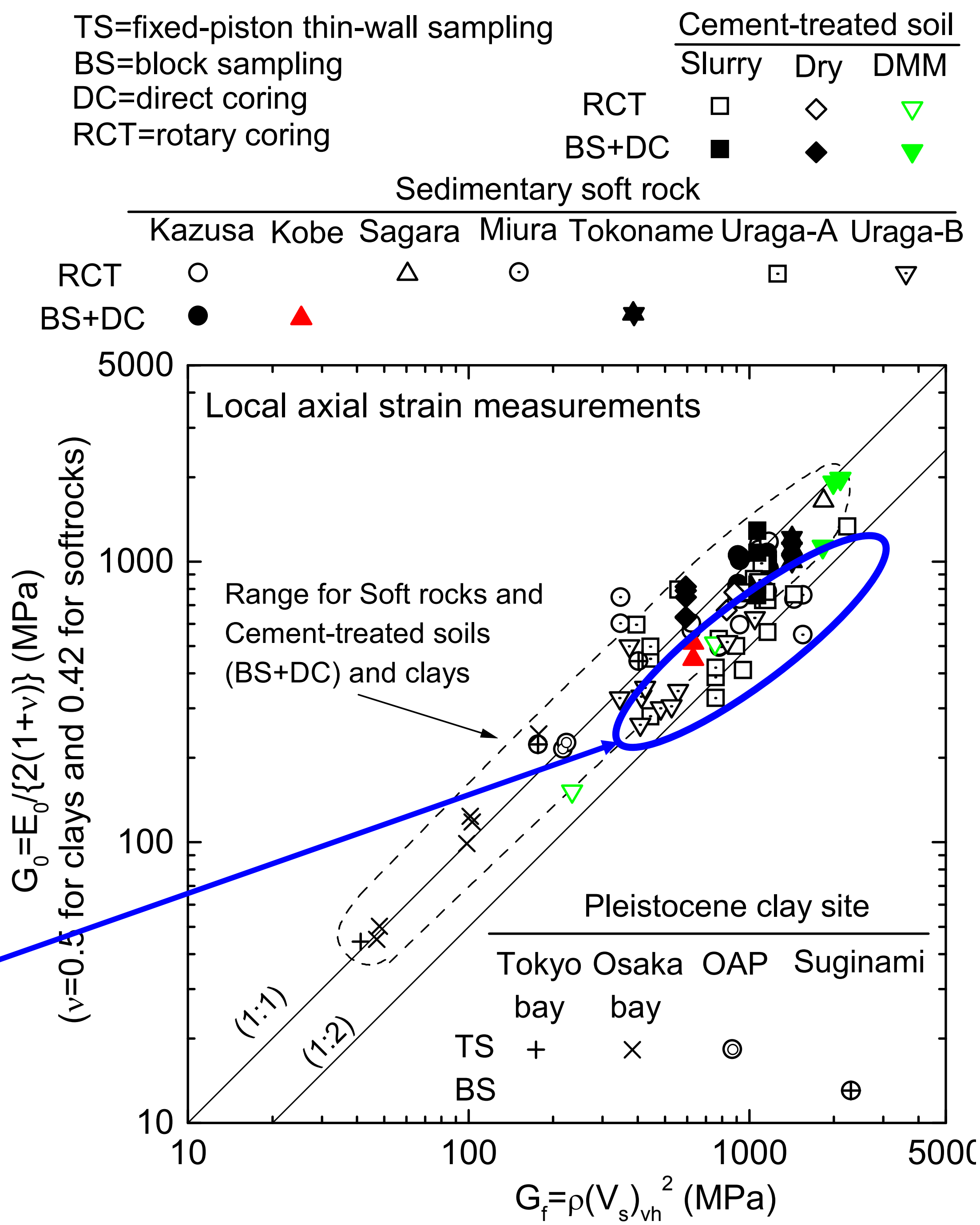




A very low rate-dependency in cyclic triaxial tests on moist Chiba gravel

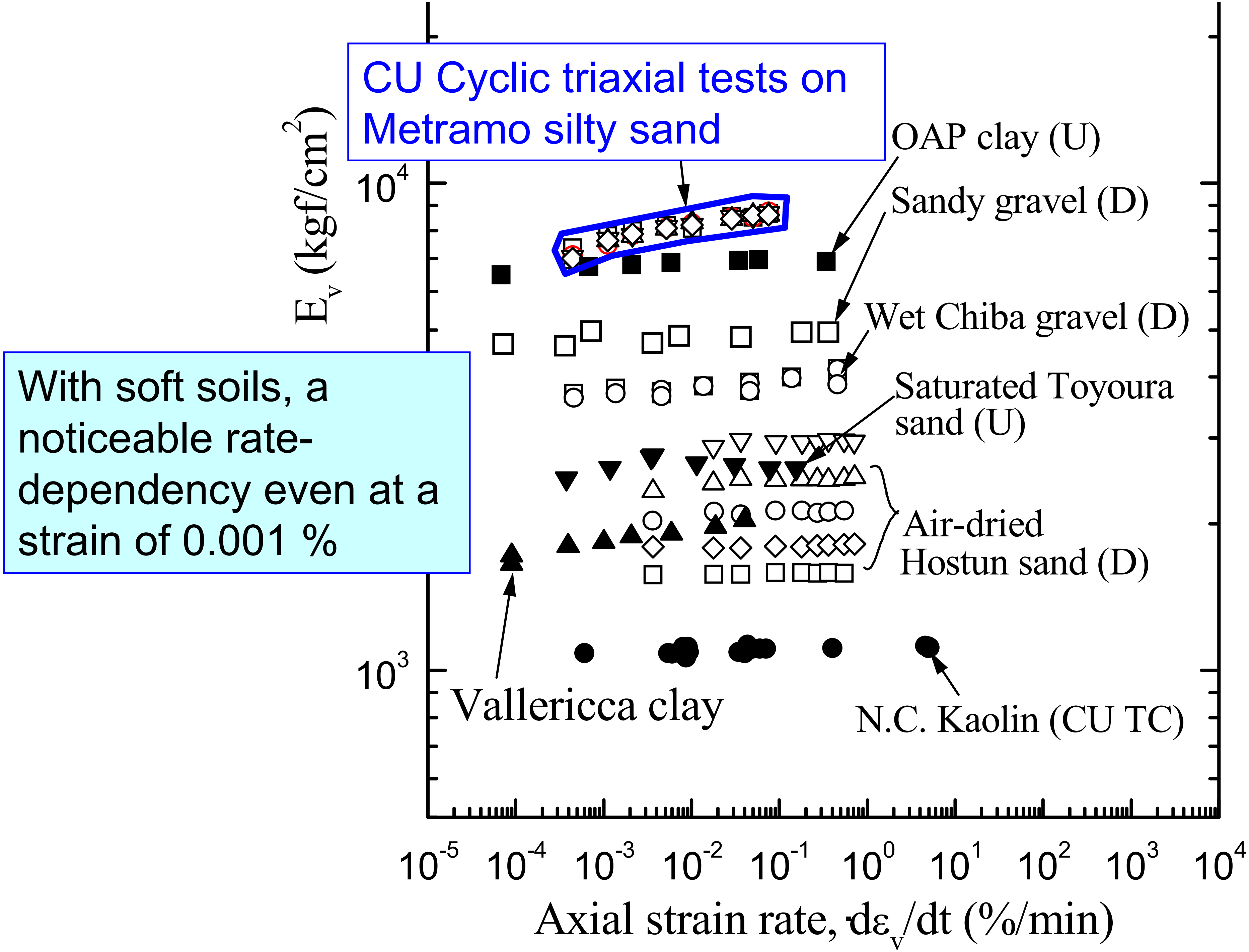
→ nearly elastic behaviour

A large number of data sets show that "the shear modulus at very small strain, G_0, of high-quality undisturbed samples by triaxial tests" is essentially the same with "G_f from field V_s" evaluated under otherwise the same conditions.

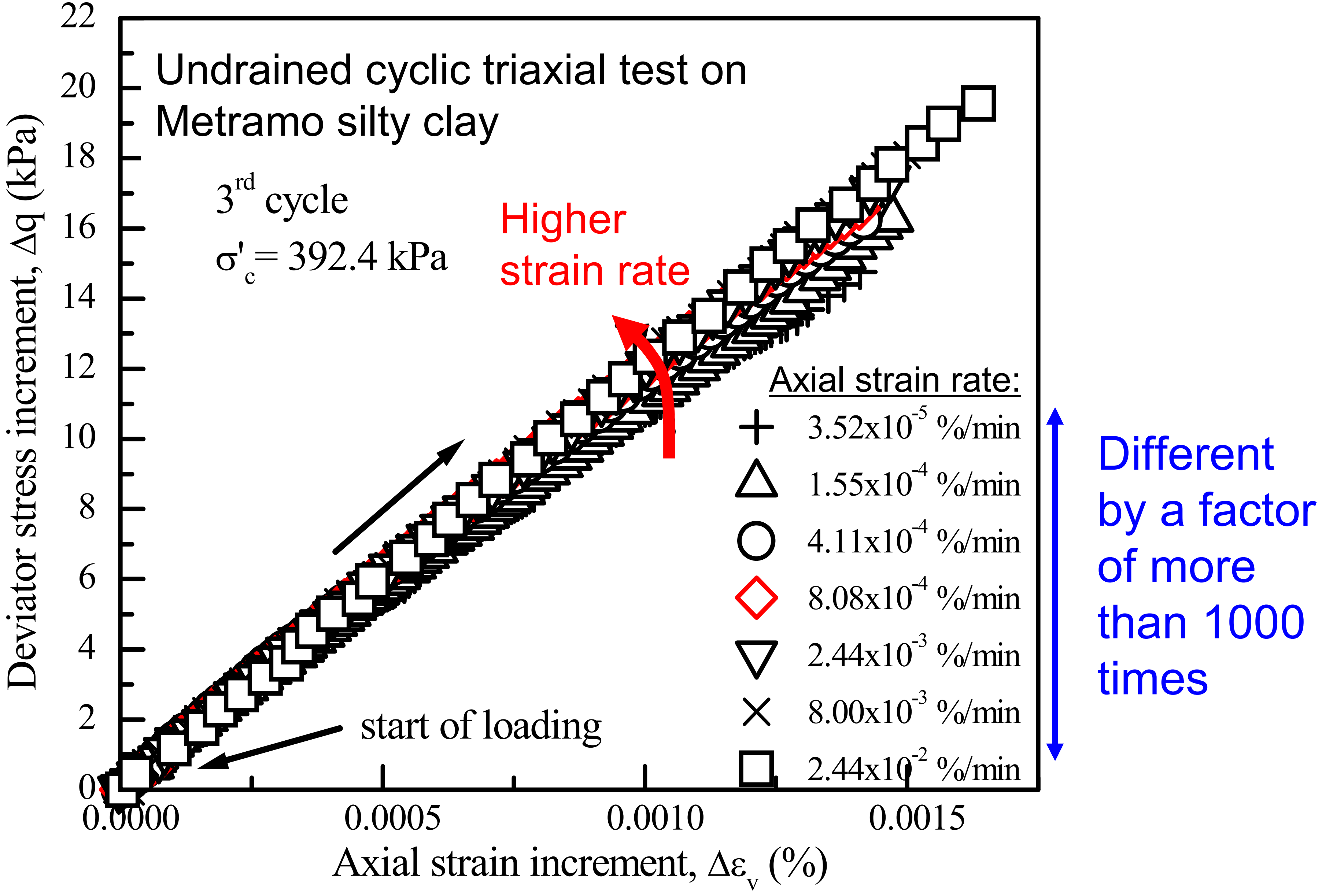


Relative low G_0 of RCT samples due to sample disturbance

(Tatsuoka et al., 1999a&b)

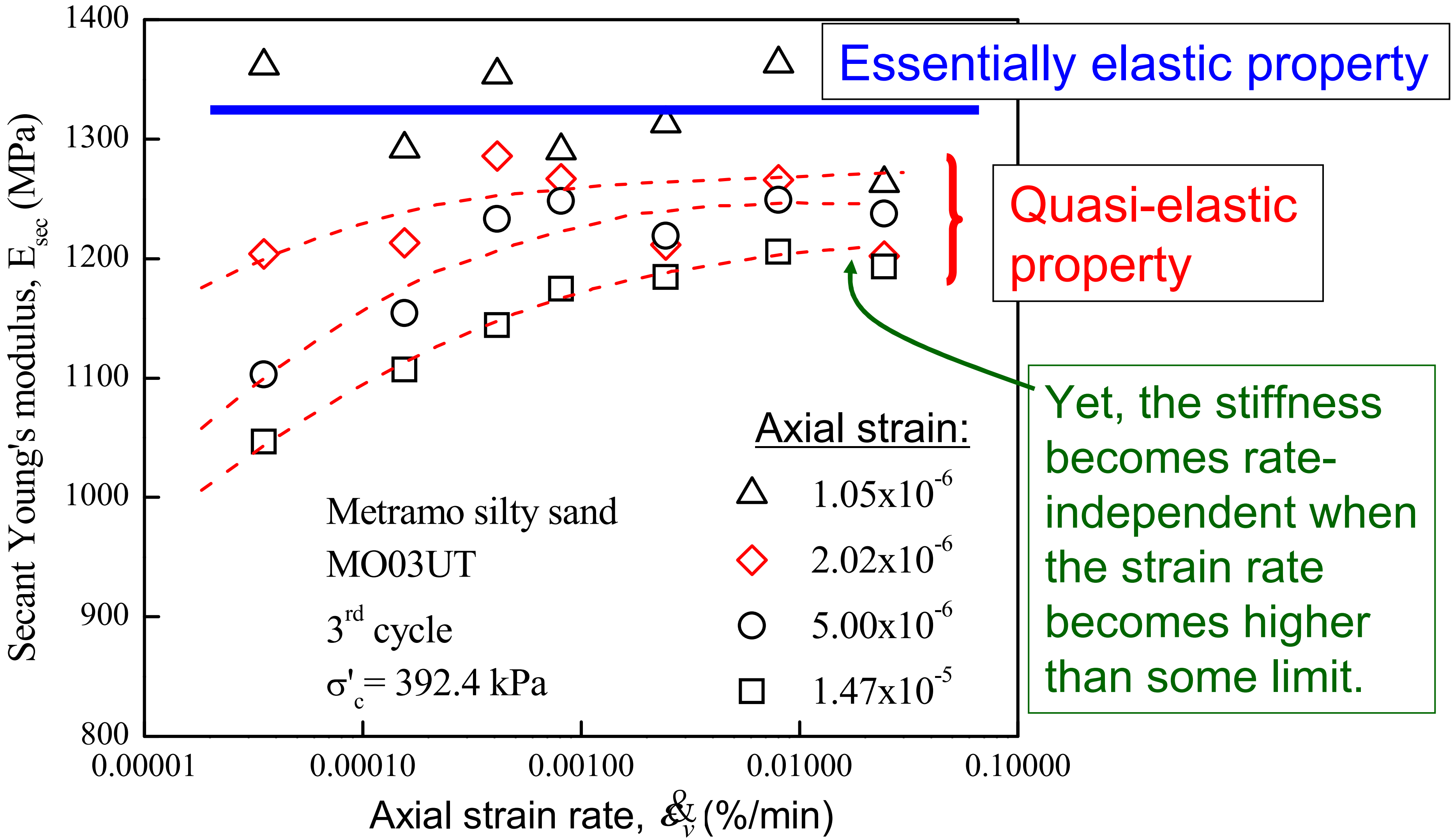

CU Cyclic triaxial tests on Metramo silty sand
With soft soils, a noticeable rate-dependency even at a strain of 0.001 %
E_v (kgf/cm^2)
10^4
10^3
OAP clay (U)
Sandy gravel (D)
Wet Chiba gravel (D)
Saturated Toyoura sand (U)
Air-dried Hostun sand (D)
Vallericca clay
N.C. Kaolin (CU TC)
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4}
Axial strain rate, $d\varepsilon_v/dt$ (%/min)

"More linear stress-strain relations" at higher strain rates

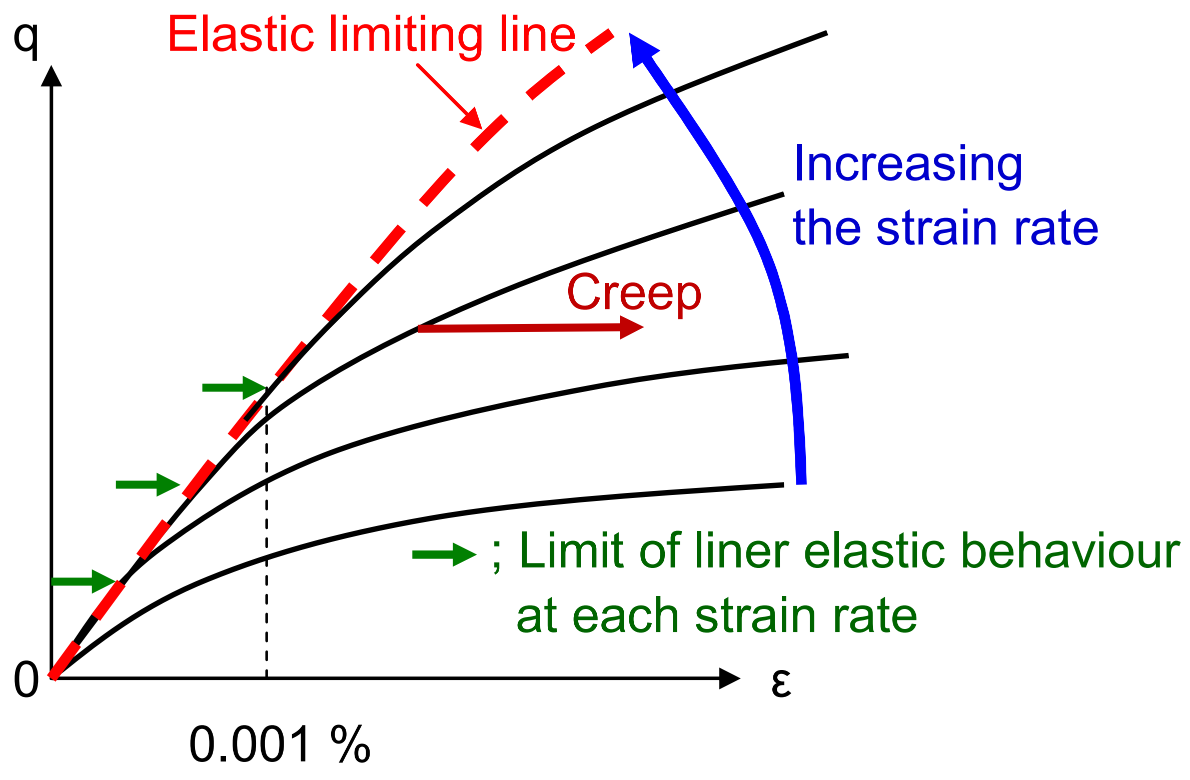


(Santucci de Magistris et al., 1999)

Essentially rate-independent & reversible (i.e., elastic) stress-strain behaviour at strains about 0.0001 % !
More rate-dependent behaviour at larger strains !



(Santucci de Magistris et al., 1999)



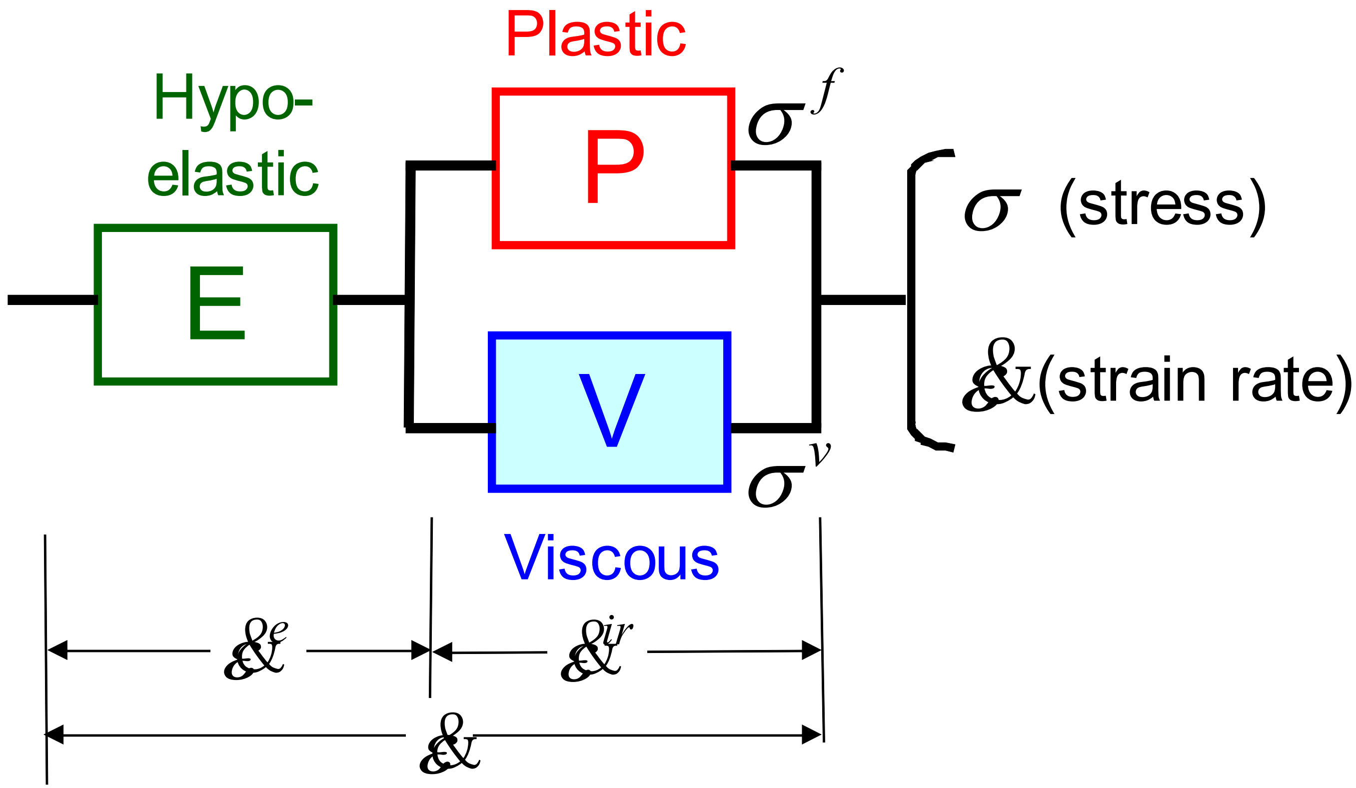
General trends of behaviour:

1. The stress-strain relation approaches the elastic limiting line as the strain rate increases.
2. The elastic zone becomes larger as the strain rate increases.
3. The elastic zone disappears at very low strain rates.

These trends can be described by the non-linear three-component model.

