PSA Novel Model of Brittleness Evaluation for Unconventional Reservoirs Based on Energy Consumption*

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Abstract

Brittleness evaluation plays an important role in unconventional oil and gas. However, the definition of brittleness is controversial and the models for brittleness evaluation have no reliable theory to support them, which makes brittleness evaluation unreliable. Rock failure is a process of energy dissipation and release. The energy dissipation leads to plastic deformation and damage of rock, while the releasable strain energy results in abrupt structural failure of rock. In this study, brittleness evaluation has been done in terms of energy. By defining it in terms of energy, rock brittleness from different areas can be compared. The influence factors ignored by other models of brittleness evaluation, such as confining pressure, temperature, and rock texture, can be addressed. Cyclic loading-unloading tests under different confining pressures have been done in order to investigate the effect of energy dissipation and release on rock failure. Most of the input energy is converted into the elastic strain energy during this process and the rest is dissipated. The energy dissipation cannot be released after unloading, while the elastic strain energy does. Therefore, the unloading curve normally falls below the loading curve to form a hysteresis loop. Then, the elastic strain energy and the energy dissipation of rock failure can be calculated from stress-strain curves or corresponding formulas in this paper. Our study shows that energy release leads to rock failure abruptly and energy dissipation determines the degree of rock fragmentation. Usually, the larger the energy dissipation during the process, the smaller the fragments after rock failure. Also, the energy dissipation of brittle rock stays low before failure and increases sharply when the failure happens, between which the ratio is usually less than 1:5. For ductile rock, there is relatively less difference in energy dissipation before and during the failure. This is because more energy is converted into plastic energy instead of the energy that increases the degree of rock fragmentation. The result is that even though the rock is failure, it does not break into pieces. Therefore, by comparing the value of energy dissipation and release not only could we evaluate rock brittleness, but also predict the degree of rock fragmentation after rock failure.

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A Novel Method of Brittleness Evaluation for Unconventional Reservoirs Based on Energy Consumption

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1 BACKGROUND

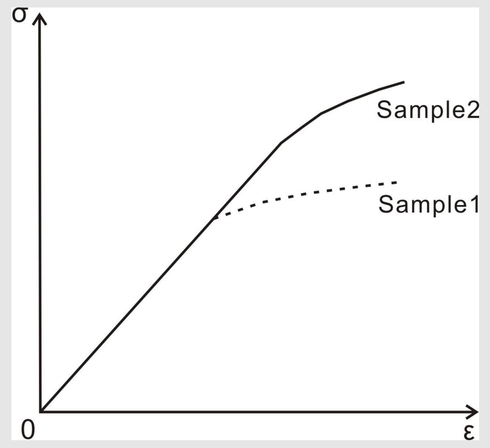
Brittleness is a parameter influenced by many factors, including rock mineralogy, rock mechanics characteristics, pressure and so on, which results in a plenty of descriptions and characterizations on brittleness.

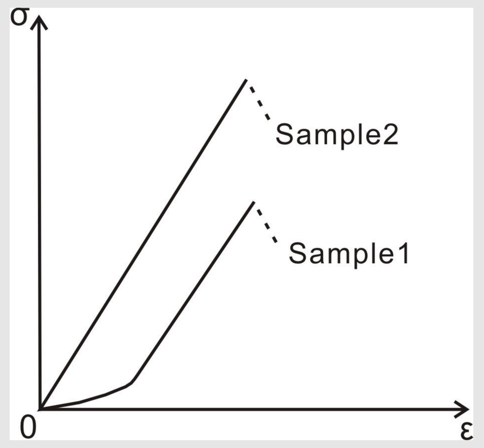
Factors like pressure, temperature and rock texture do have influence on brittleness, which should be considered in brittleness evaluation. Hu et al., 2016 proposed analytical models, which consider the influence of temperature, confining and pore pressure, respectively. However, those models does not work when temperature, confining and pore pressure change at the same time.