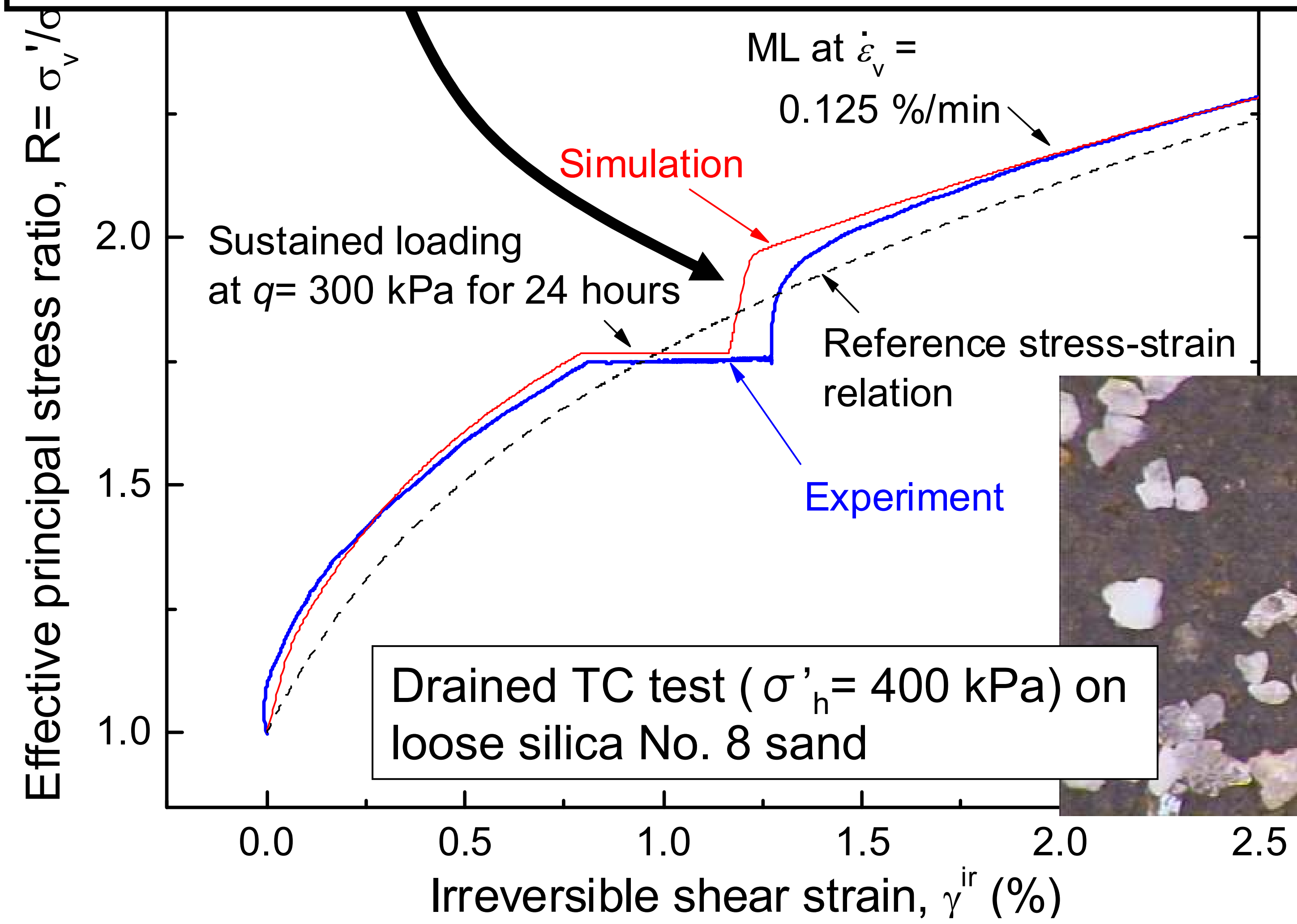
The test results are interpreted and simulated by:

the non-linear three-component model (Di Benedetto & Tatsuoka, 1997; Di Benedetto et al., 2002; Tatsuoka et al., 2002, 2008)



A large quasi-elastic zone develops upon the restart of ML at a constant strain rate after creep deformation.

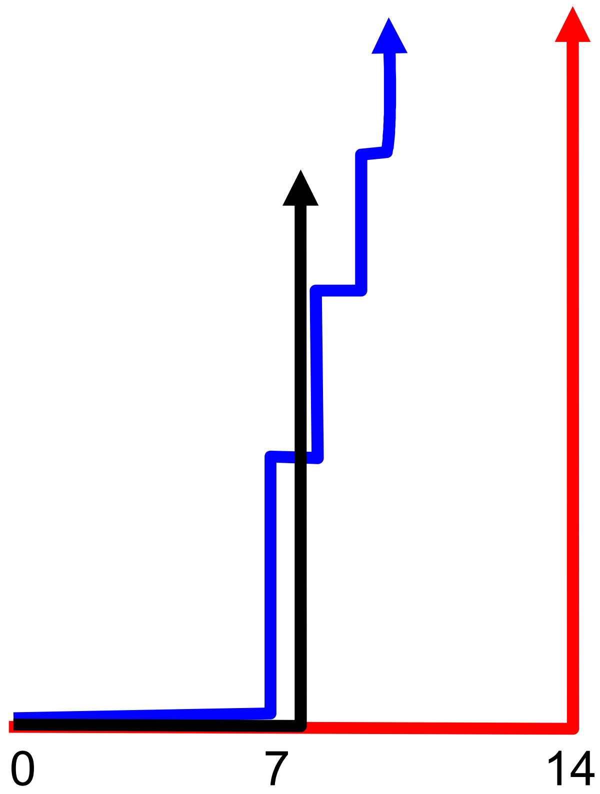
■ The size becomes larger with an increase in the creep strain and the strain rate during ML.



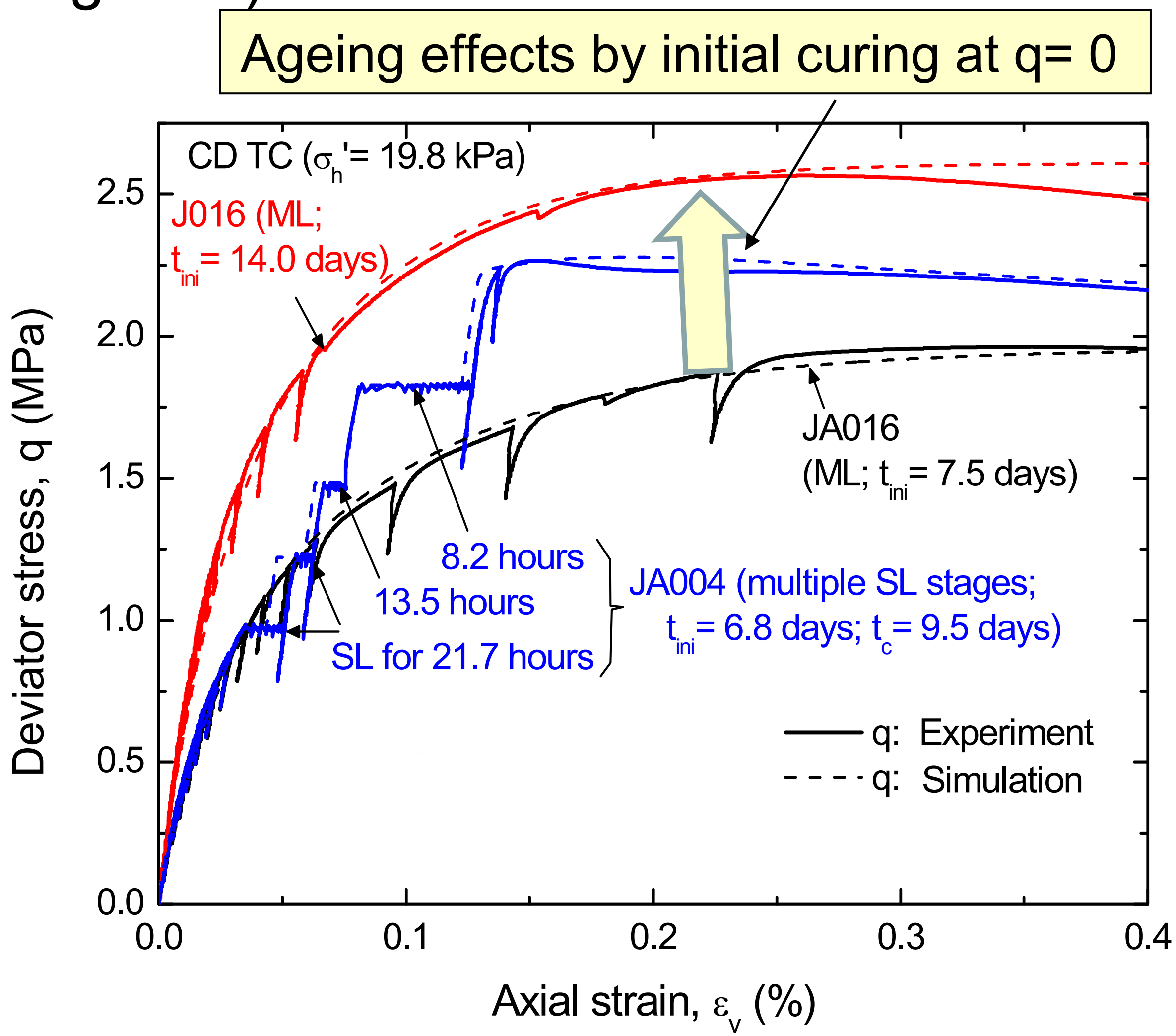
(Kiyota & Tatsuoka, 2006, *S&F*; Tatsuoka et al., 2008a, *S&F*)

Multiple large quasi-elastic zones develop by ageing effects (i.e., bonding) in addition to creep deformation;
drained TC tests on compacted moist cement-mixed well-graded gravelly soil (model Chiba gravel)

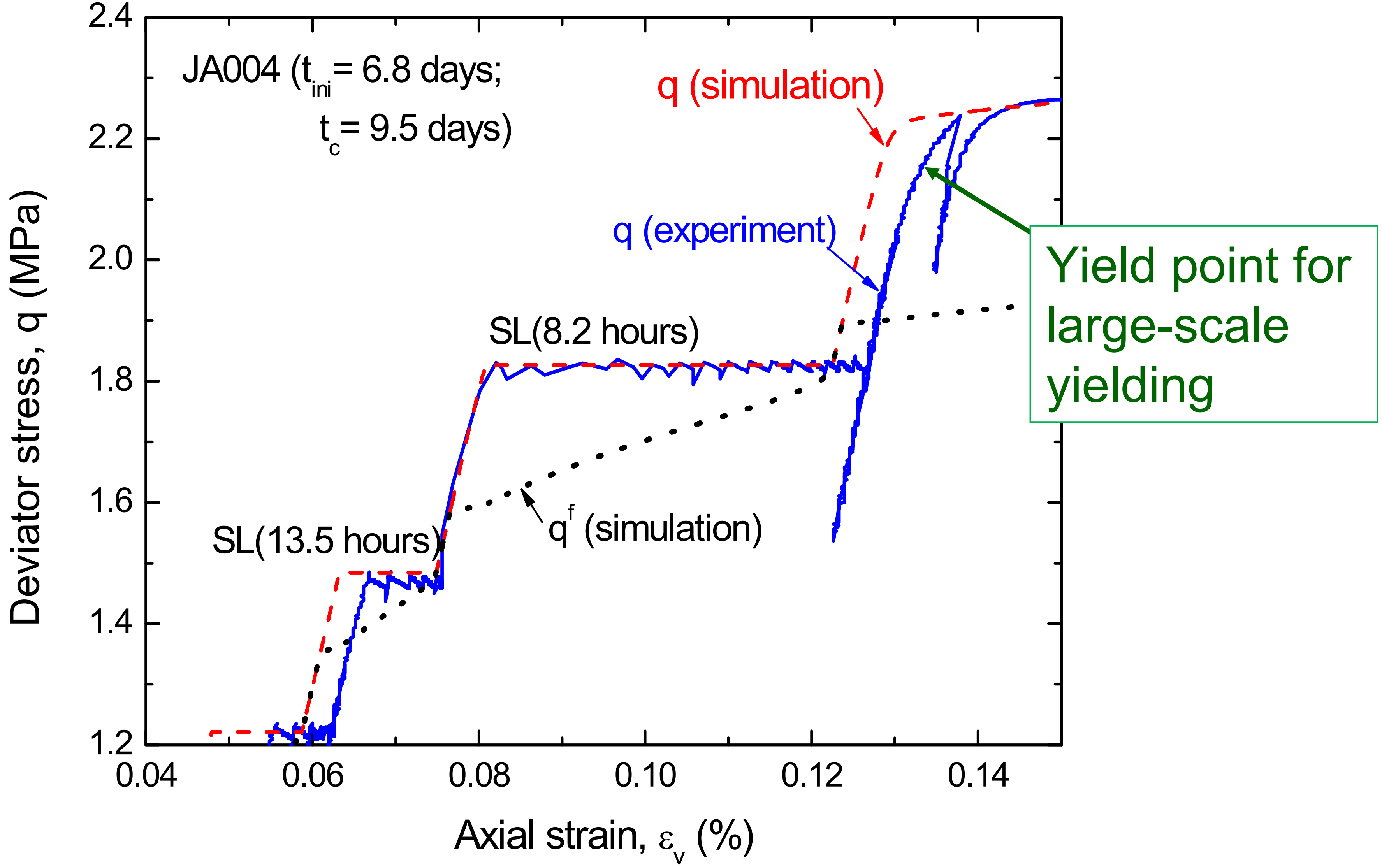
Loading histories



(Tatsuoka et al. 2008b, *S&F*)

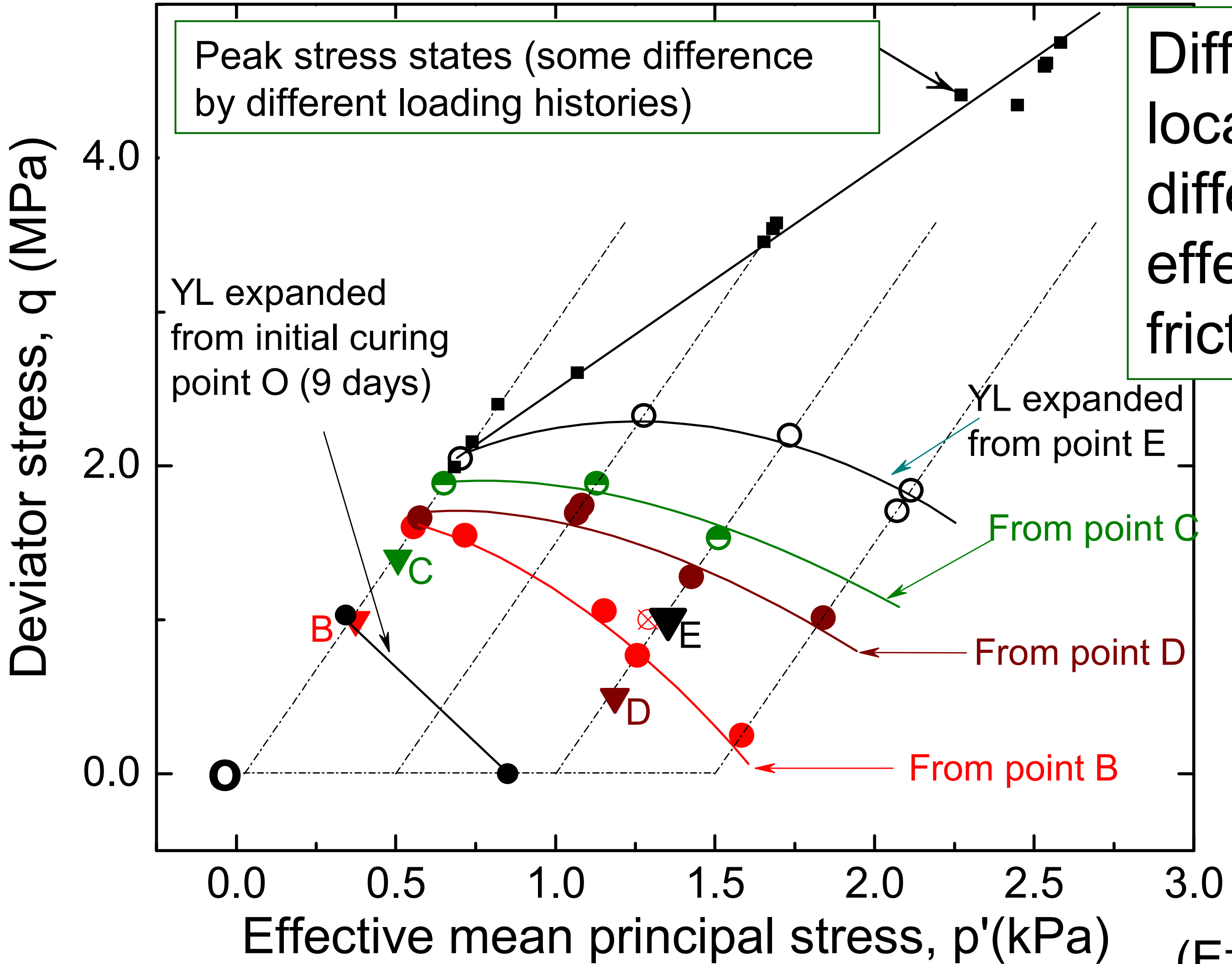


Kinematic development of quasi-elastic zone by ageing effects in addition to creep deformation at multiple stress states



(Tatsuoka et al. 2008b, *S&F*)

Kinematic development of yield locus by ageing and creep:
- initial curing for 9 days at stress point **O**; and
- initial curing for 7 days at **O** + re-curing for 2 days at stress points B, C, D & E (cement-mixed model Chiba gravel)



Different shapes and locations of YL by different combined effects of bonding & friction mechanisms !

(Ezaoui et al. 2010, *S&F*)

Rate-independent behaviour: summary-1

1) The elastic deformation characteristics can be evaluated by not only dynamic tests but also static tests.

‘*Static*’ & ‘*dynamic*’: terminologies for systems,
not for material properties

Static Young’s modulus & dynamic Young’s modulus:
should not be used.

Static and dynamic measurements of Young’s modulus: OK !

Rate-independent behaviour: summary-2

2) Statically and dynamically measured elastic deformation properties are essentially the same with fine-grained geomaterials.

With heterogeneous materials (e.g., concrete, very coarse-grained geomaterials and hard rocks having dominant discontinuities), the elastic modulus from wave velocity with a short wave length could be significantly larger than the statically determined average value of a given mass.

3) The size of quasi-elastic zone increases with an increase in:

i) the strain rate and the creep strain (due to the viscous properties); and

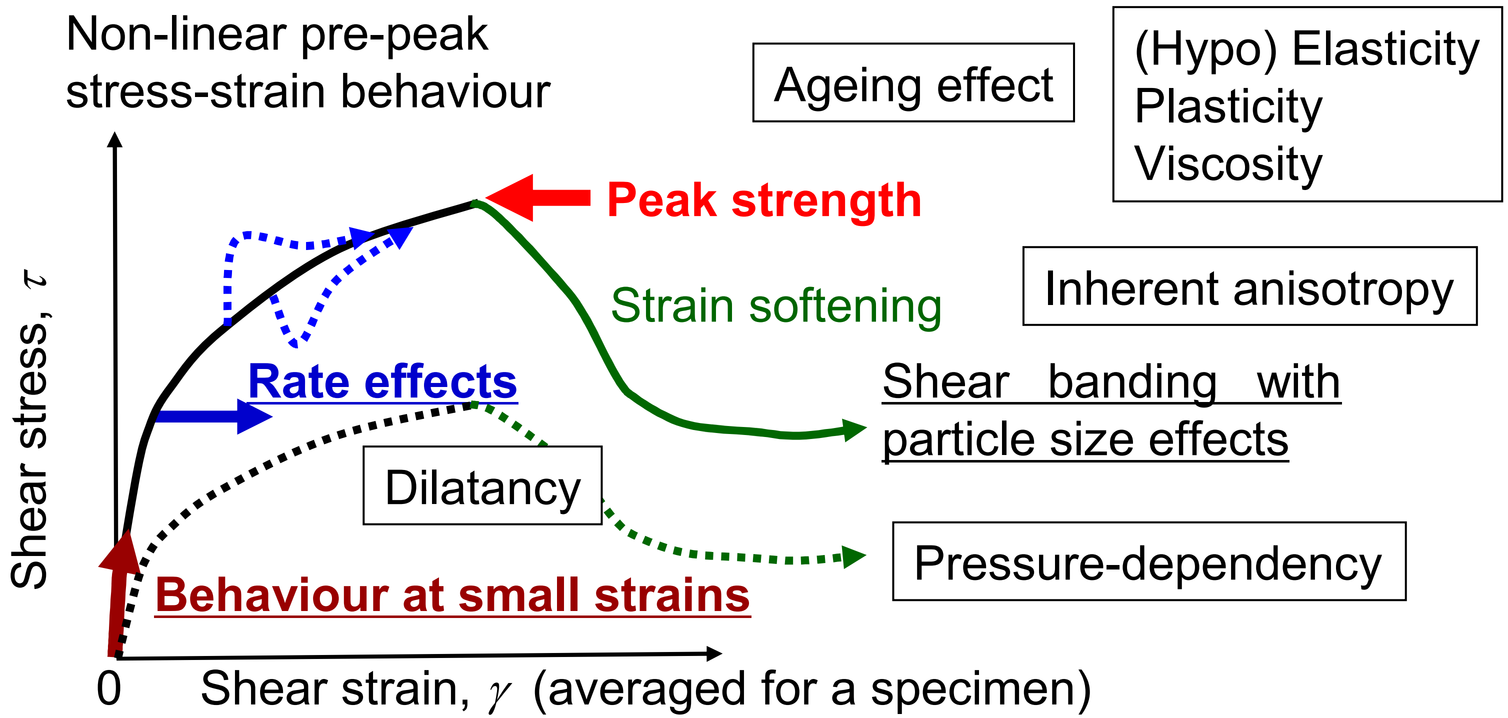
ii) ageing effect.

1) quasi-elastic stress-strain behaviour;

2) rate-dependent stress-strain behaviour; and

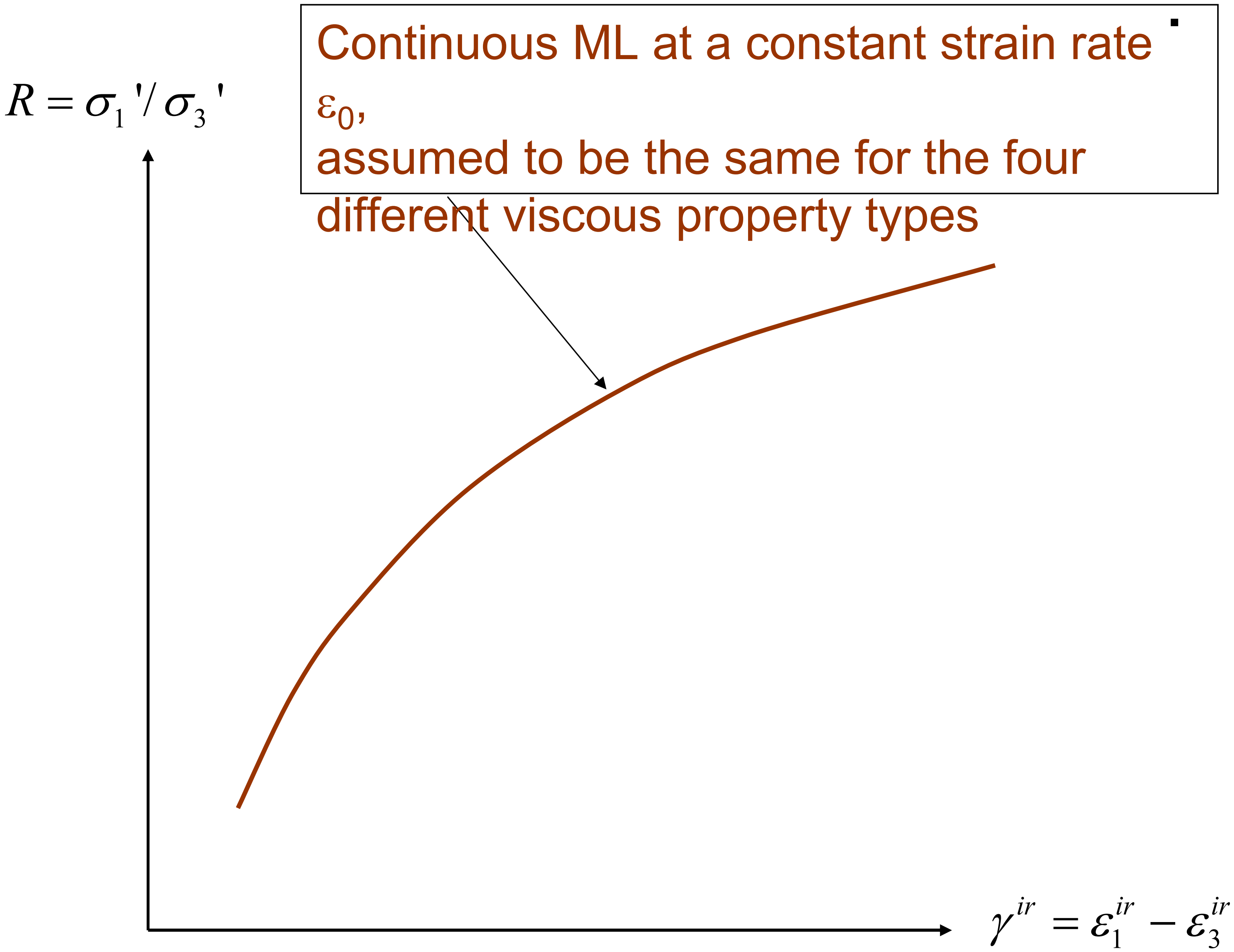
3) strength and stiffness of compacted soil related to
field fill compaction control and design;

among other many important topics.



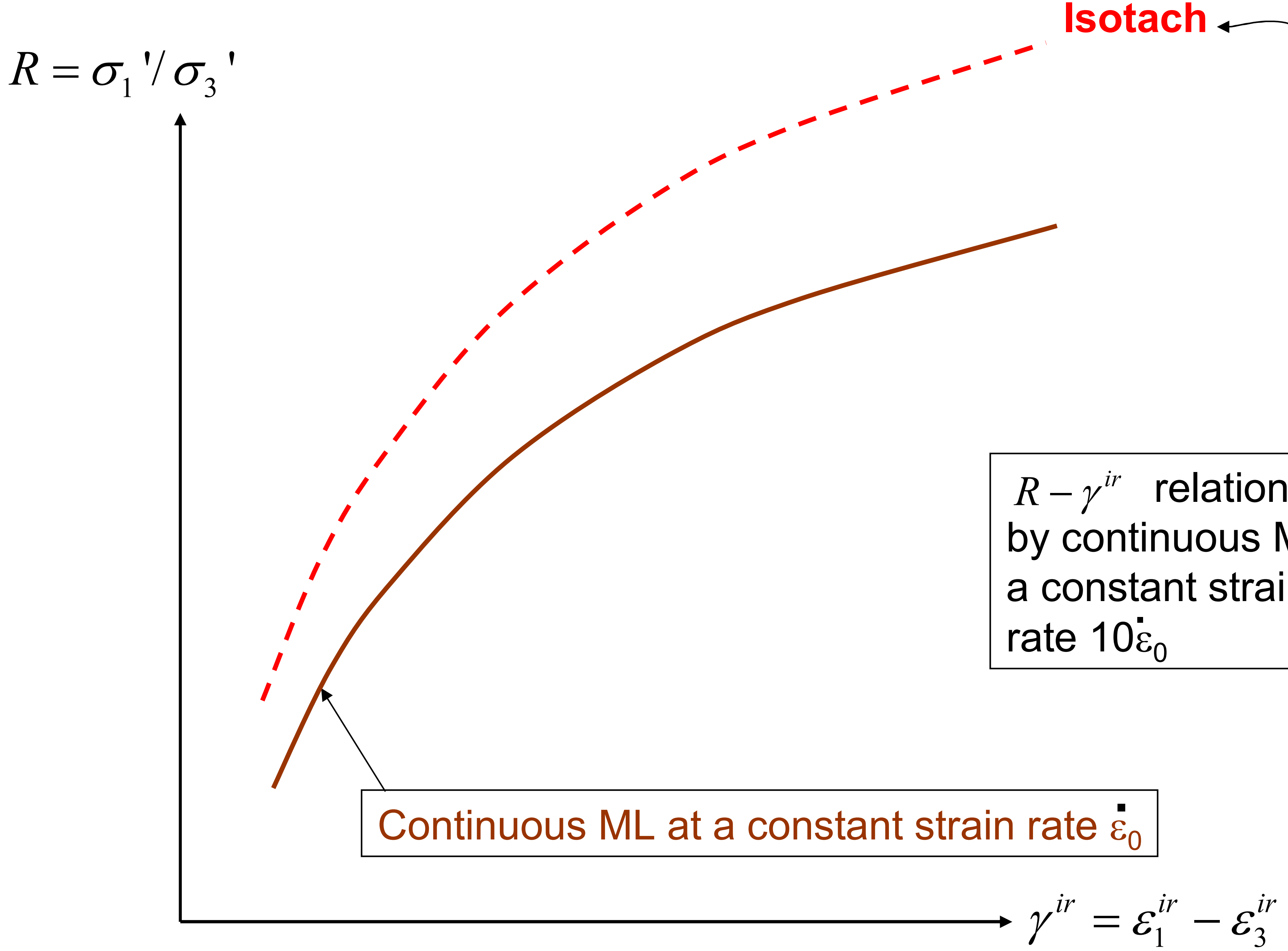
Rate-dependent stress-strain behaviour

- **Isotach and non-Isotach types in drained TC**
- Viscous behaviour of sand in direct shear
- Viscous behaviour of clay in 1D compression
- Mechanism of non-Isotach viscous behaviour
- Rate-sensitivity and viscosity type parameter
- Creep and stress relaxation
- Summary

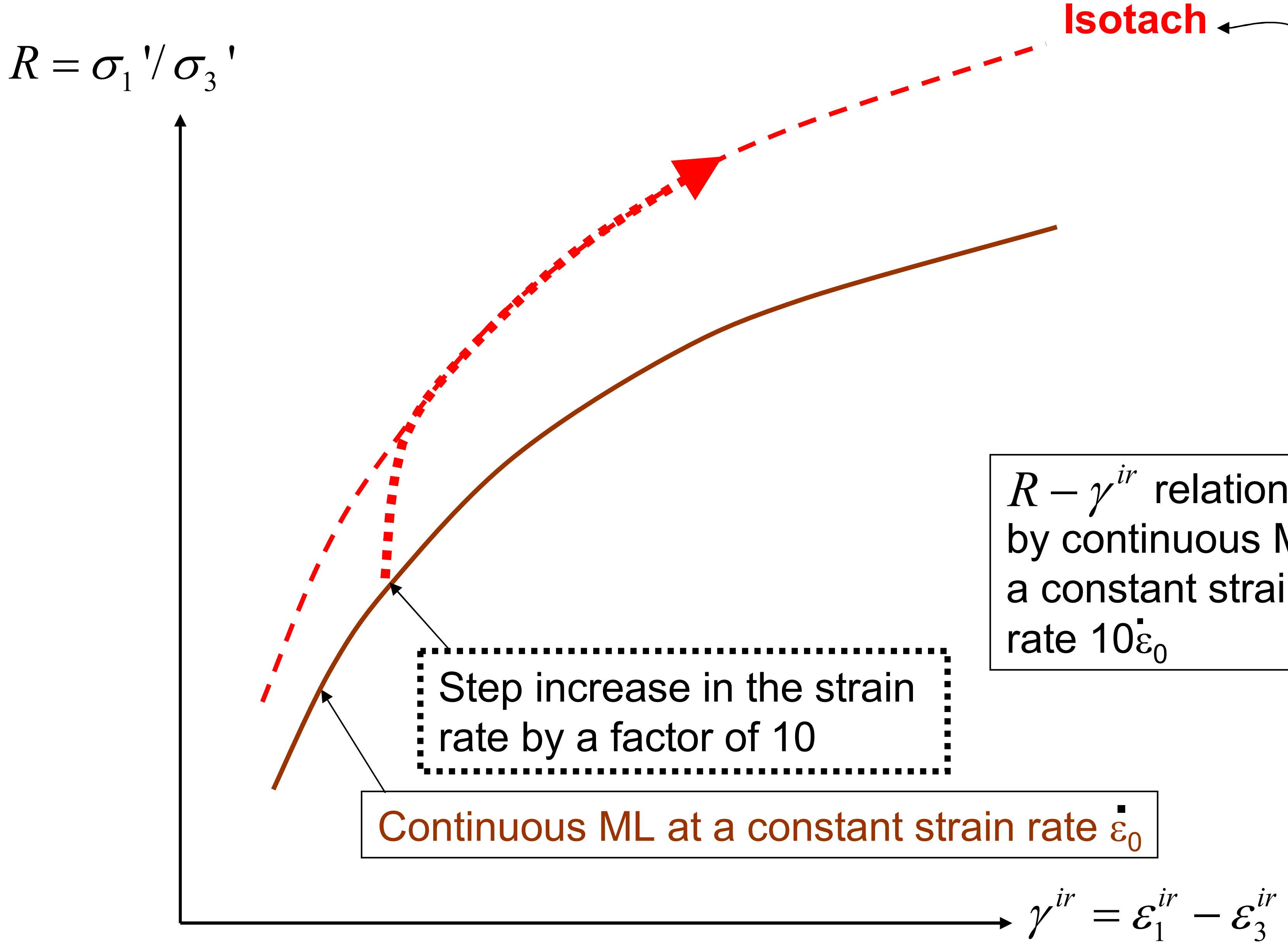


$R = \sigma_1'/\sigma_3'$
Continuous ML at a constant strain rate $\dot{\varepsilon}_0$,
assumed to be the same for the four different viscous property types
$\gamma^{ir} = \varepsilon_1^{ir} - \varepsilon_3^{ir}$

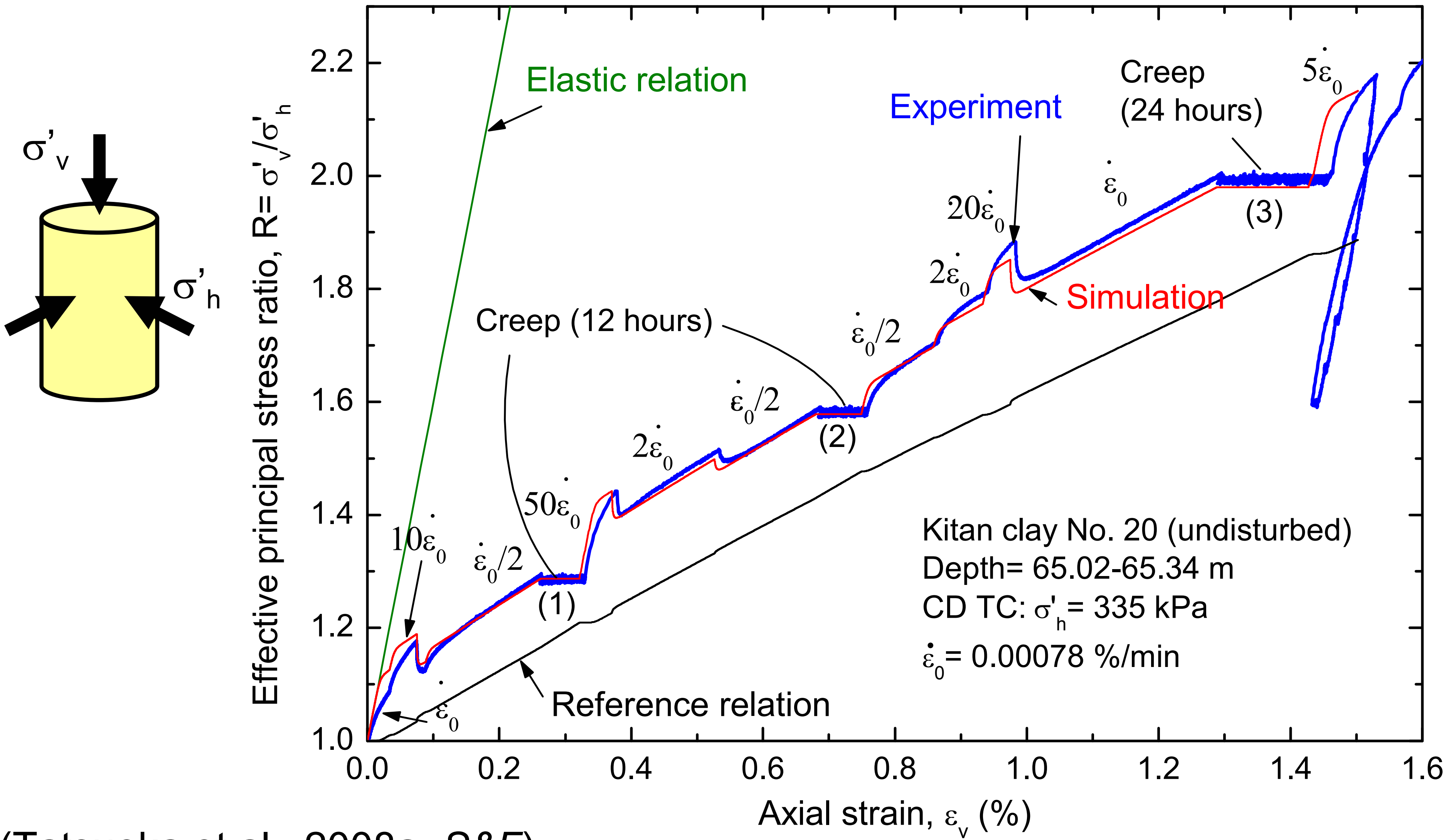
Isotach type: the strength during ML at constant strain rate <u>increases</u> with an <u>increase</u> in the strain rate; and......



The current stress is a unique function of instantaneous strain and its rate. Most classical & popular in modelling

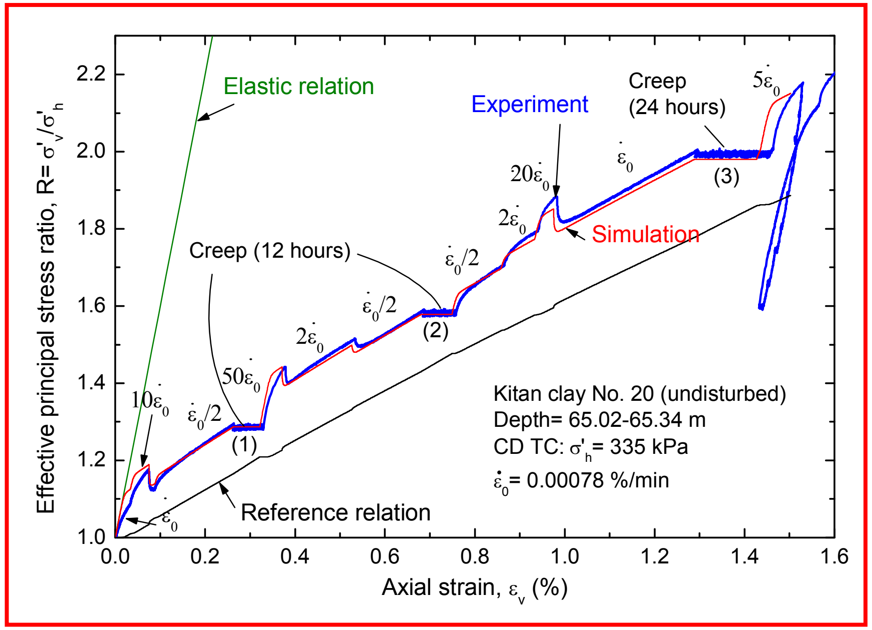


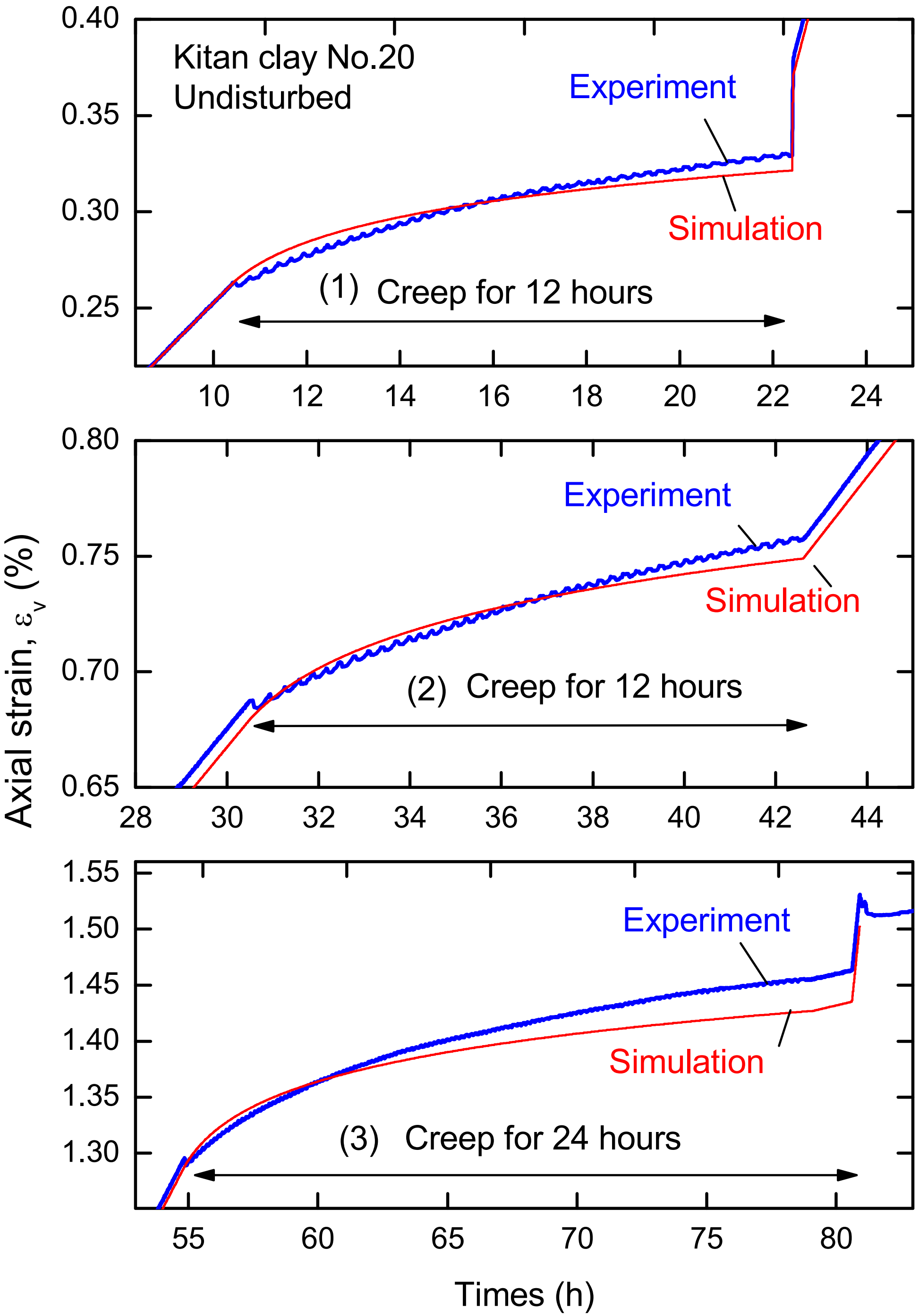
Isotach behaviour in drained TC on undisturbed Pleistocene clay (e_0= 0.81; *PI*= 41.1) and simulation



(Tatsuoka et al., 2008a, *S&F*)

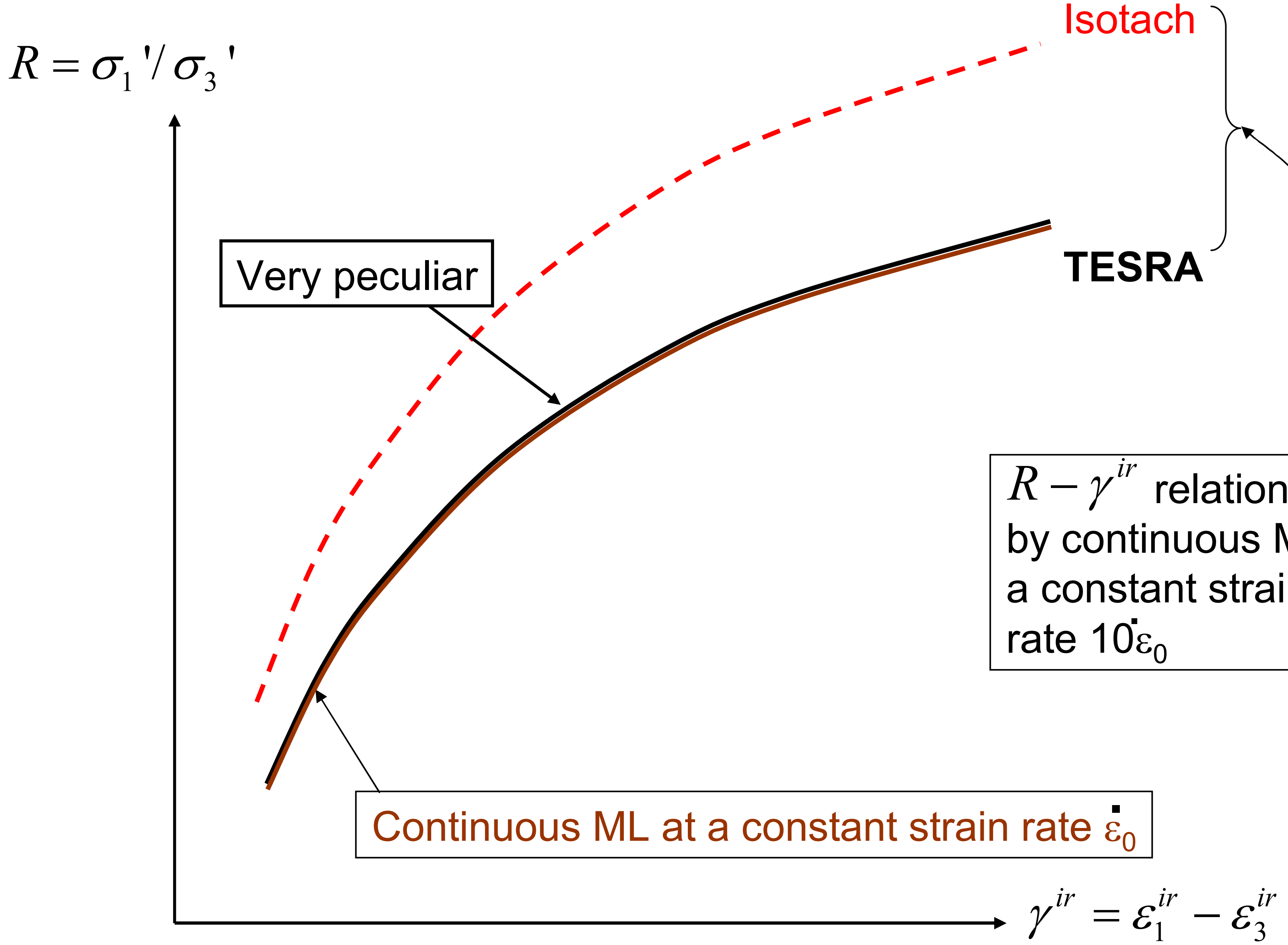
Creep deformation



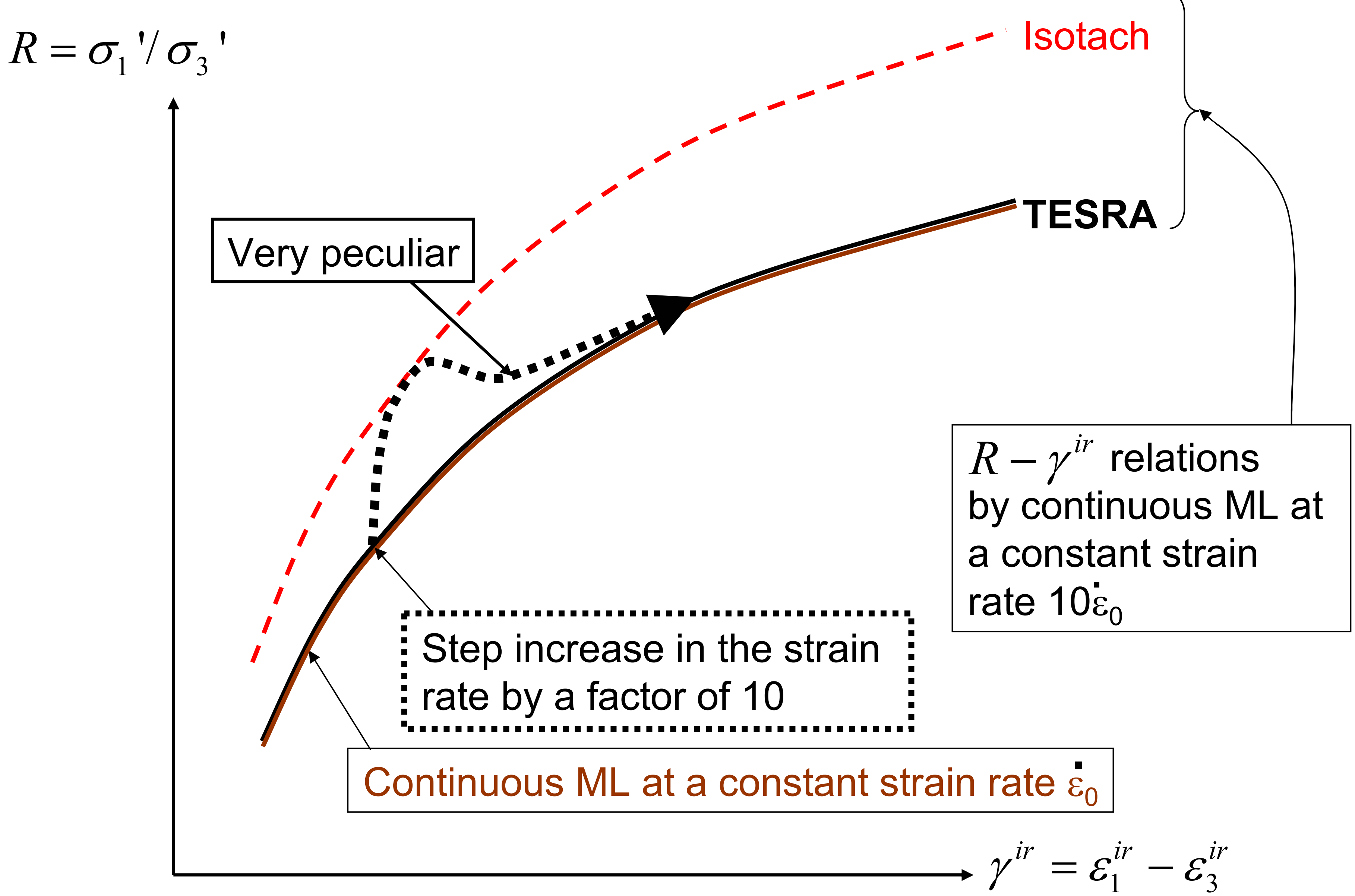


(Tatsuoka et al., 2008a, *S&F*)