Brittleness Indices		Reference
$B_1=\frac{\varepsilon_{el}}{\varepsilon_{tot}}$	ε_{el} : elastic strain ε_{tot} : total strain	Coates
$B_2=\frac{W_{el}}{W_{tot}}$	W_{el} : elastic energy W_{tot} : total energy	Baron
$B_3=\frac{C_0-T_0}{C_0+T_0}$	C_0 : compressive strength T_0 : tensile strength	Hucka and Das
$B_4=\sin\varphi$	φ : friction angle	Hucka and Das
$B_5=\frac{\tau_{max}-\tau_{res}}{\tau_{max}}$	τ_{max} : peak strength τ_{res} : residual strength	Bishop
$B_6=\left\lvert\frac{\varepsilon_f^p-\varepsilon_c^p}{\varepsilon_c^p}\right\rvert$	ε_f^p : plastic strain at failure ε_c^p : specific strain beyond failure	Hajiabdolmajid and Kaiser
$B_7=\left(\frac{\sigma_{v,max}}{\sigma_v}\right)^b$	$\sigma_{v,max}$: max previous experienced effective vertical stress σ_v : current effective vertical stress b : empirical value ~0.89	Ingram and Urai
$B_8=\frac{1}{2}(\frac{E_{dyn}(0.8-\phi)}{8-1}+\frac{\upsilon_{dyn}-0.4}{0.15-0.4})\cdot 100$	E_{dyn} : dynamic Young's modulus υ_{dyn} : dynamic Poisson's ratio ϕ : porosity	Rickman et al.
$B_Q=\frac{Q}{Q+C+Cl}$	Q : quartz weight % C : carbon weight % Cl : clay weight %	Jarvie et al.

2 Why / PURPOSE

How to definite brittleness of two simples with the same elastic parameters?





How to definite brittleness in the following two cases:

- Case I: the rock needs more energy to failure, however, with high rock fragmentation degree after the failure
- Case II: the rock needs less energy to failure, however, with low rock fragmentation degree after the failure.

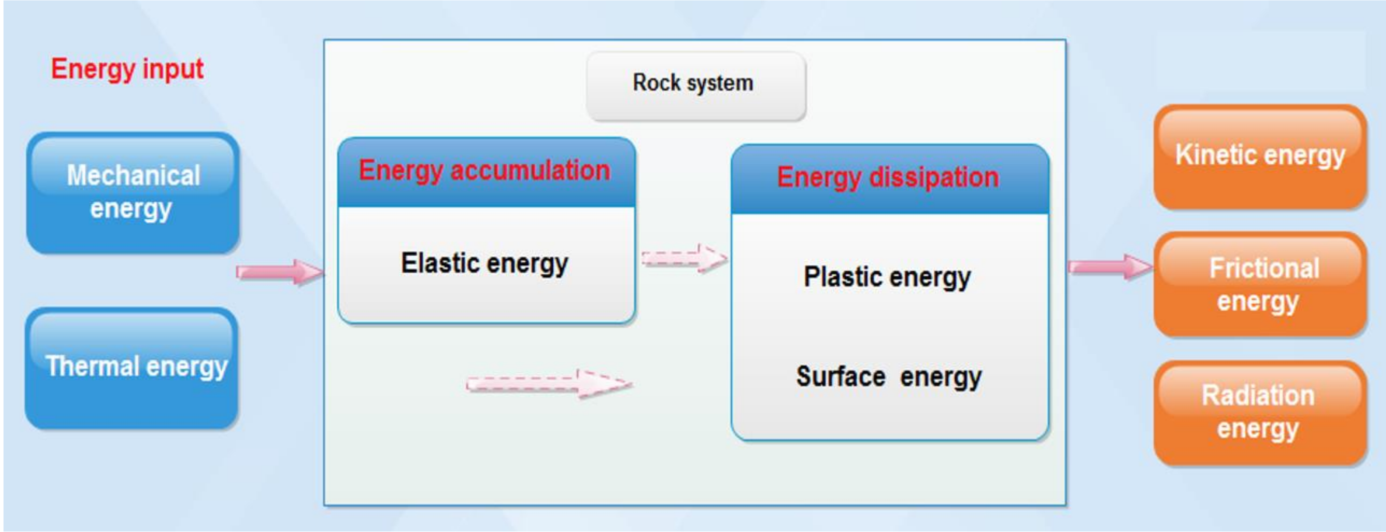
Case I: broken to pieces, with energy density 0.58MJ*mm-3 (Xie et al., 2005)