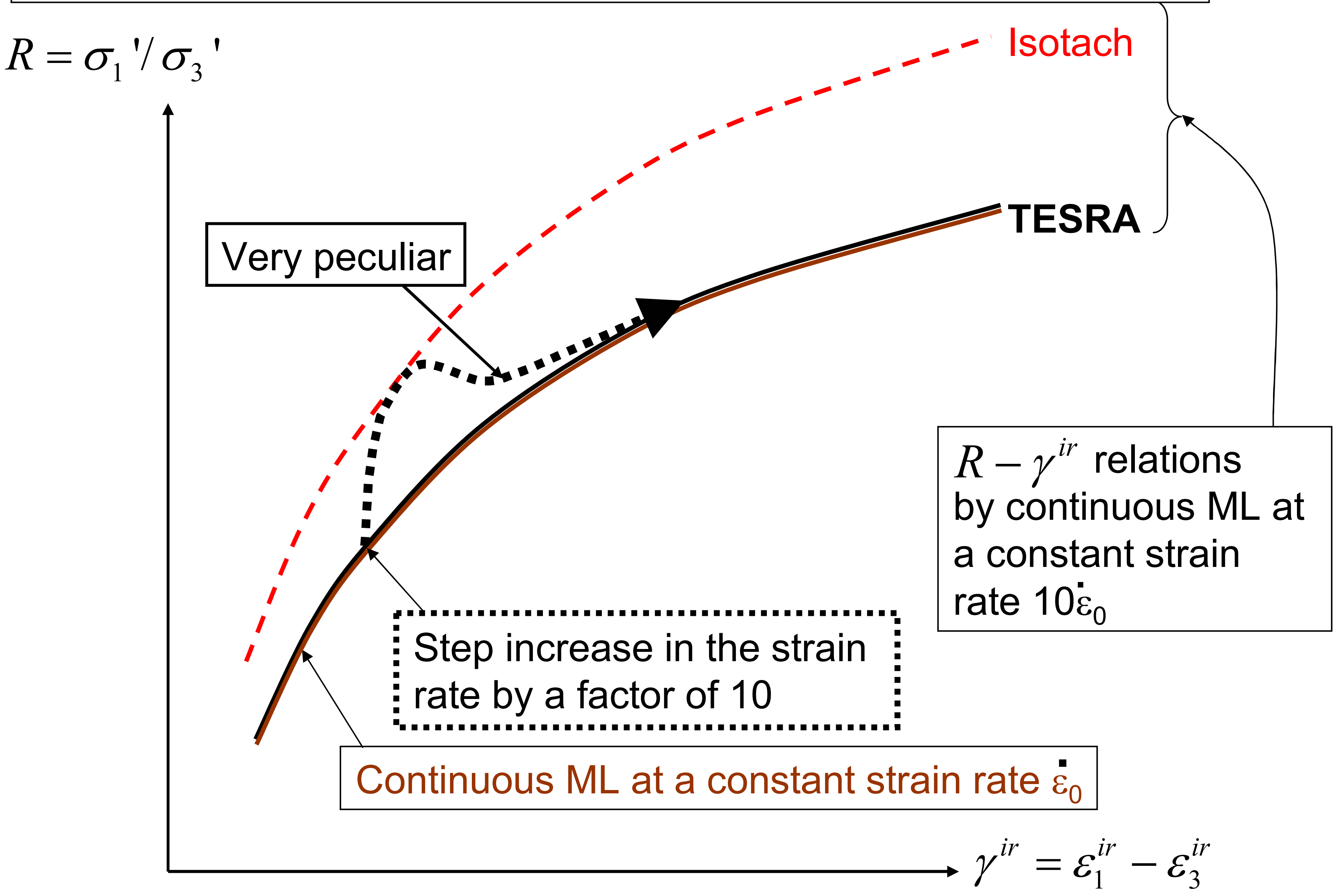
TESRA type: the strength during ML at constant strain rate is independent of strain rate; and…



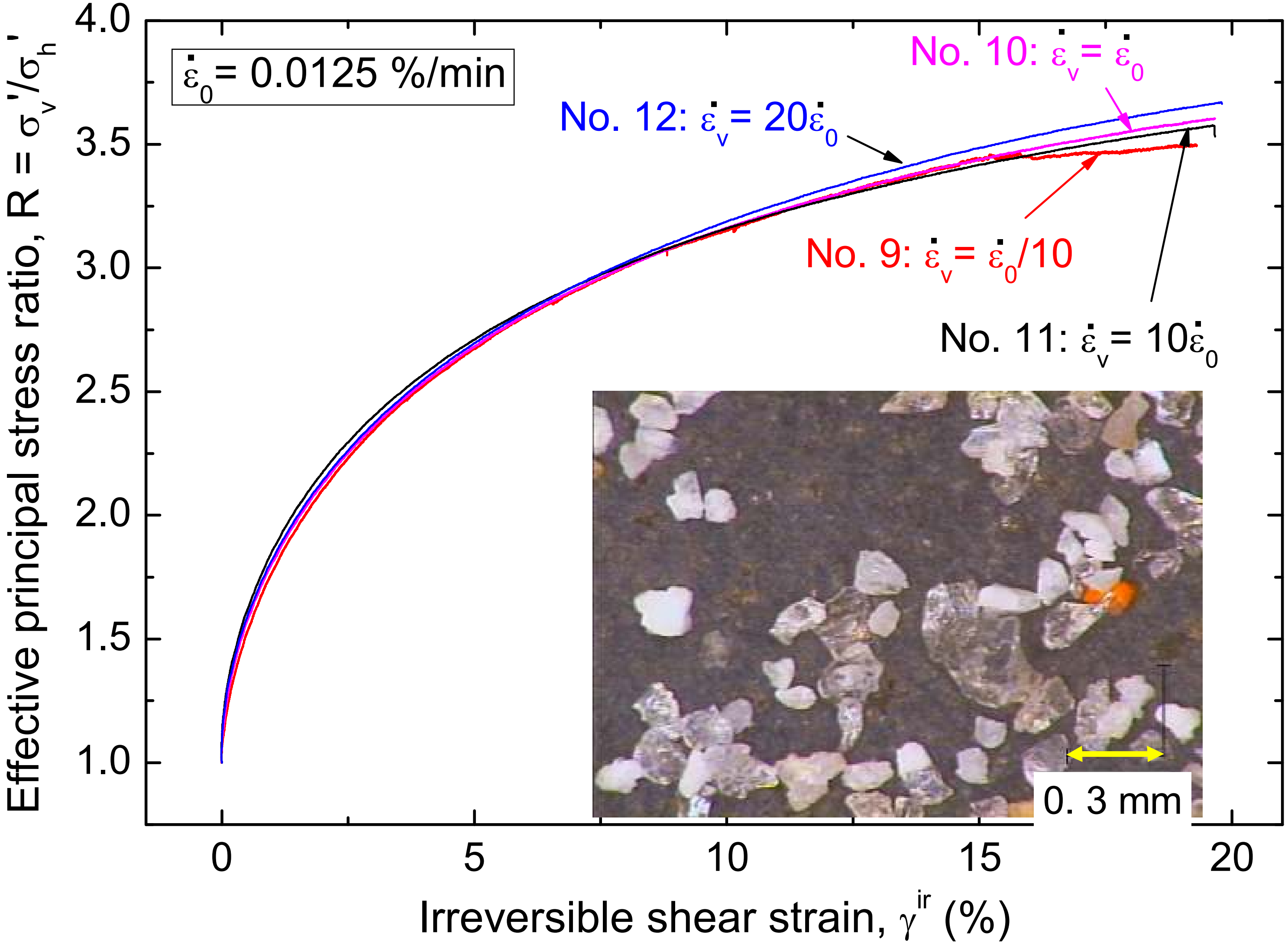
A positive stress jump upon a step increase in the strain rate decays with strain towards zero.



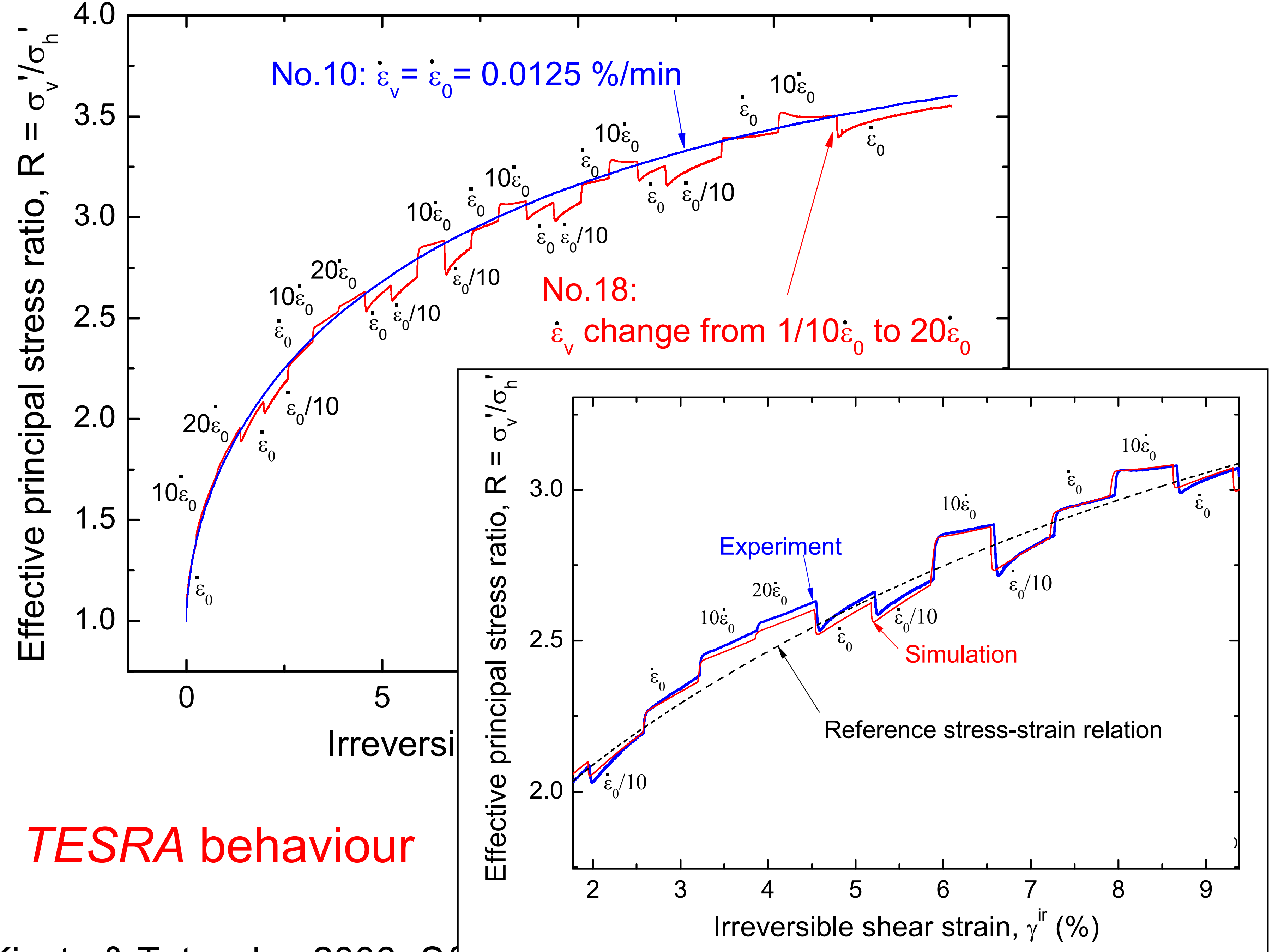
TESRA= **T**emporary **E**ffects of **S**train **R**ate and strain **A**cceleration (i.e., rate of strain rate)



TESRA behaviour in drained TC (σ'_h= 400 kPa); saturated loose Silica No. 8 sand

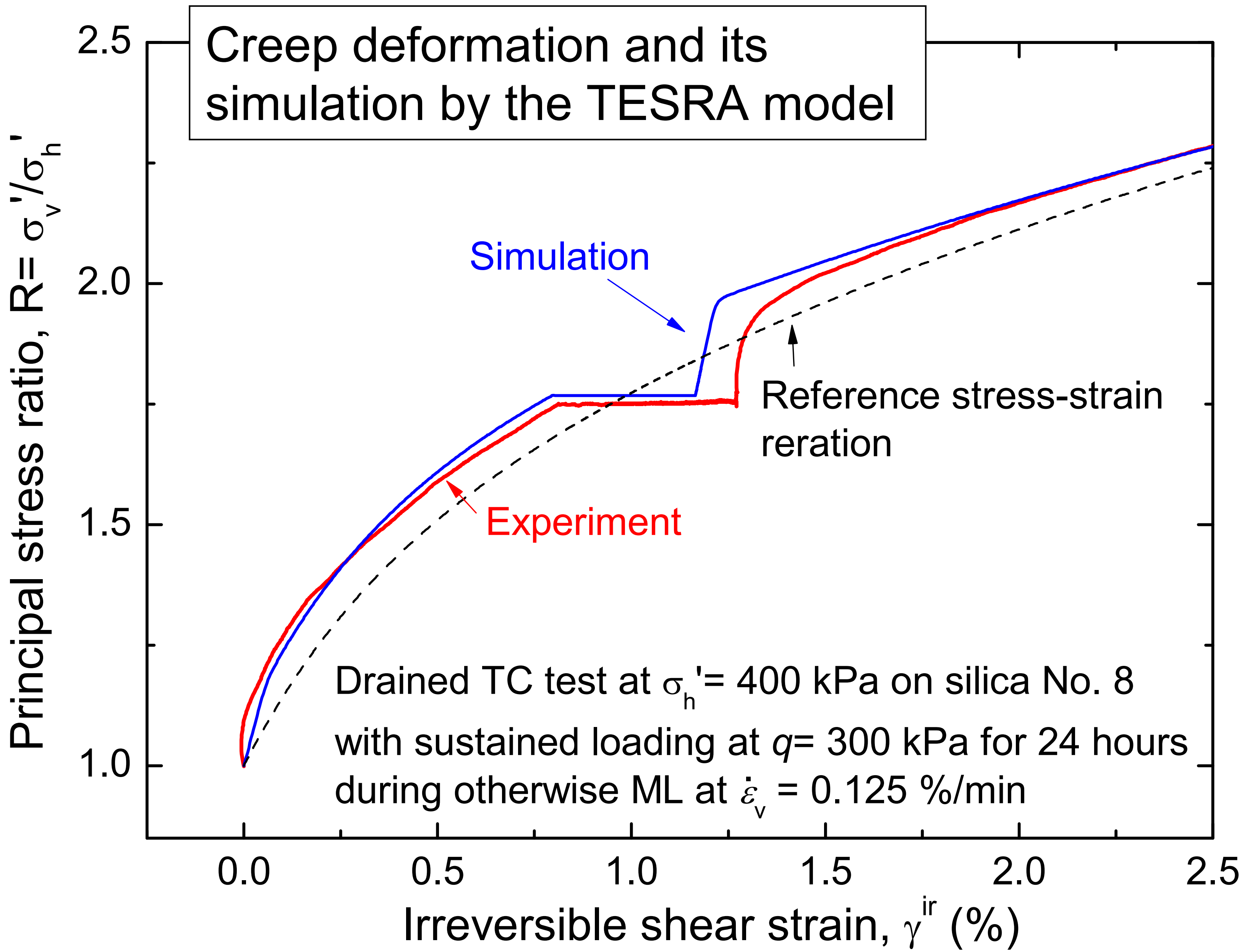


(Kiyota & Tatsuoka, 2006, *S&F*; Tatsuoka et al., 2008a, *S&F*)



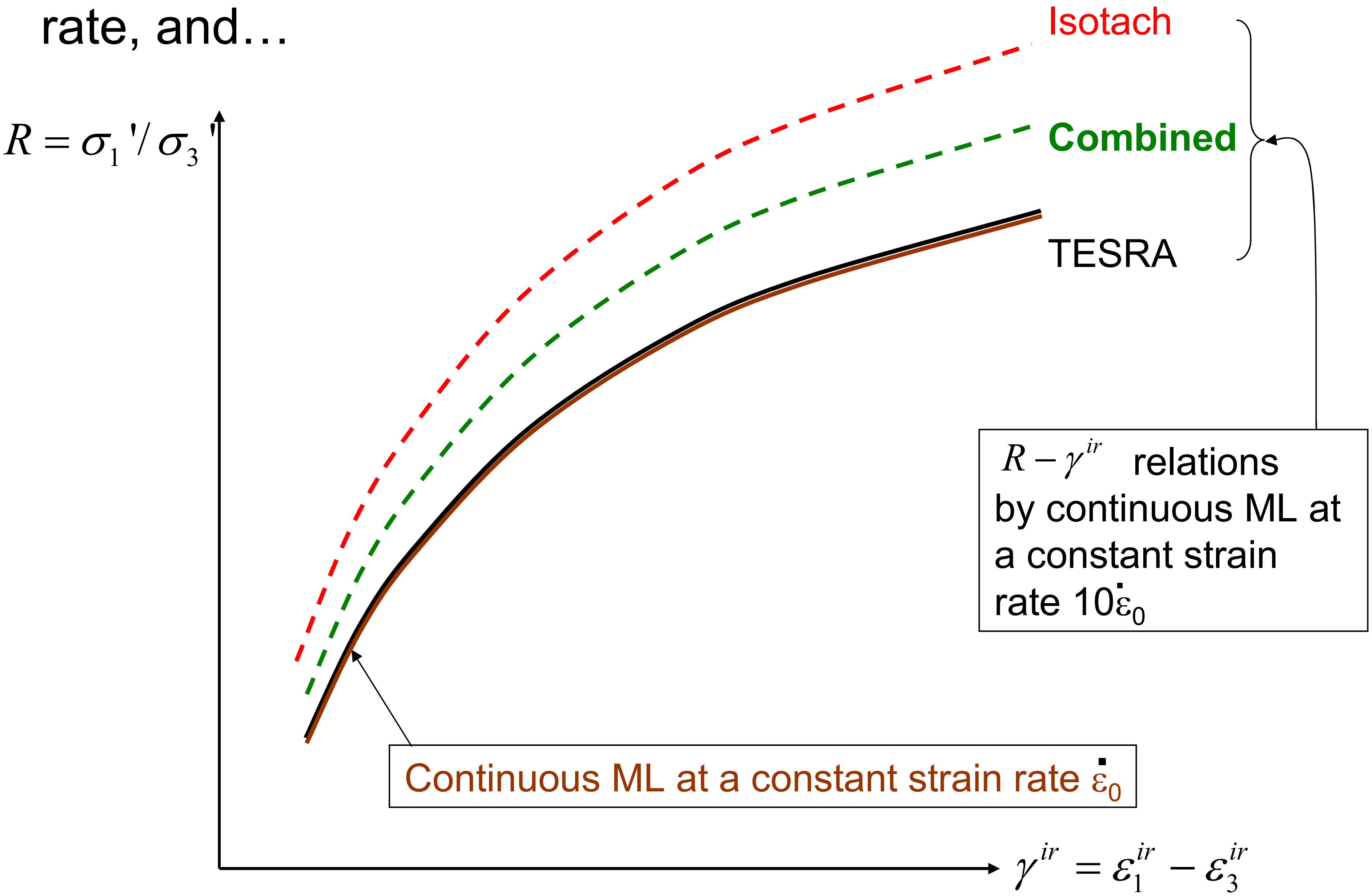
TESRA behaviour

(Kiyota & Tatsuoka, 2006, *S&F*; Tatsuoka et al., 2008a, *S&F*)

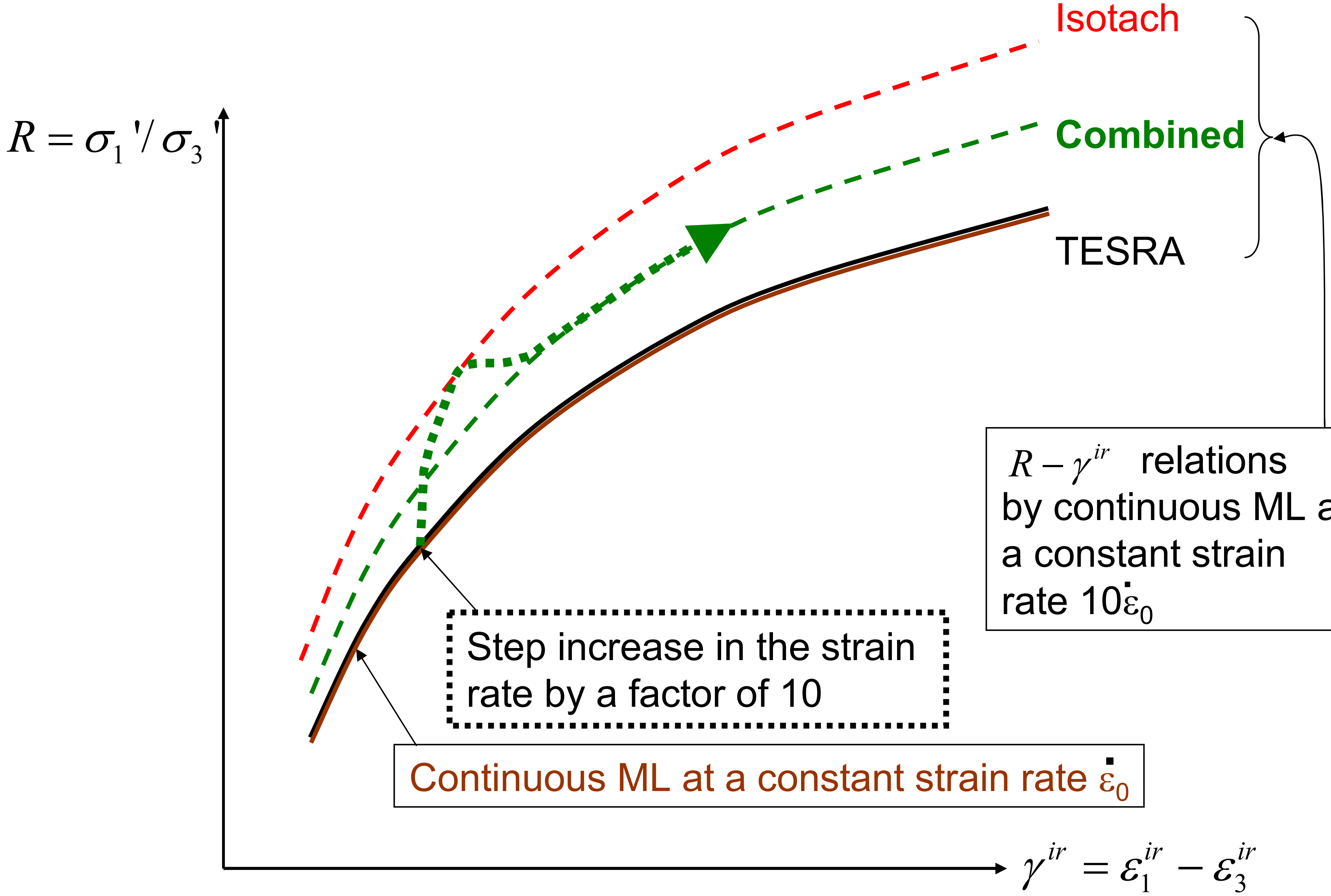


Kiyota & Tatsuoka (2006), *S&F*

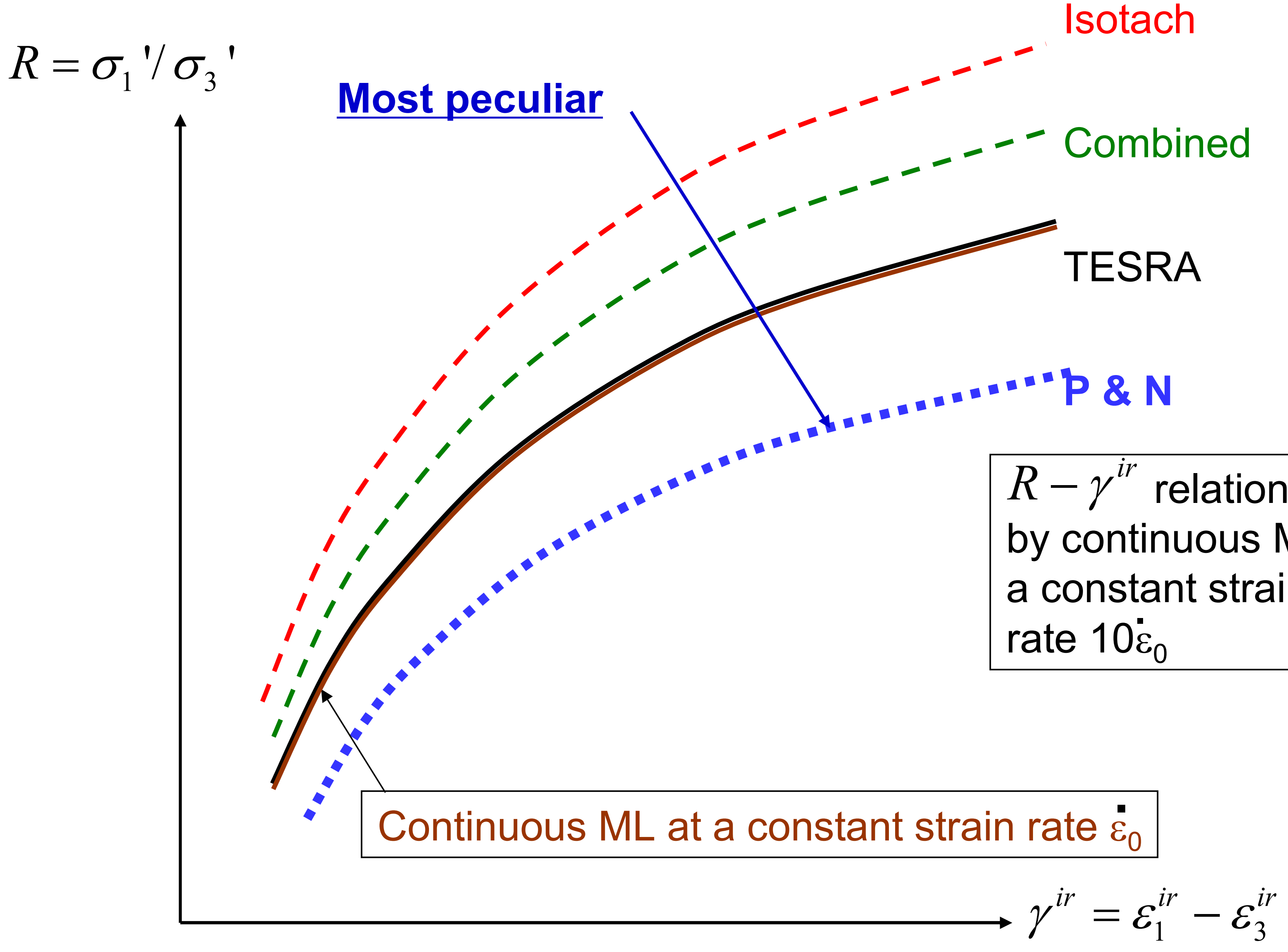
Combined type; combining Isotach & TESRA types, the strength at a constant strain rate increases with strain rate, and…



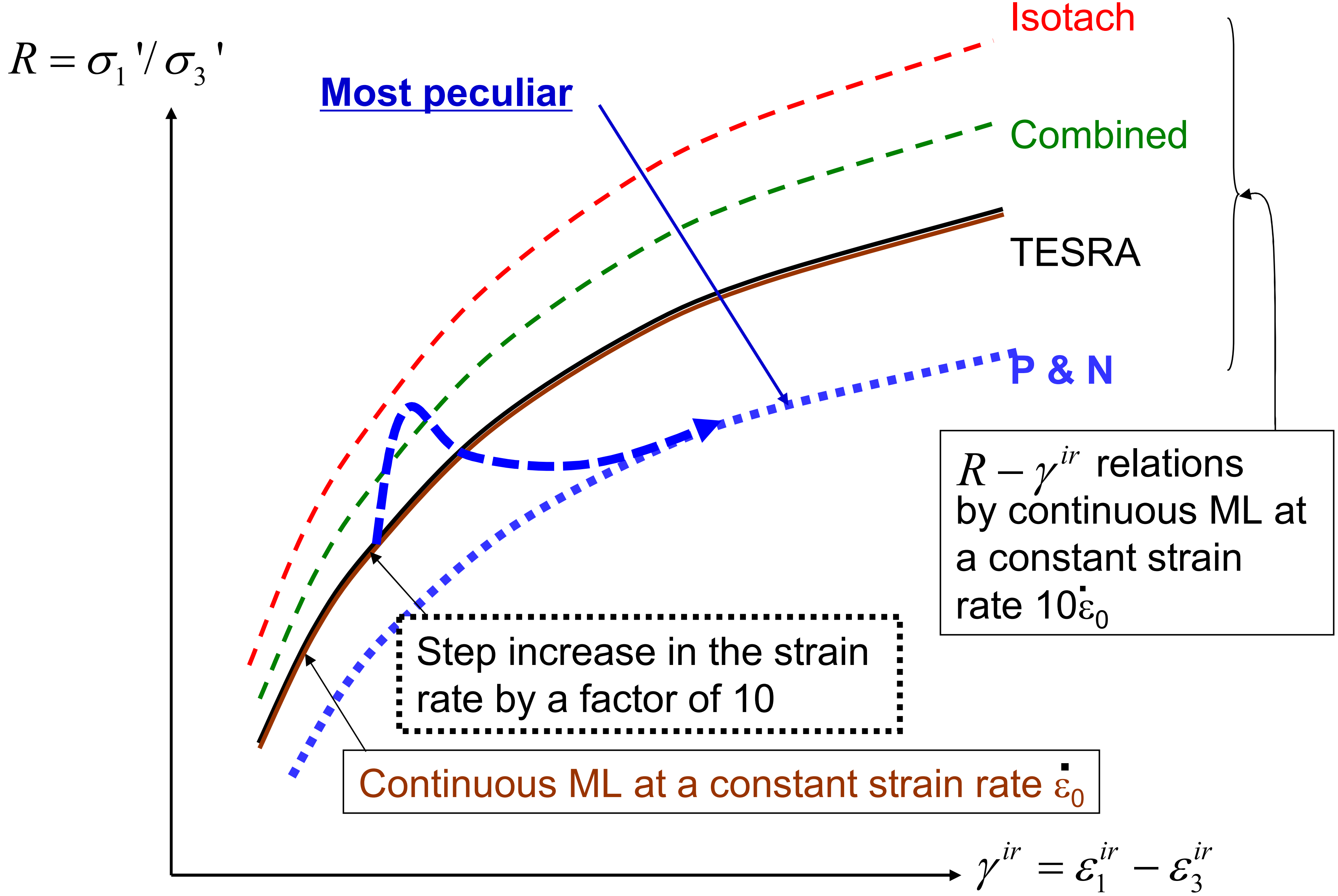
A positive stress jump upon a step increase in the strain rate decays with strain to a smaller positive non-zero value



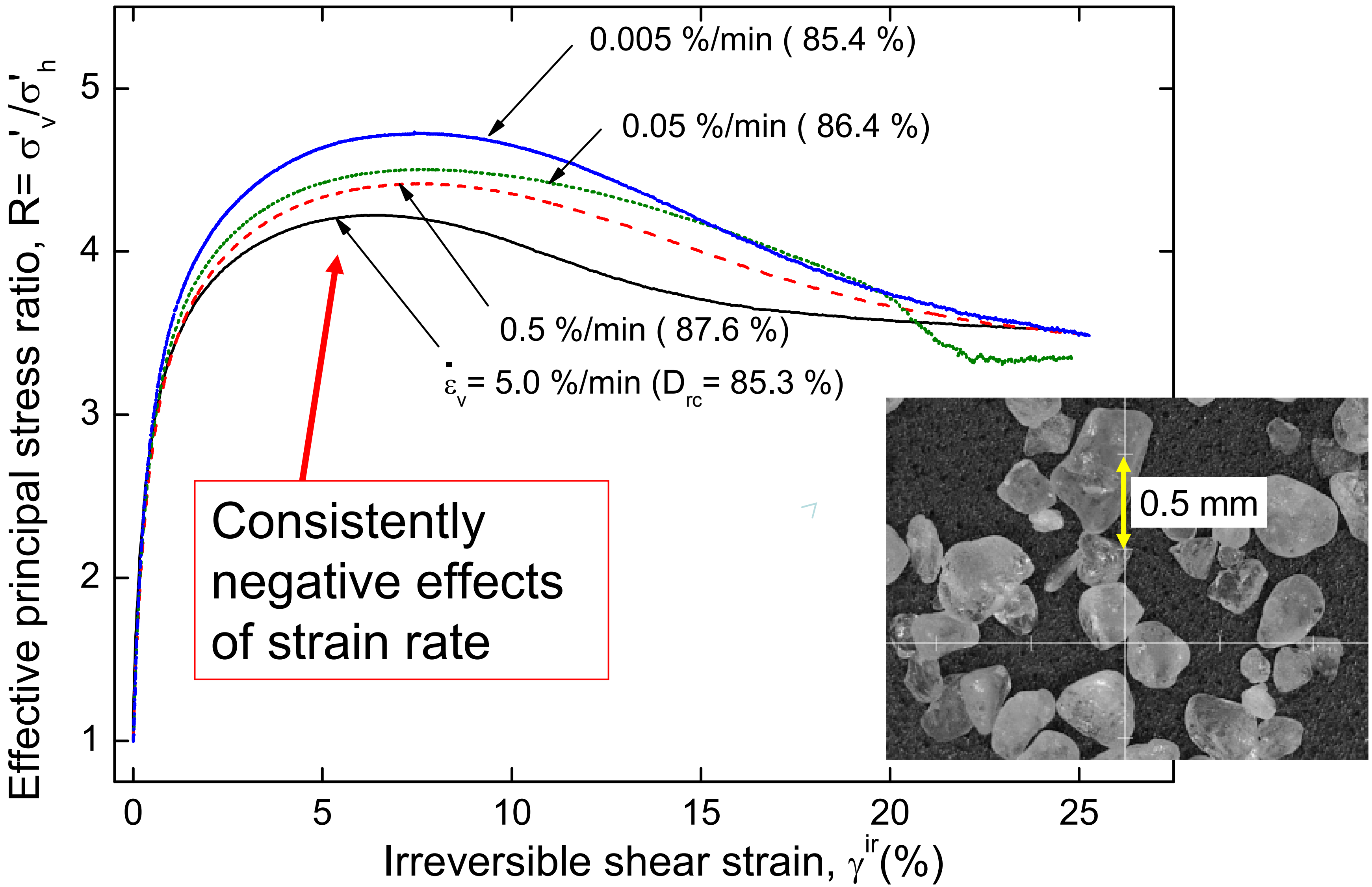
Positive & Negative type: the strength decreases with an increase in the constant strain rate, and…..



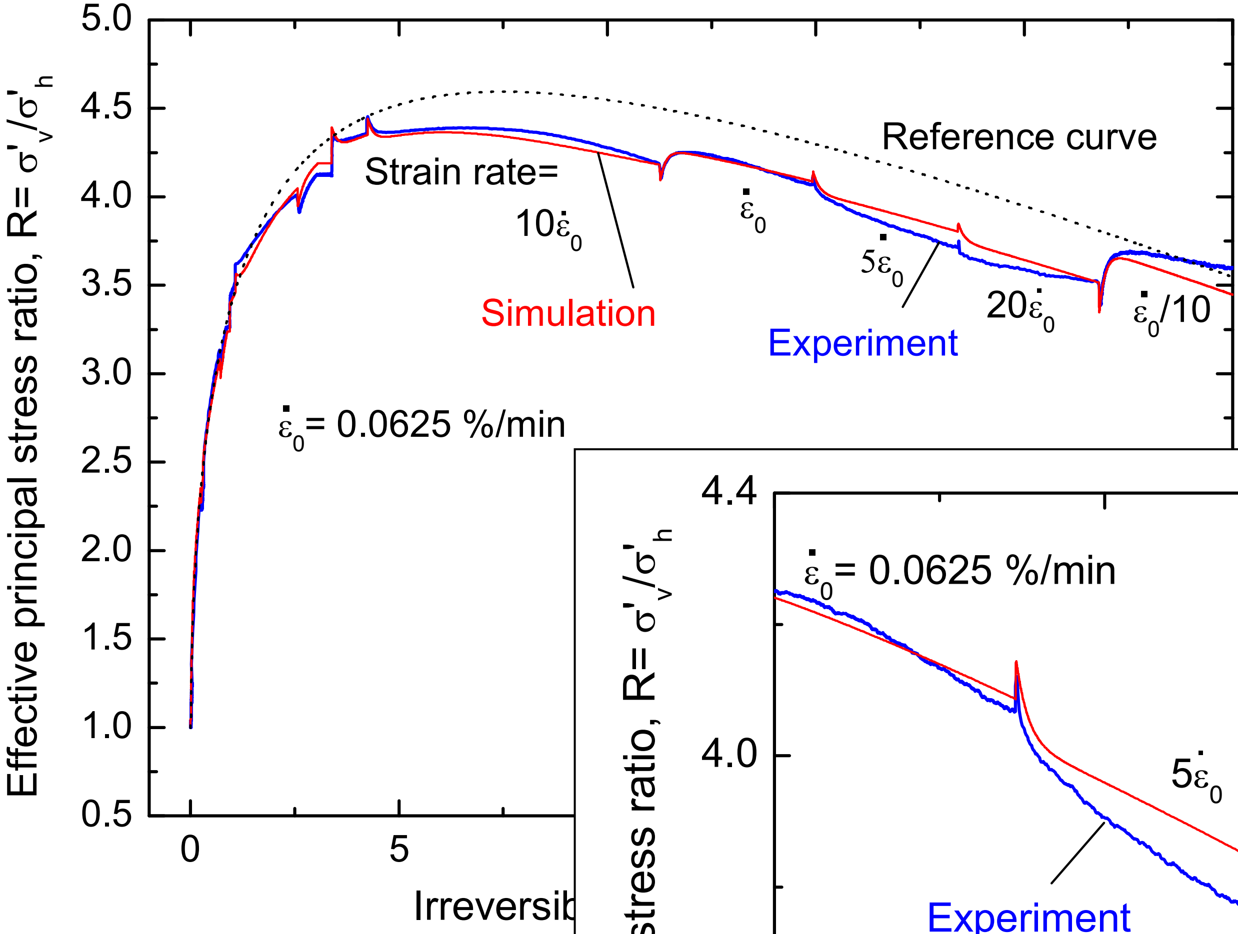
A positive stress jump upon a step increase in the strain rate decays with strain towards a negative value.



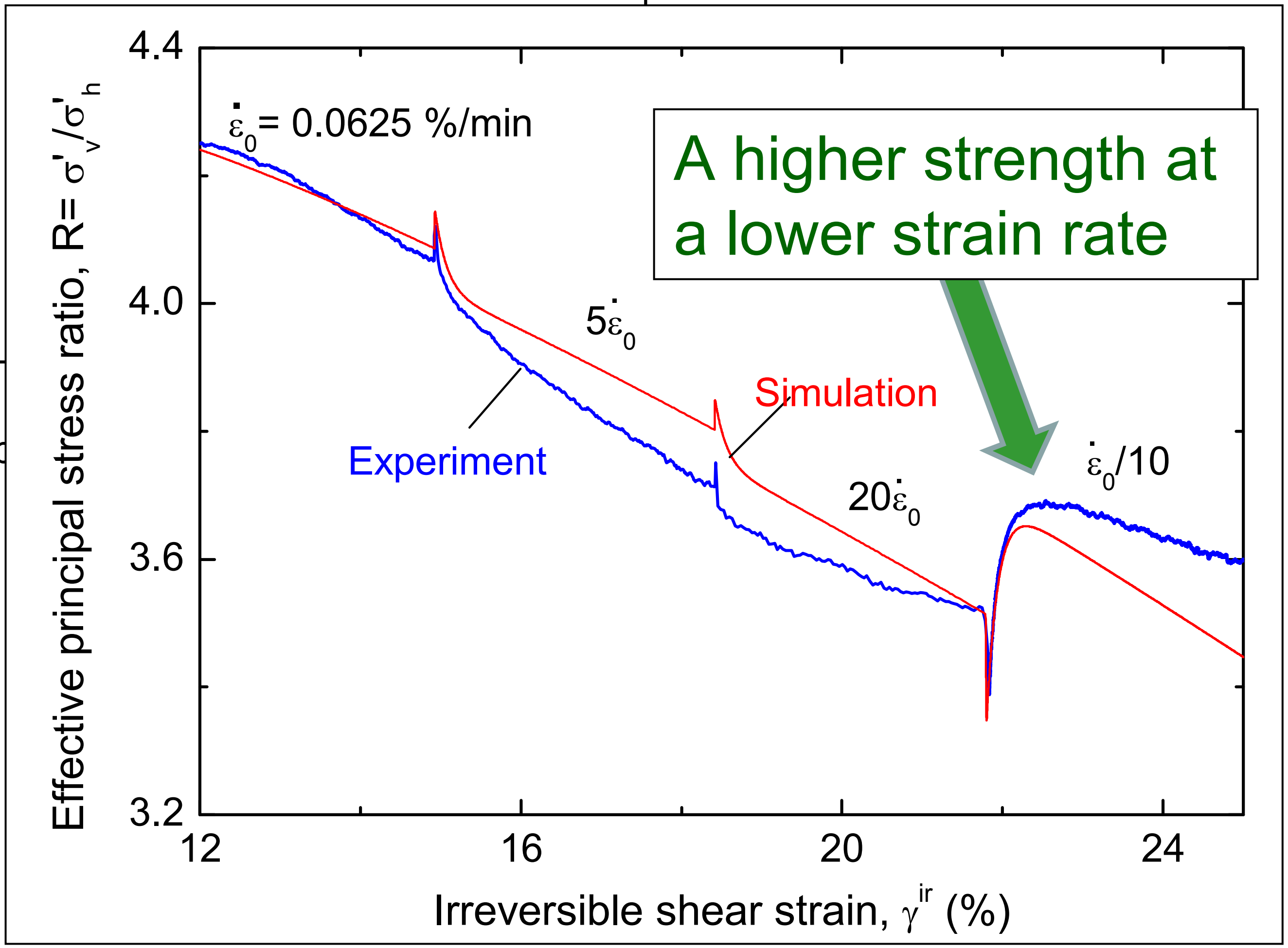
P&N behaviour in drained TC (σ'_h= 400 kPa); air-dried dense Albany sand (poorly-graded & round; D_{50}= 0.30 mm, U_c= 2.22, G_s= 2.67, e_{max}= 1.335 & e_{min}= 0.73)



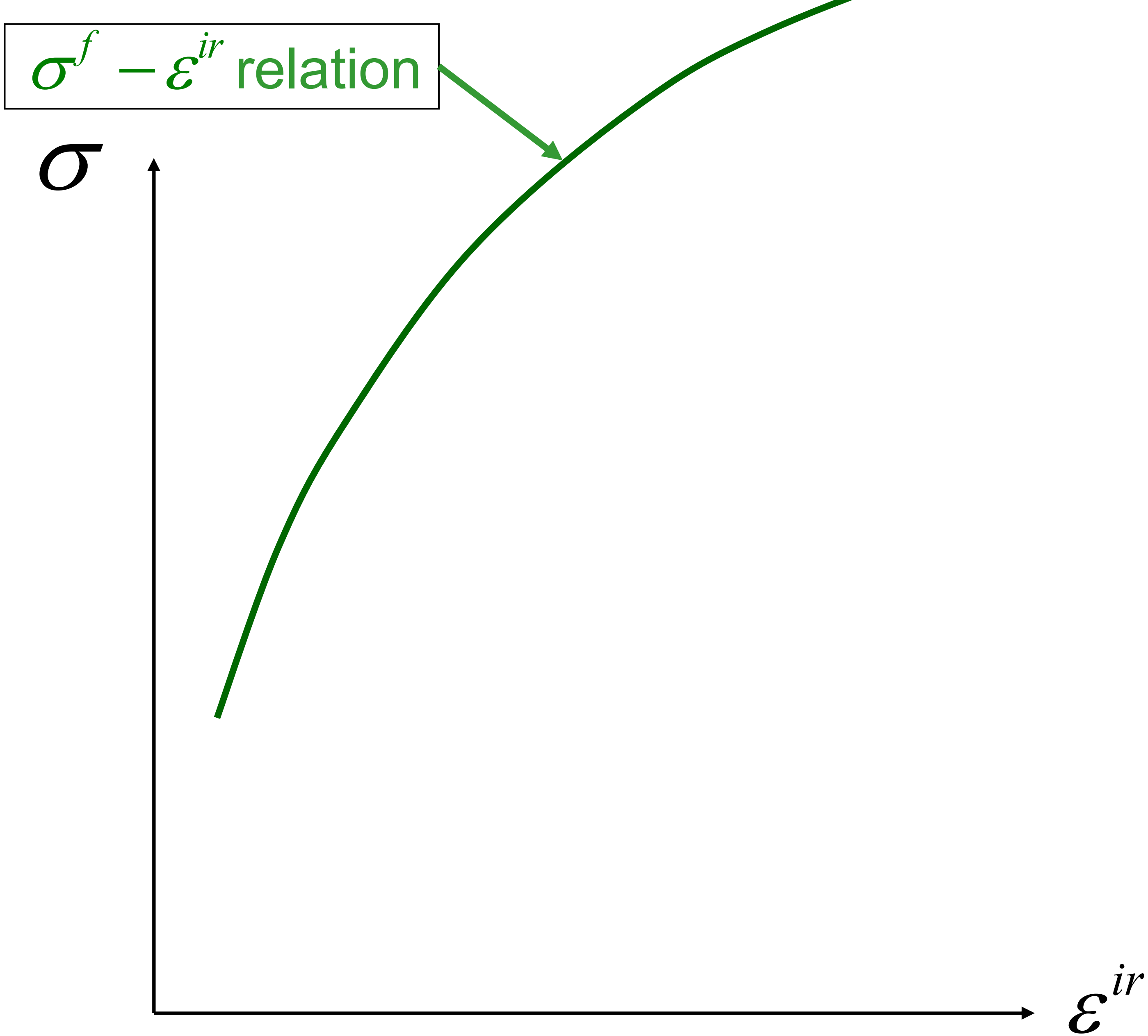
Tatsuoka et al. (2008a, S&F)