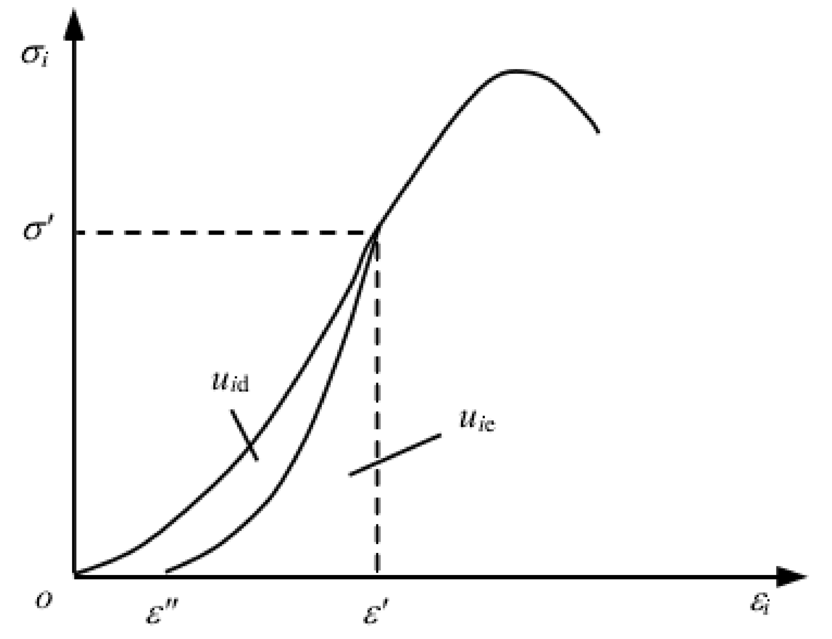
Case II: cleavage, with energy density 0.18MJ*mm-3 (Xie et al., 2005)

- The influence factors ignored by other models, such as confining pressure, temperature and rock texture, can be addressed in terms of energy.
- By defining BI in terms of energy, rock brittleness from different areas can be compared.
- The degree of rock fragmentation can be described by energy dissipation.

3 METHODOLOGY

Rock failure is a process of energy dissipation and release (Xie et al., 2005). Elastic energy stored in the rock is reversible and can be released in certain conditions. When rock failure , elastic energy transfers into surface energy to fracture the rock and plastic energy to make rock deformation. Therefore, how much elastic energy can be stored inside the rock and be released and how much of them can be used as dissipation energy is important to predict the degree of rock fragmentation .





Loading and unloading stress-strain curves of rock

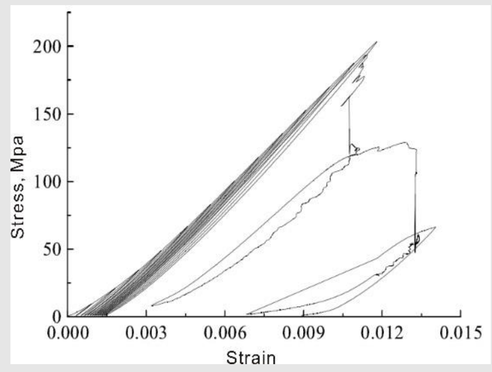
$$U_i^d=\int_0^{\varepsilon'}\sigma_i d\varepsilon_i-\int_{\varepsilon''}^{\varepsilon'}\sigma_i d\varepsilon_i$$

$$U_i^e=\int_{\varepsilon''}^{\varepsilon'}\sigma_i d\varepsilon_i$$

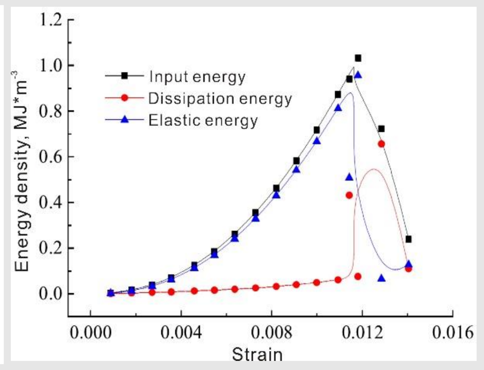
MTS815 electro hydraulic servo system

- Cyclic loading-unloading tests have been done in order to investigate the effect of energy dissipation and release on rock failure.
- Loading and unloading stress-strain curves can be used to calculate the dissipation energy and elastic energy, since releasable strain energy is reversible. The energy released from unloading is equal to the elastic energy accumulated from previous loading.