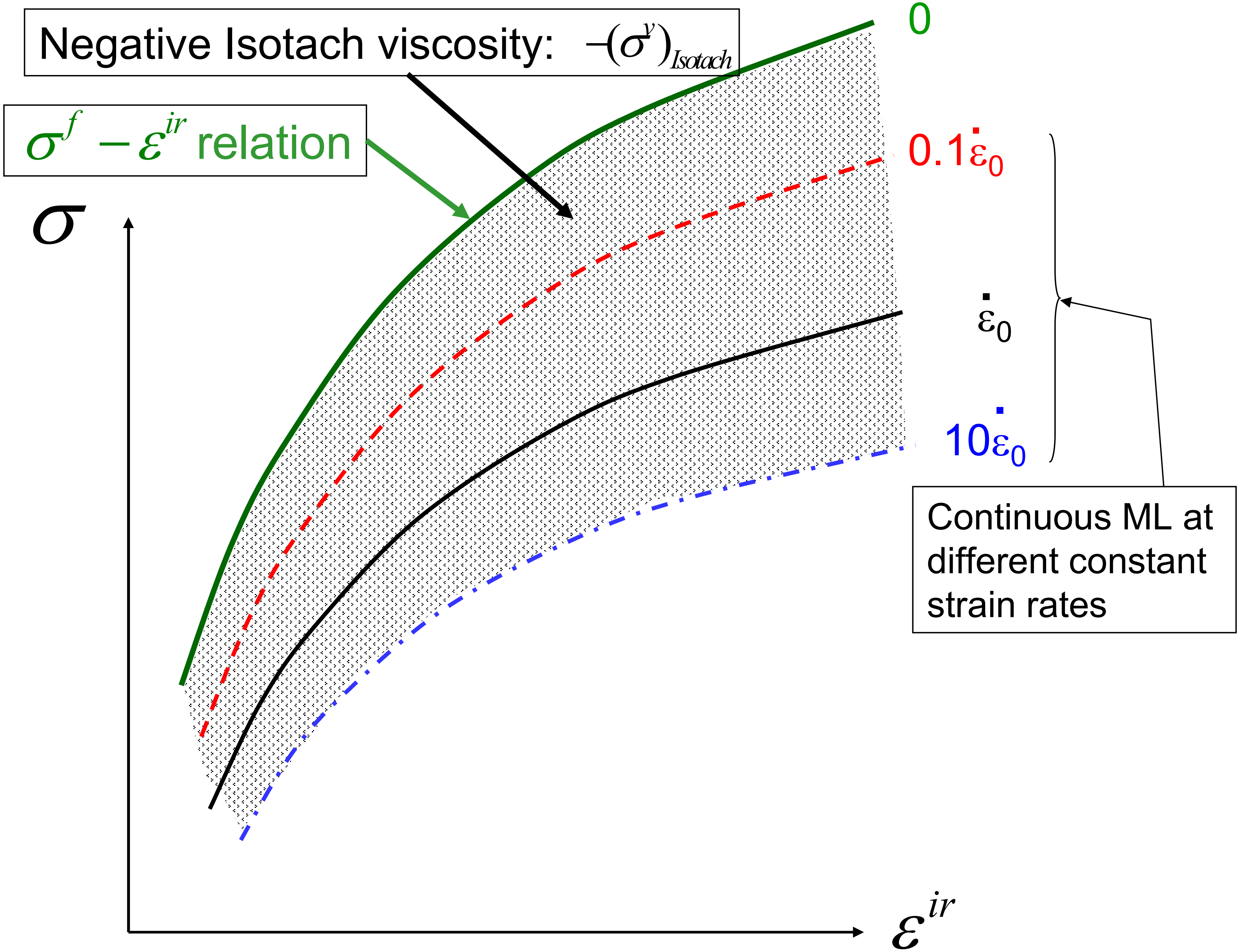


Note: nearly the same trend of rate effect when air-dried and saturated

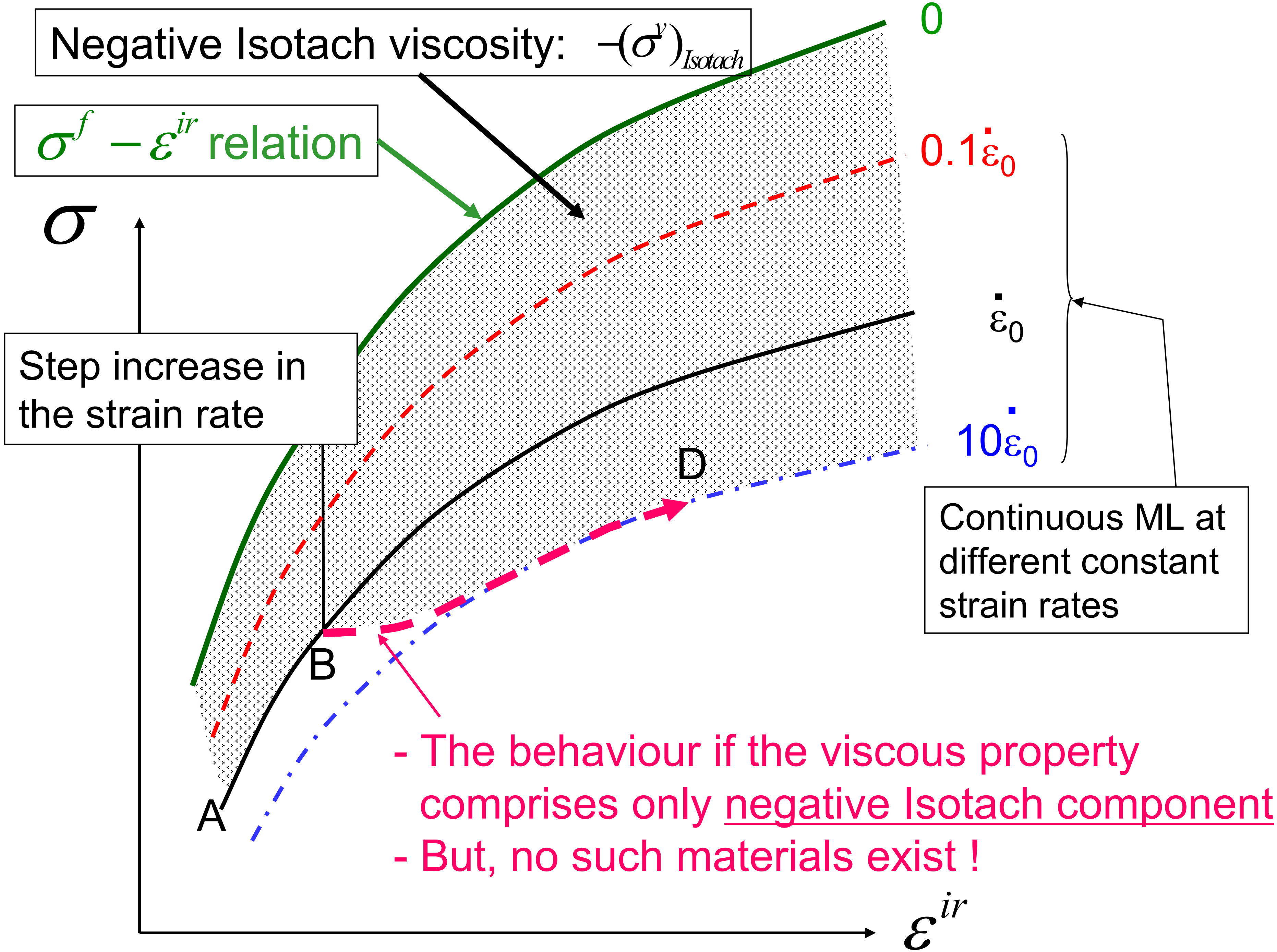


Interpretation of the peculiar test result

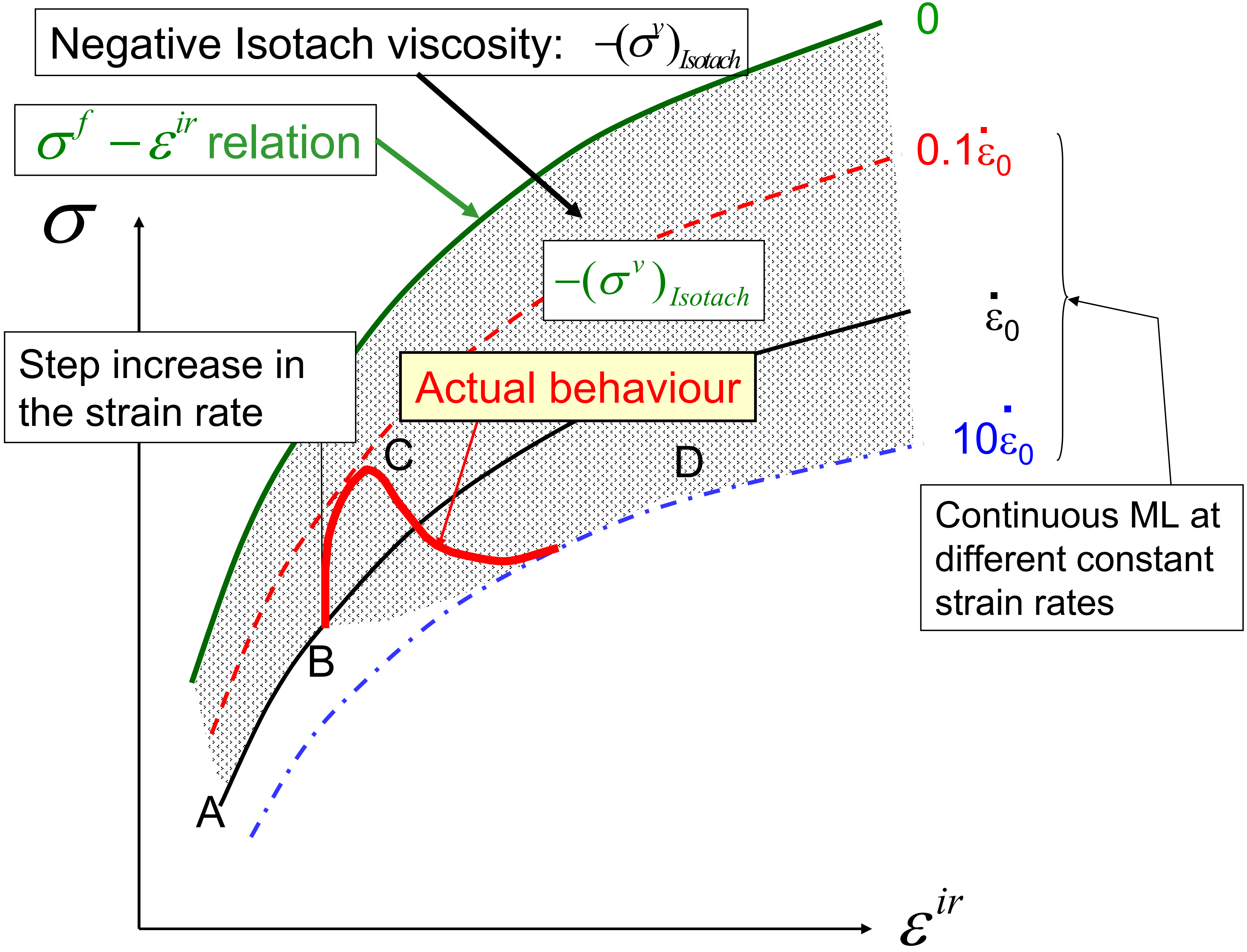


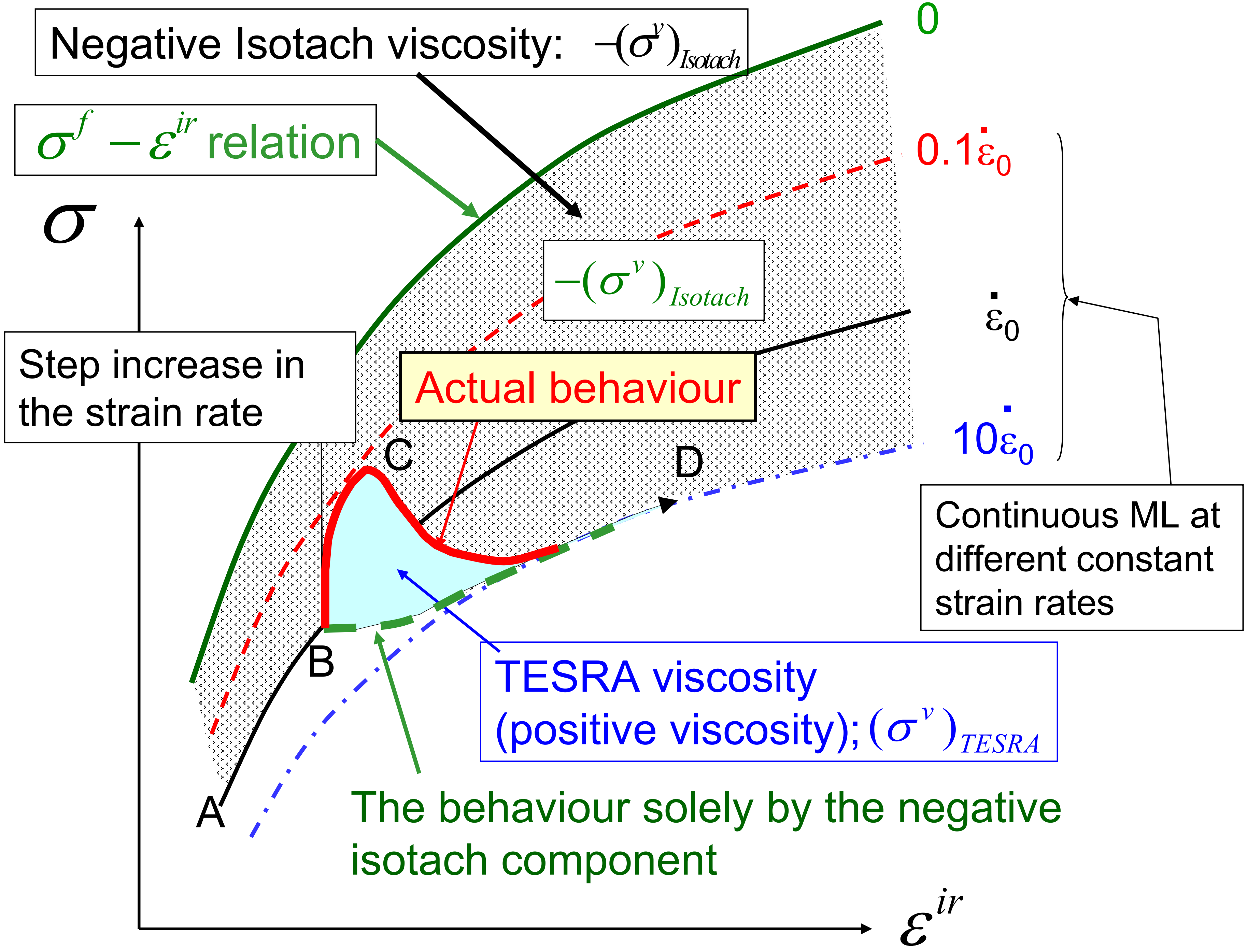


Negative Isotach viscosity: $-(\sigma^{v})_{Isotach}$
$\sigma^{f}-\varepsilon^{ir}$ relation
σ
ε^{ir}
0
$0.1\dot{\varepsilon}_0$
$\dot{\varepsilon}_0$
$10\dot{\varepsilon}_0$
Continuous ML at different constant strain rates

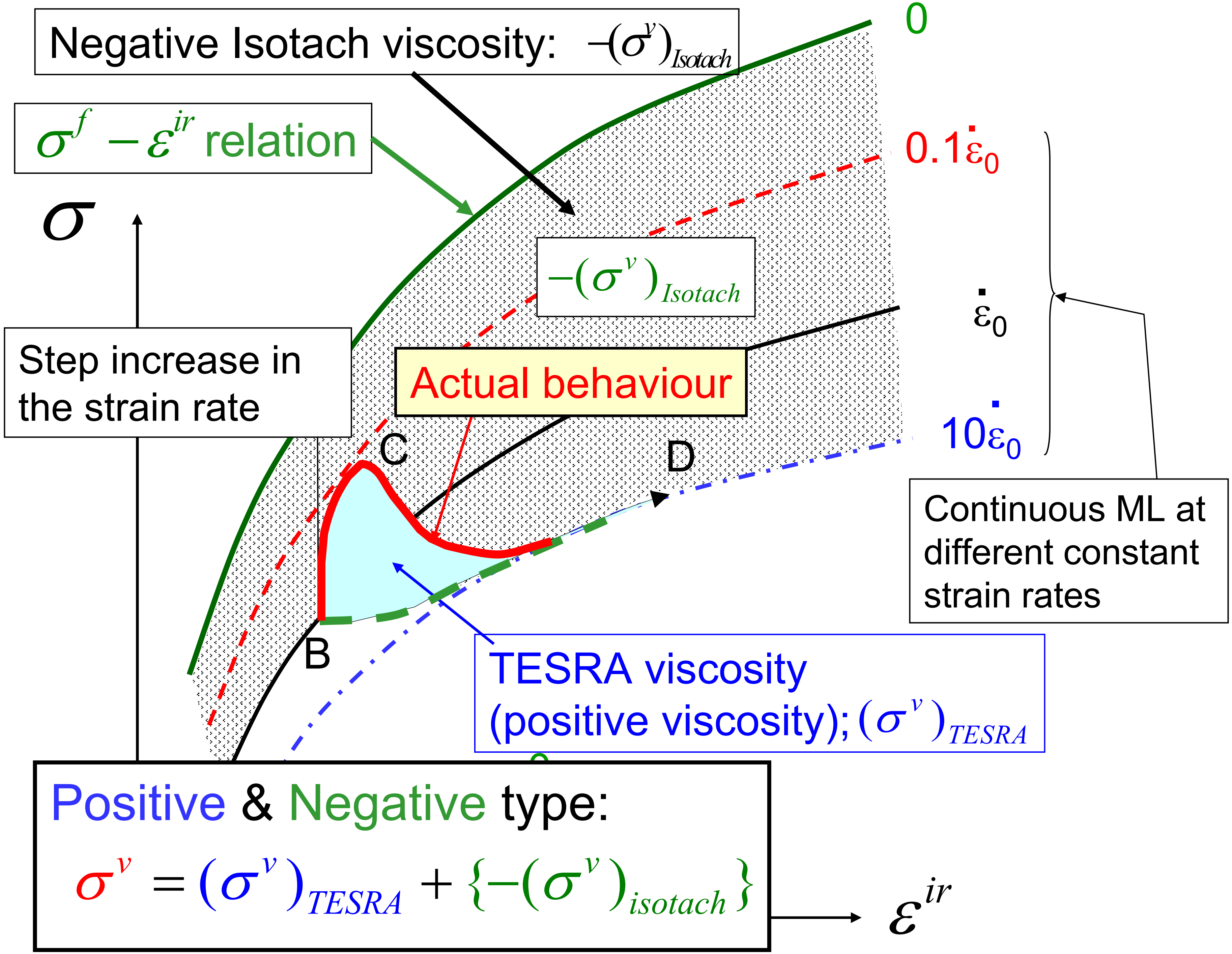


Negative Isotach viscosity: $-(\sigma^{v})_{Isotach}$
$\sigma^{f} - \varepsilon^{ir}$ relation
σ
Step increase in the strain rate
0
$0.1\dot{\varepsilon}_0$
$\dot{\varepsilon}_0$
$10\dot{\varepsilon}_0$
D
B
A
Continuous ML at different constant strain rates
- The behaviour if the viscous property comprises only negative Isotach component
- But, no such materials exist !
ε^{ir}

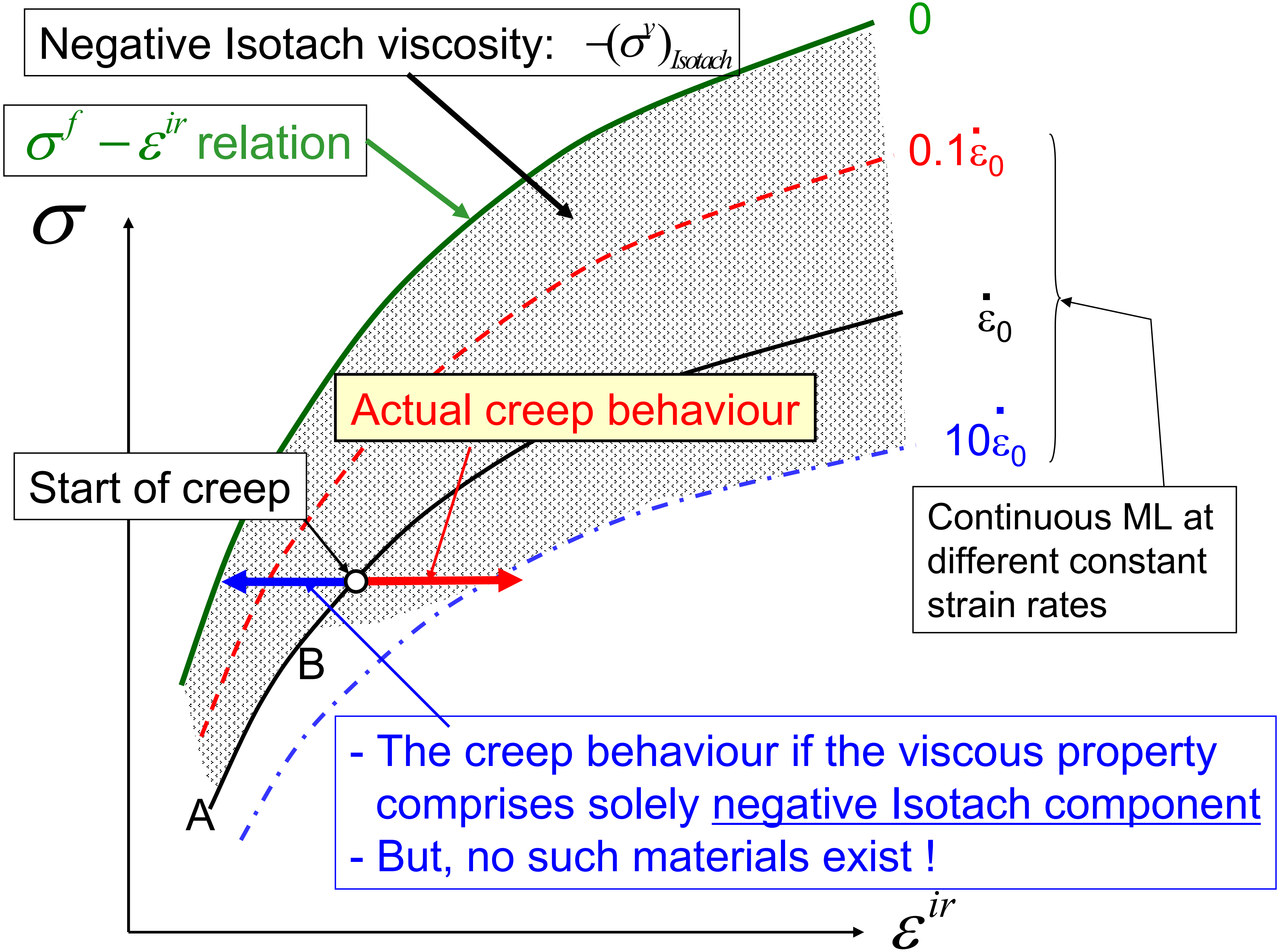

Negative Isotach viscosity: $-(\sigma^{v})_{Isotach}$
$\sigma^{f} - \varepsilon^{ir}$ relation
σ
0
$0.1\dot{\varepsilon}_0$
$-(\sigma^{v})_{Isotach}$
$\dot{\varepsilon}_0$
Step increase in the strain rate
Actual behaviour
$10\dot{\varepsilon}_0$
C
D
Continuous ML at different constant strain rates
B
A
ε^{ir}



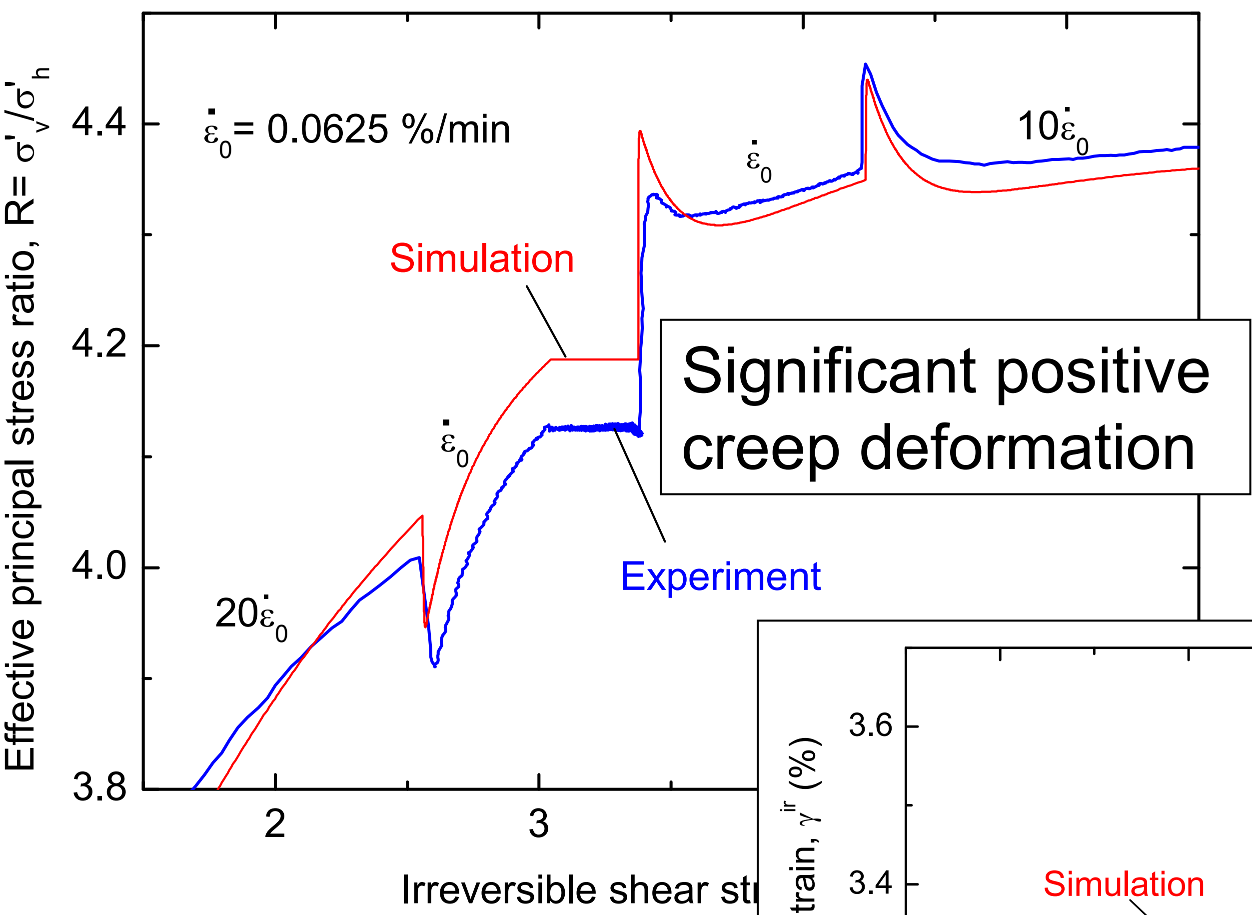
Negative Isotach viscosity: $-(\sigma^v)_{Isotach}$
$\sigma^f - \varepsilon^{ir}$ relation
σ
0
$0.1\dot{\varepsilon}_0$
$-(\sigma^v)_{Isotach}$
$\dot{\varepsilon}_0$
Step increase in the strain rate
Actual behaviour
$10\dot{\varepsilon}_0$
C
D
Continuous ML at different constant strain rates
B
TESRA viscosity (positive viscosity); $(\sigma^v)_{TESRA}$
A
The behaviour solely by the negative isotach component
ε^{ir}



Negative Isotach viscosity: $-(\sigma^{v})_{Isotach}$
$\sigma^{f}-\varepsilon^{ir}$ relation
σ
0
$0.1\dot{\varepsilon}_0$
$-(\sigma^{v})_{Isotach}$
$\dot{\varepsilon}_0$
Step increase in the strain rate
Actual behaviour
$10\dot{\varepsilon}_0$
C
D
B
Continuous ML at different constant strain rates
TESRA viscosity
(positive viscosity); $(\sigma^{v})_{TESRA}$
Positive & Negative type:
$\sigma^{v}=(\sigma^{v})_{TESRA}+\{-(\sigma^{v})_{isotach}\}$
ε^{ir}

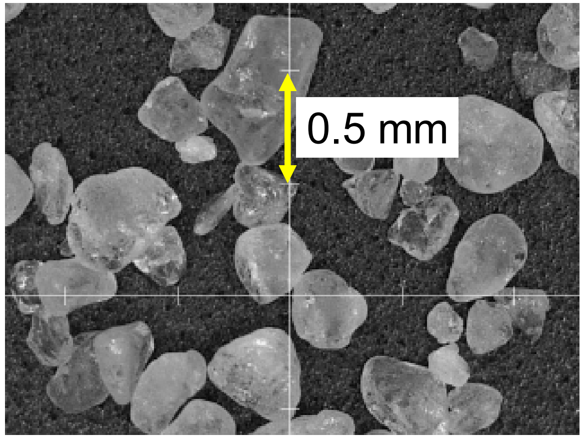


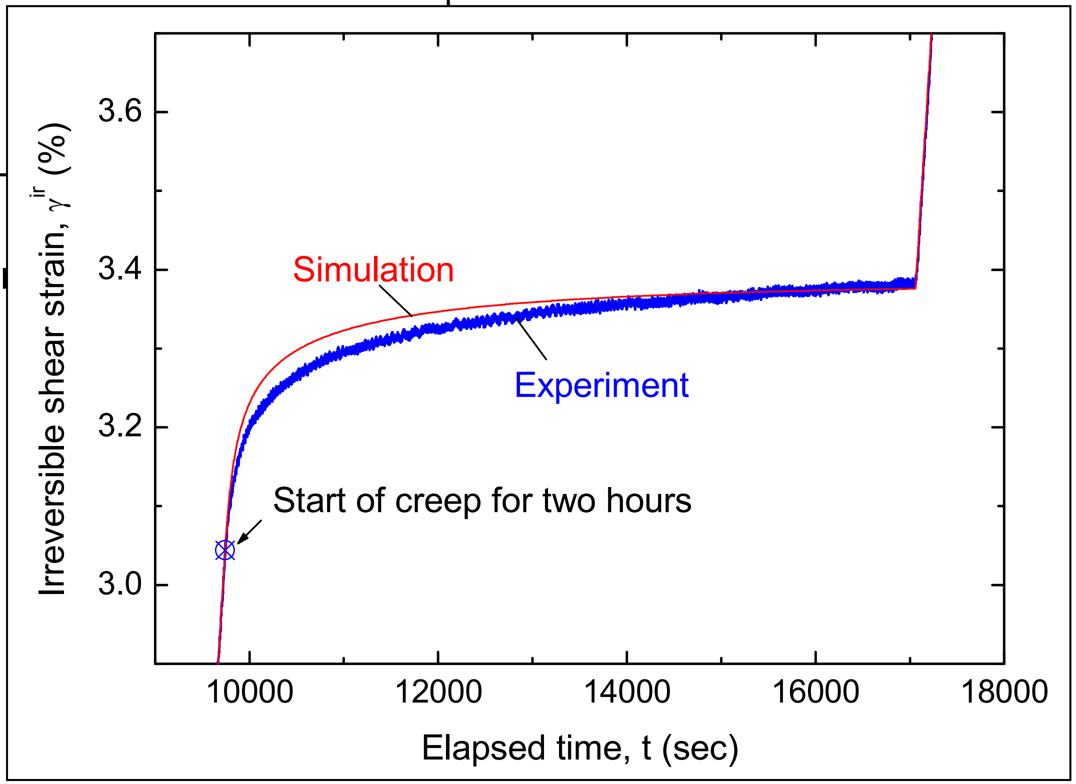
Negative Isotach viscosity: $-(\sigma^v)_{Isotach}$
$\sigma^f - \varepsilon^{ir}$ relation
σ
0
$0.1\dot{\varepsilon}_0$
$\dot{\varepsilon}_0$
$10\dot{\varepsilon}_0$
Actual creep behaviour
Start of creep
Continuous ML at different constant strain rates
B
A
- The creep behaviour if the viscous property comprises solely negative Isotach component
- But, no such materials exist !
ε^{ir}



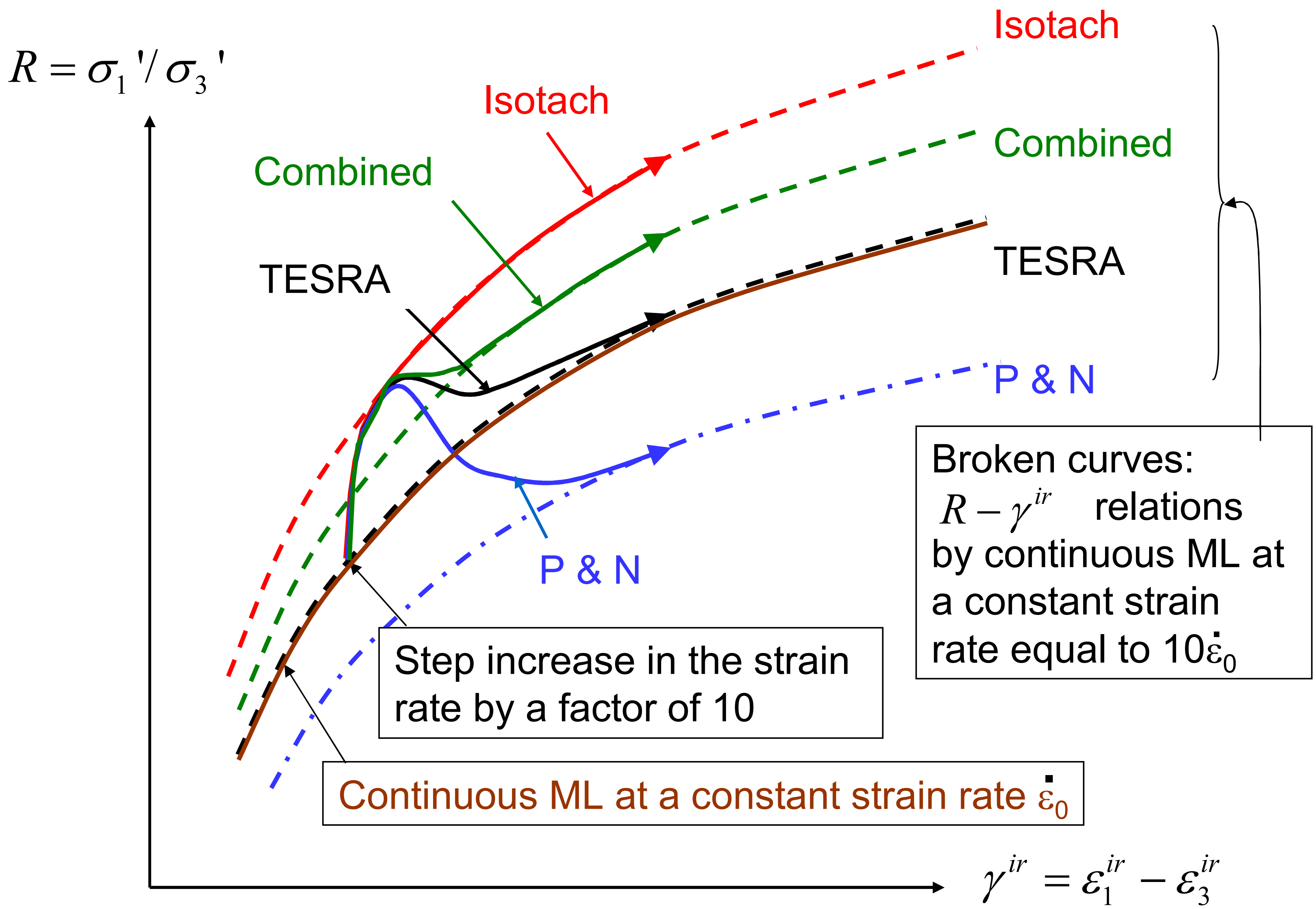
Significant positive creep deformation

Albany sand





Summary: At least, four different viscous property types by a wide variety of geomaterials in TC and PSC tests



Rate-dependent stress-strain behaviour

- Isotach and non-Isotach types in drained TC
- **Viscous behaviour of sand in direct shear**
- Viscous behaviour of clay in 1D compression
- Mechanism of non-Isotach viscous behaviour
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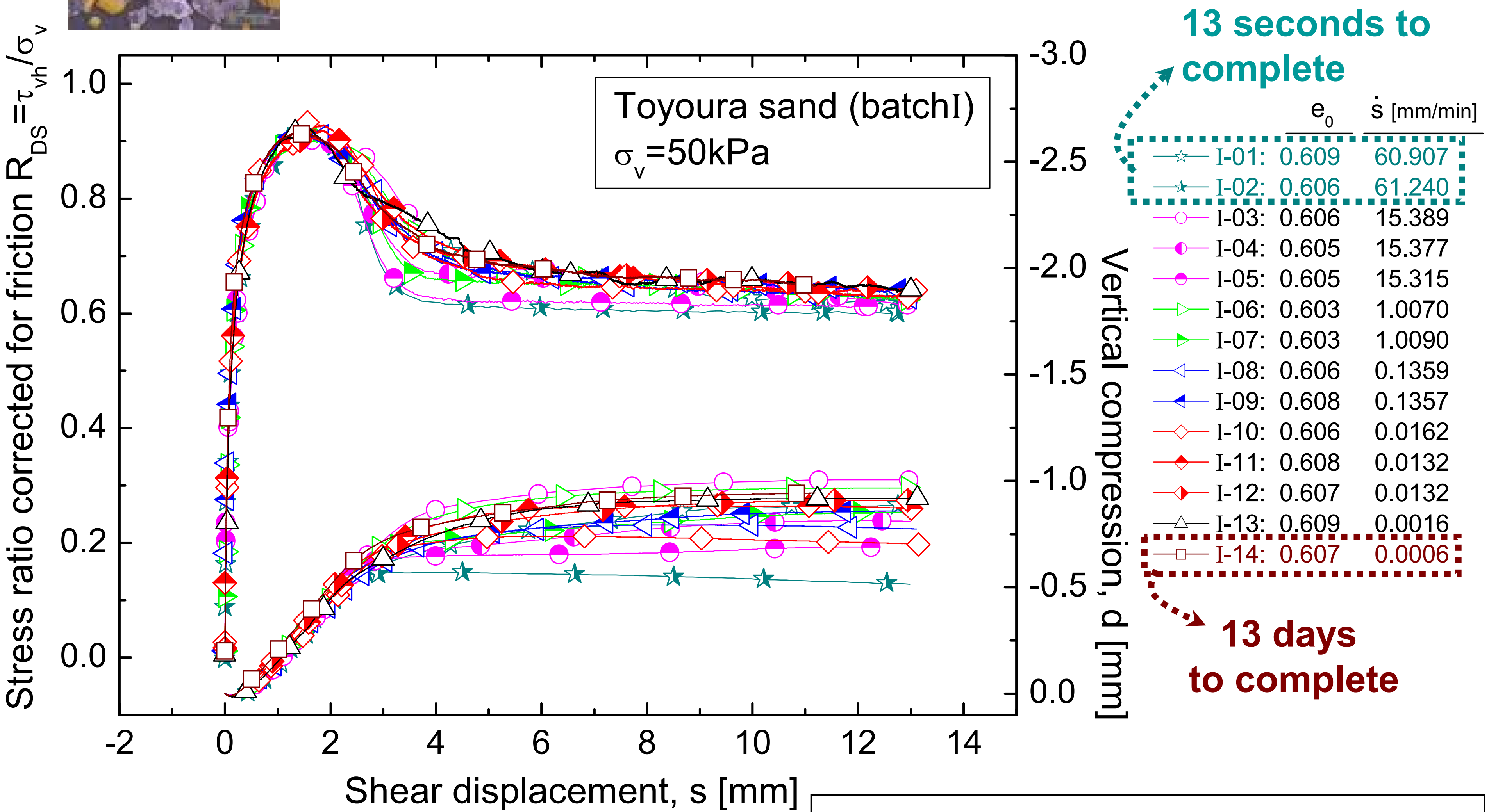
- Summary

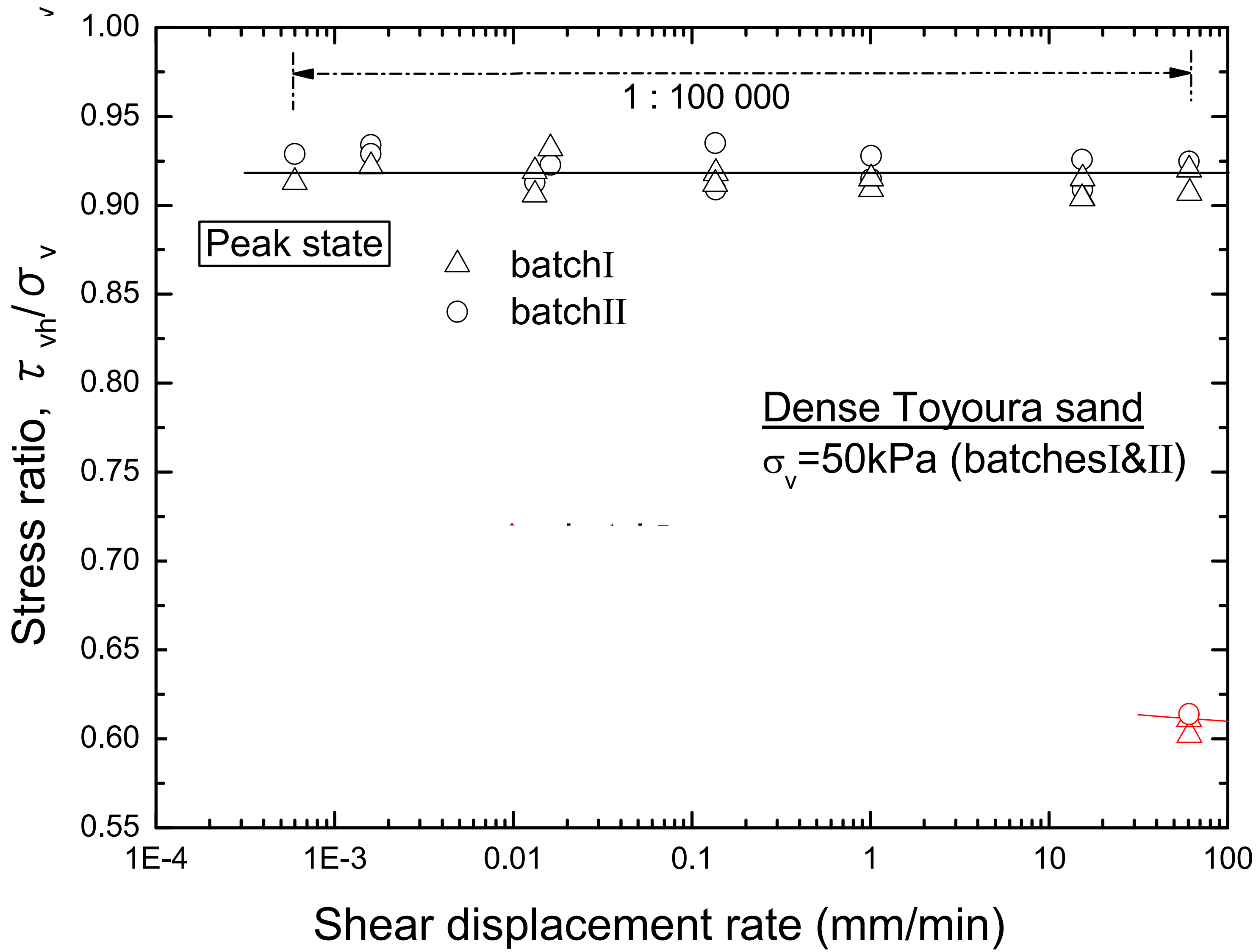
Air-dried dense Toyoura sand



A series of ML tests at shear displacement rates different by a factor of up to 10^5

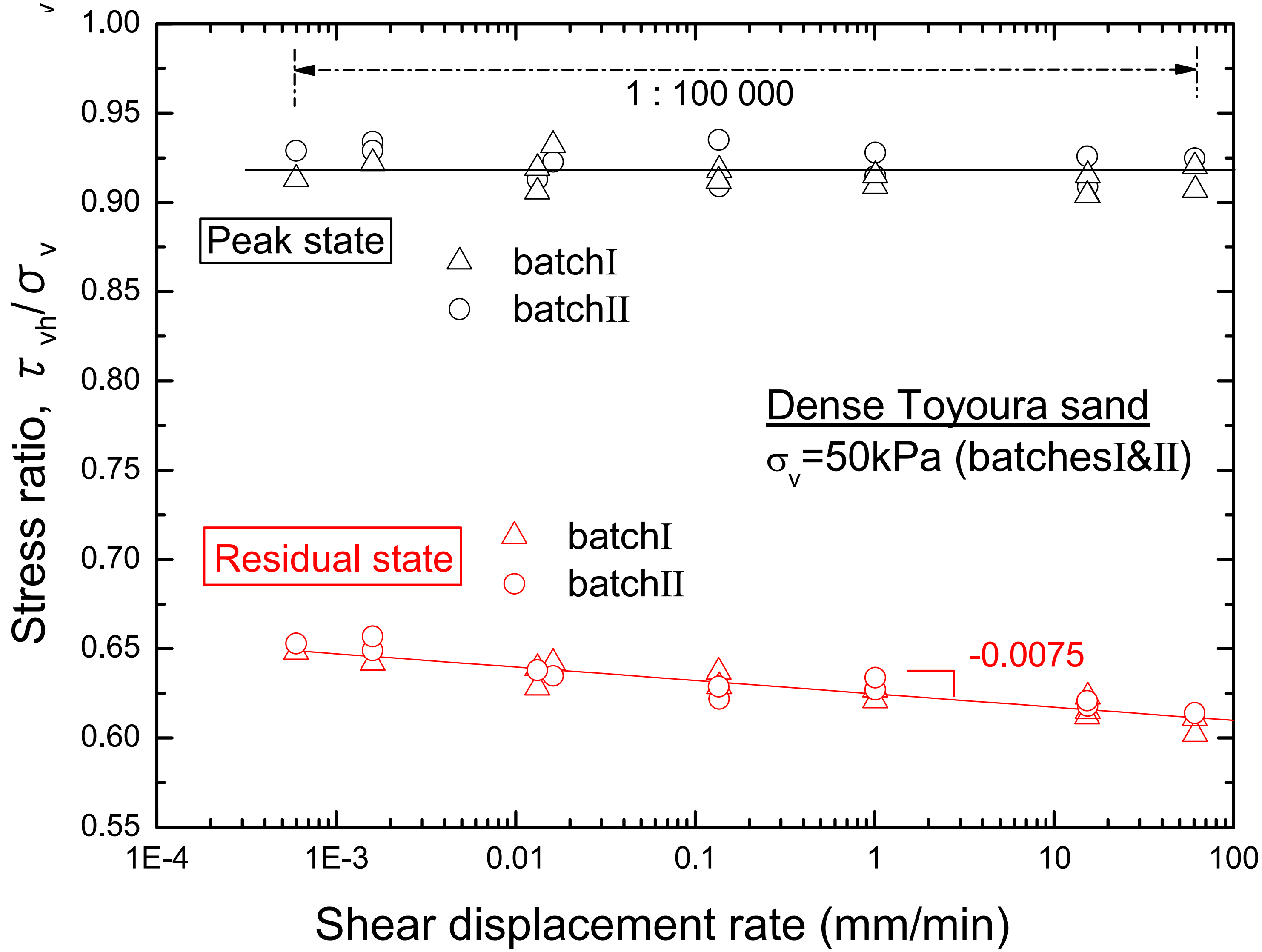
(Duttine et al., 2009a, *S&F*)

Peak strength: essentially independent of shear displacement rate (i.e., TESRA viscosity)