4 RESULTS

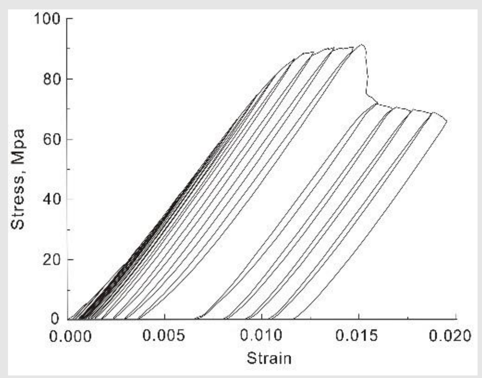


Loading and unloading stress-strain curves of sandstone (Zhang, 2013)

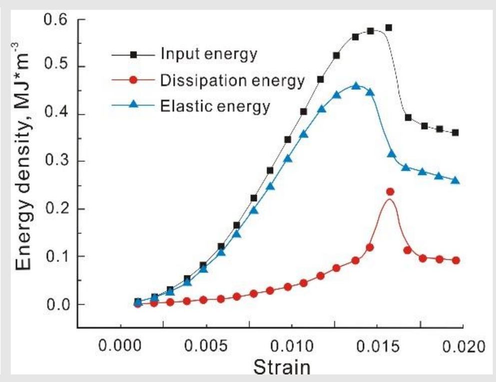


Energy evolution curves of sandstone (Zhang, 2013)

➢ The dissipation energy of brittle rock stays low before failure and increases sharply when the failure happens, between which the ratio is usually less than 1:5.



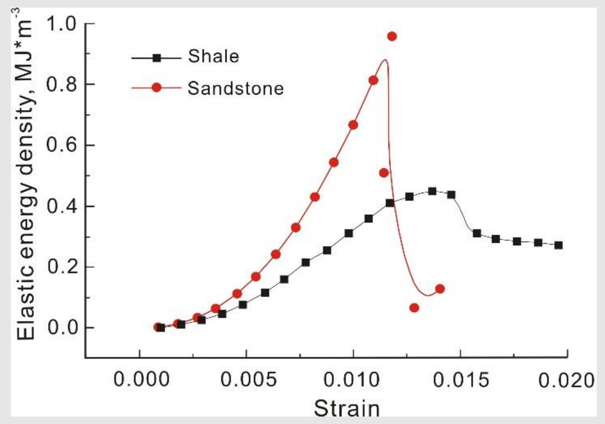
Loading and unloading stress-strain curves of shale



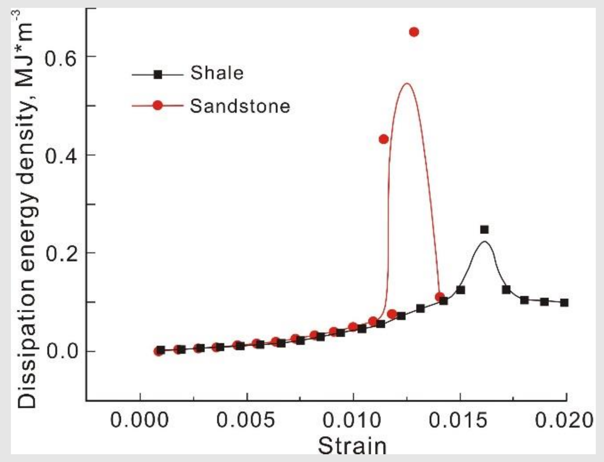
Energy evolution curves of shale

➢ For ductile rock, there is relatively less difference in energy dissipation before and during the failure, since more energy is converted into plastic energy instead of the surface energy.

Lithology	Maximum elastic energy density (MJ*mm^{-3})	Elastic energy density after failure (MJ*m^{-3})	Maximum dissipation energy density (MJ*m^{-3})
Sandstone	0.956	0.122	0.649
Shale	0.449	0.281	0.247



Variation of elastic energy density



Variation of dissipation energy density

Comparing with the ductile rock, more energy is converted into dissipation energy for the brittle rock. Even assuming that the plastic energy is the same for both the rocks, the energy being used to fracture the brittle rock is larger than the ductile one.

For brittle rocks, if we ignore the energy consumption of plastic deformation,

$$u^d\approx w_f=(4n\pi r^2-2\pi Rh-2\pi R^2)\gamma$$

Then, we can simplify the model by assuming that the rock will break into n balls of the same size.

According to volume conservation,

$$\frac{4}{3}n\pi r^3=\pi R^2 h$$

Therefore, we can get the relationship between the equivalent degree of rock fragmentation and the dissipation energy.

$$n=\frac{(\frac{u^d}{\gamma}+2\pi Rh+2\pi R^2)^3}{36\pi^3R^4h^2}$$

- For brittle rocks, the larger the energy dissipation during the process, the smaller the fragments after rock failure.
- For plastic rocks, the energy consumption of plastic deformation should be considered.

n: the equivalent number of rock fragments
u^d: the dissipation energy
γ: surface free energy
h: the height of the sample
R: the radius of the sample
r: the equivalent radius of the rock fragments