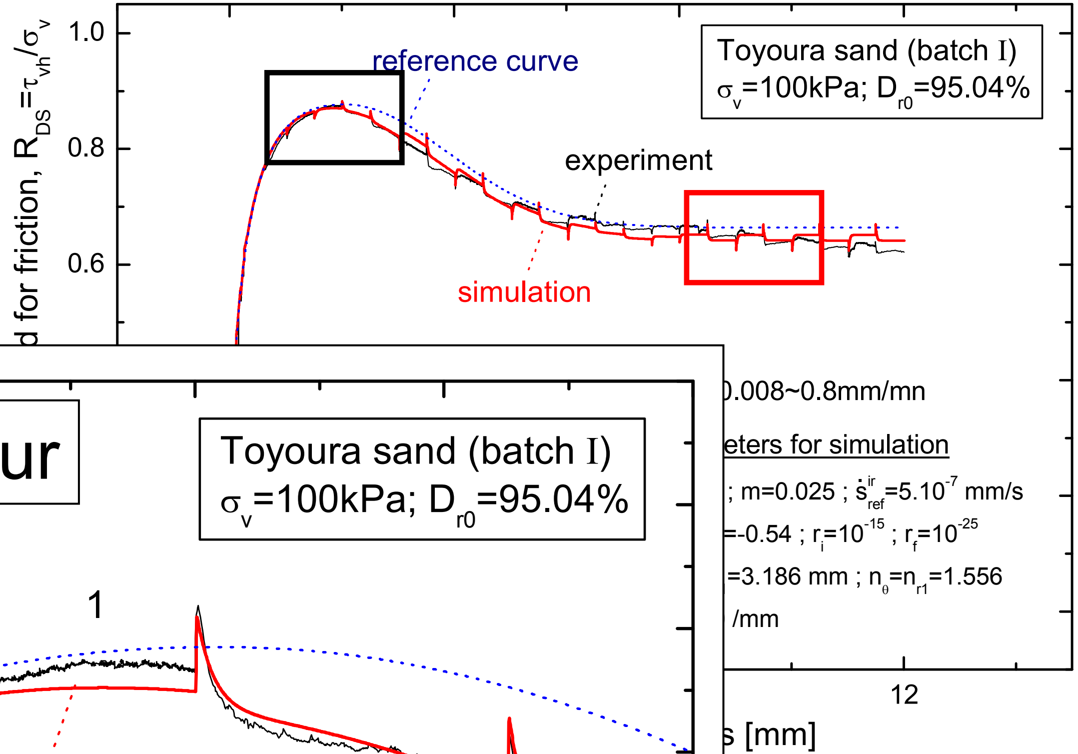
(Duttine et al., 2009a; *S&F*)

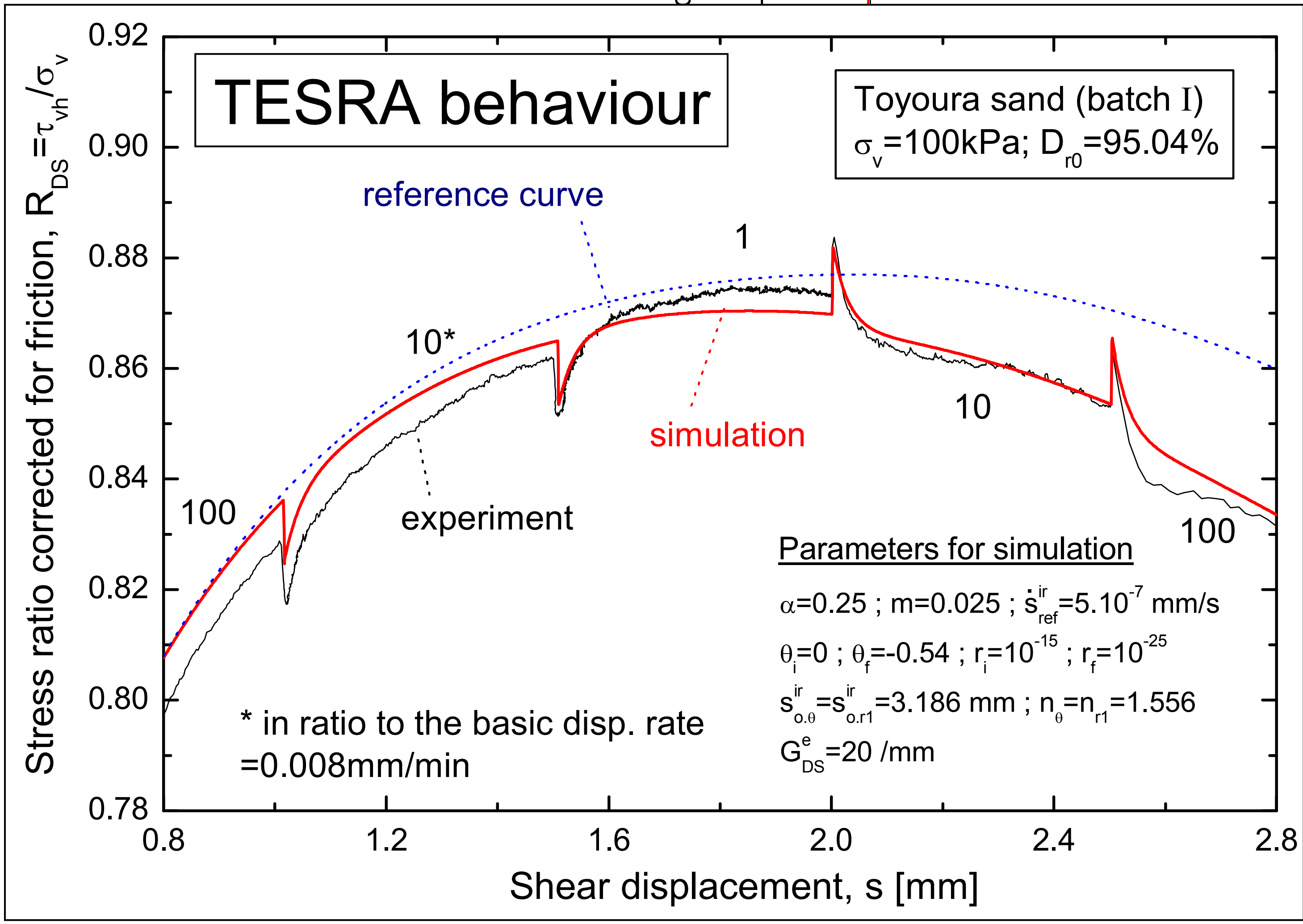
Residual strength: decreases with an increase in shear displacement rate (i.e., P&N viscosity)



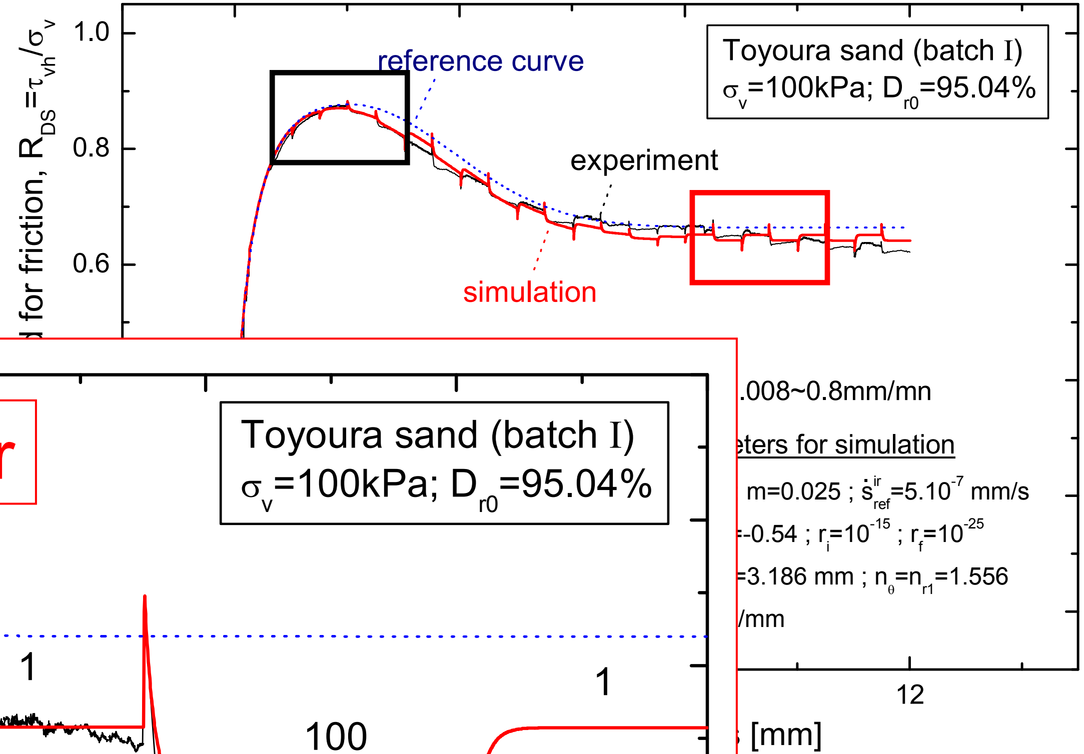
(Duttine et al., 2009a; *S&F*)

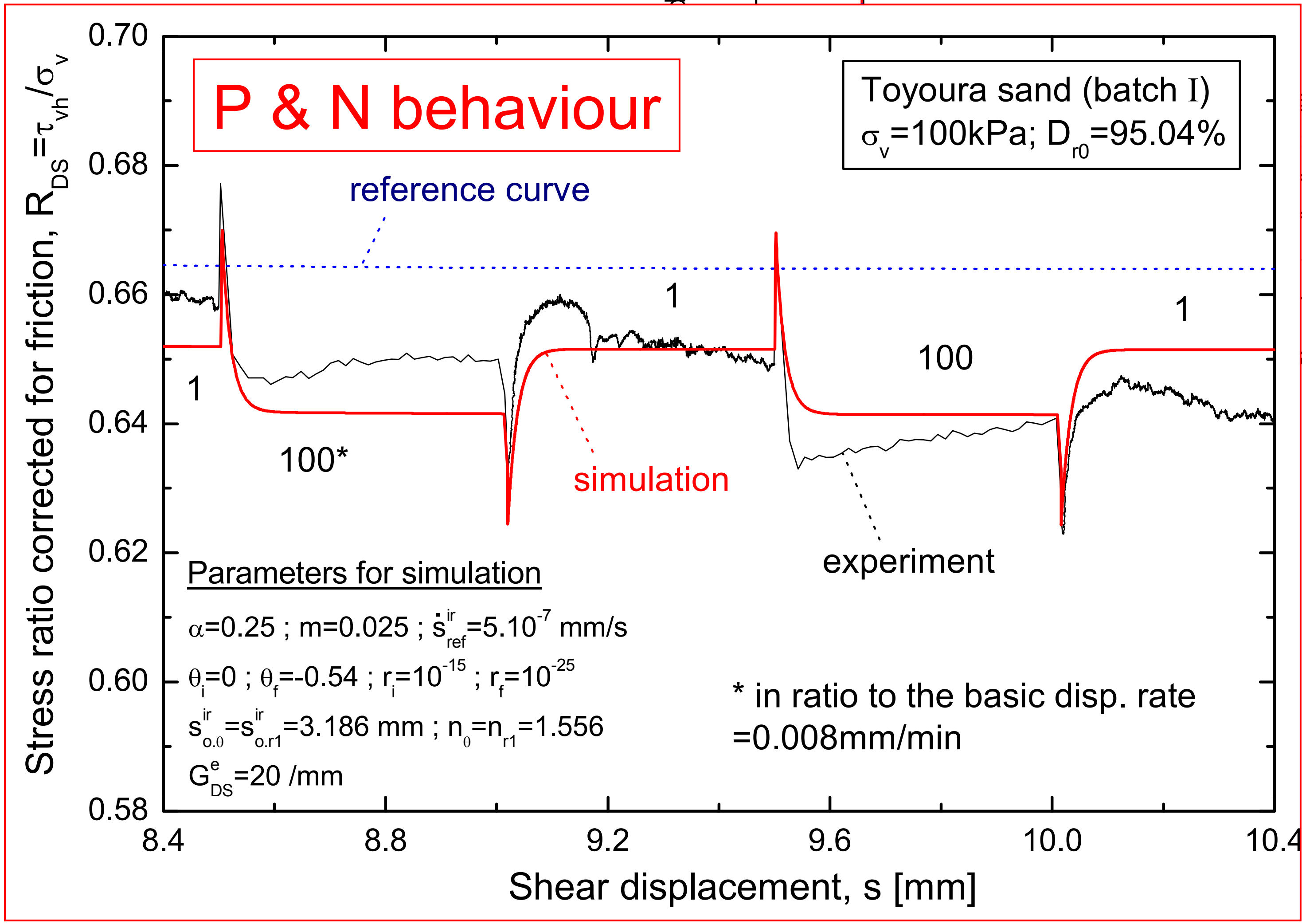
Significant rate effects





The viscous property type changes with strain in a single test.





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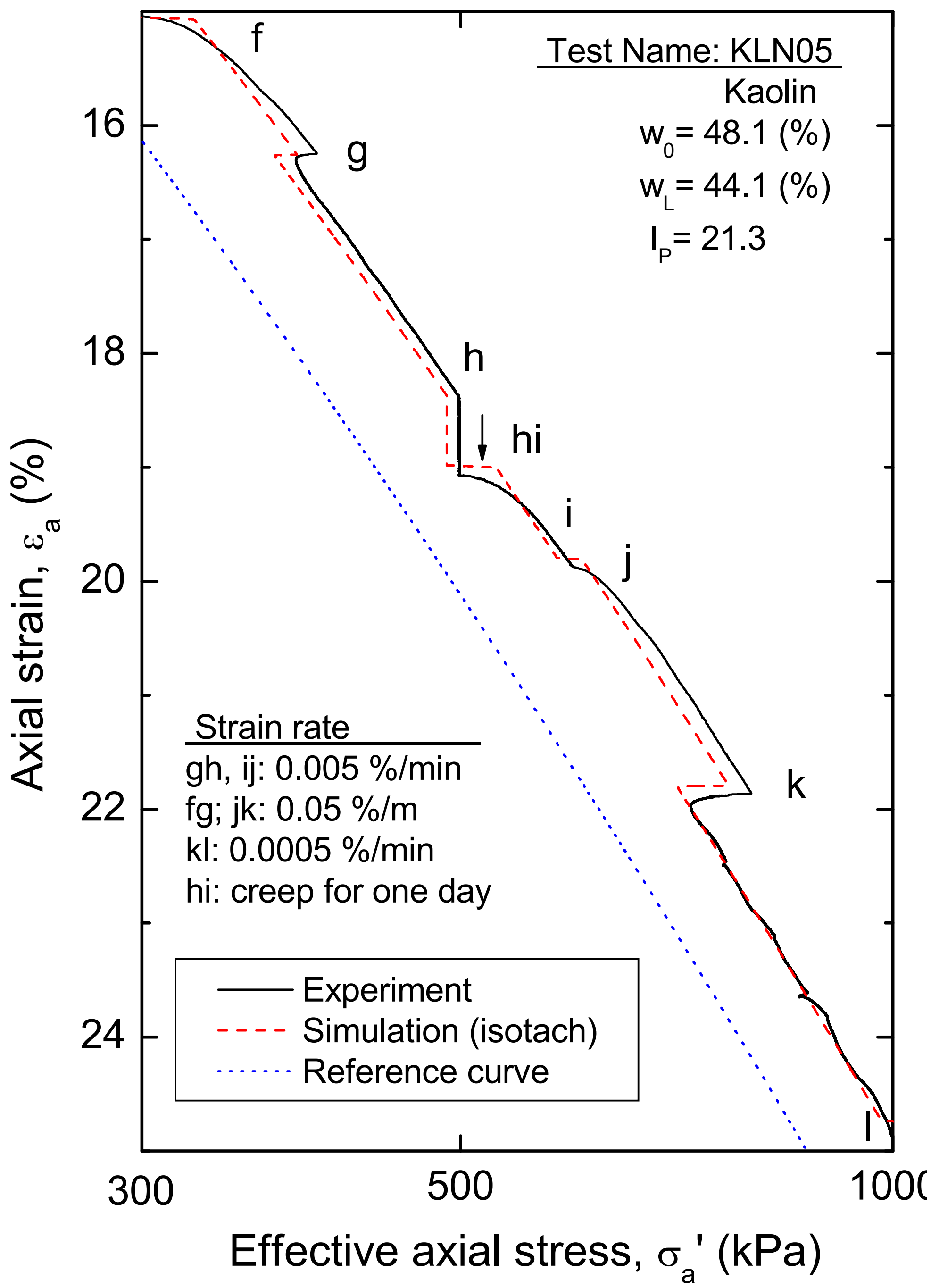
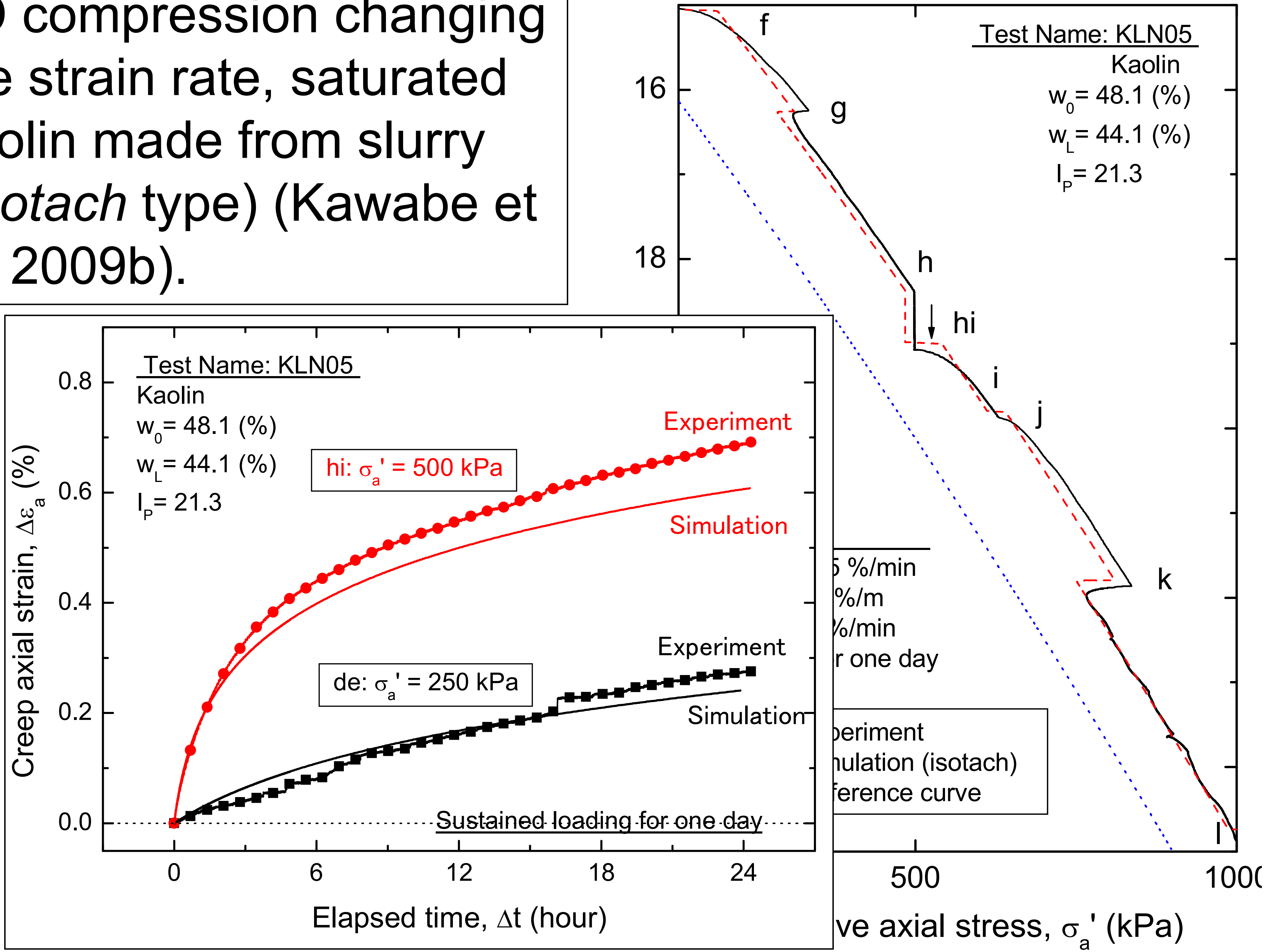
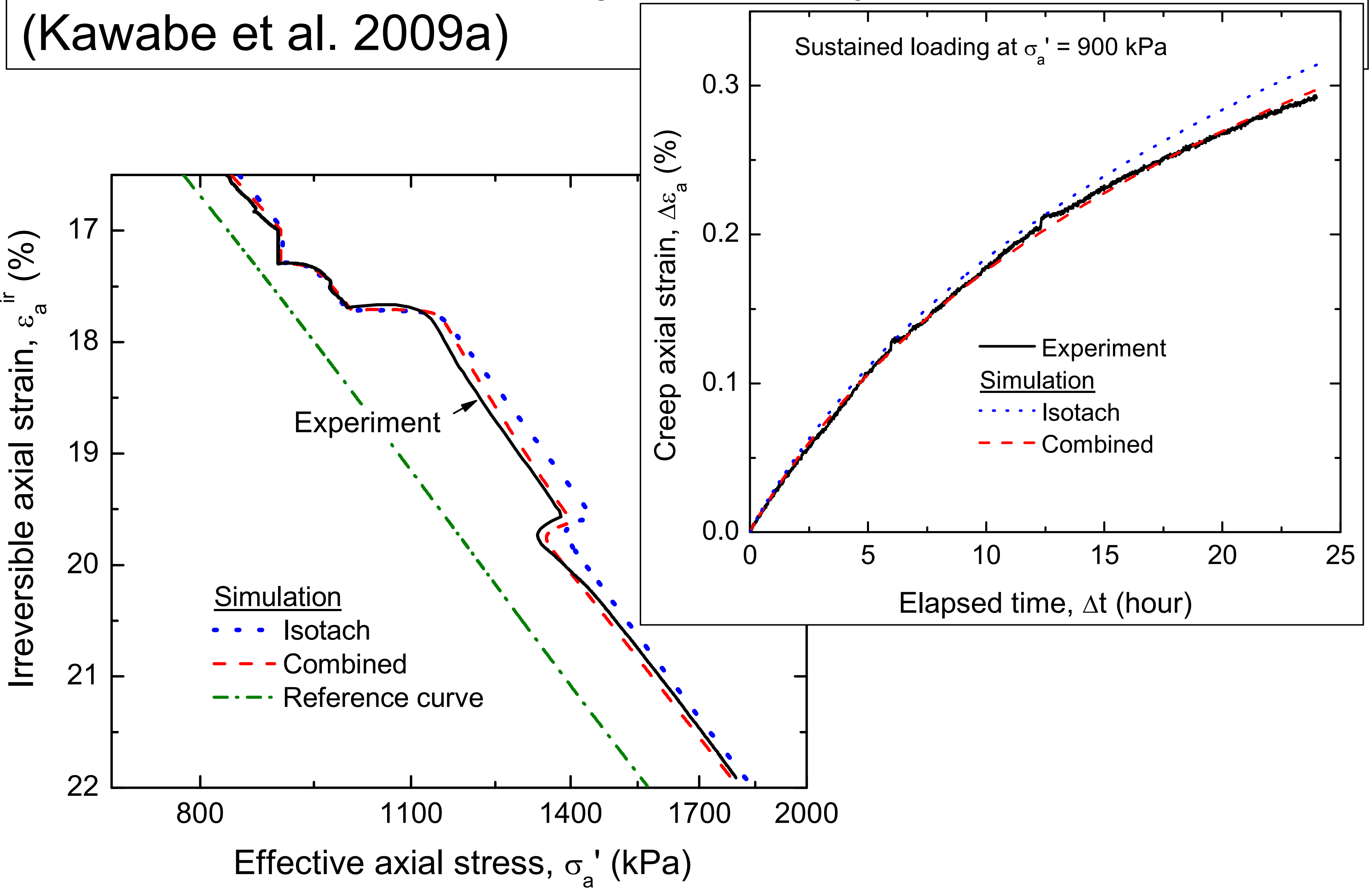
1D compression changing the strain rate, saturated kaolin made from slurry (*Isotach* type) (Kawabe et al. 2009b).



1D compression changing the strain rate, saturated kaolin made from slurry (*Isotach* type) (Kawabe et al. 2009b).



Non-Isotach behaviour (combined type) in 1D compression, saturated reconstituted Fujinomori clay (Kawabe et al. 2009a)



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Non-Isotach behaviour in DS tests on unbound interfaces between various types of solid (i.e., rocks and others), Dieterich and Kilgore (1994)

*M*obilised friction coefficient

$$\mu = \frac{\tau_{ave} \cdot A}{\sigma_{ave} \cdot A} = \frac{\tau_{contact} \cdot \alpha}{\sigma_{contact} \cdot \alpha}$$