Water Saturation Effects on Rocks – Review and New Insights

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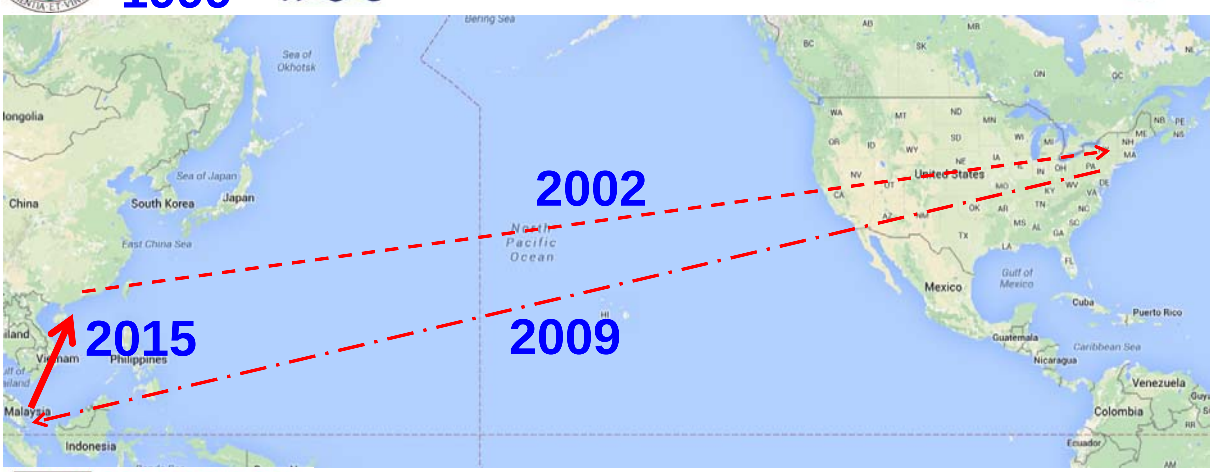
CDM
listen. think. deliver.

1999

CEDD

Massachusetts Institute of Technology



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1 Introduction - Motivation

- I want to study water weakening effect on compressive and tensile strength of a meta-sedimentary rock.
- Literature search
  - Recent compilations of experimental data on the influence of water on the strength of rock (e.g. Dyke & Dobereiner 1991; Vásárhelyi & Ván 2006)
  - Inconsistent laboratory procedures of determining the "water content", "water absorption" and "degree of water saturation"

1 Introduction - Objective

To reveal some of the problematic issues of quantifying the amount of water in rocks and the difficulty of obtaining a fully-saturated state in rocks.

1 Introduction - Approach

- Review **29** references (papers, books, standards, etc)
- Compare and contrast **definitions** of various commonly-used terminologies and measurement techniques
- **Three case studies** based on some data sets collected from published papers are analyzed.

Outline

- Introduction – motivation, objective, approach
- Results
  - terminologies
  - some comparisons
- Relationship between water content and related parameters
- Case studies
- Conclusions – Part 1
- Experiment
- Conclusions – Part 2

2 Results - terminologies

- ❑ **Water content or moisture content (含水量)**
- ❑ **Water absorption by weight or water absorption (吸水率)**
- ❑ **Degree of saturation, saturation degree and saturation coefficient (飽和度)**
- ❑ **Water absorption coefficient (吸水系數)**

2 Results – some comparisons

Water content

=

Water absorption?

2 Results – some comparisons

Water content (*w*) is defined as (Ulusay & Hudson 2007; Brown 1981; ASTM 1999)

$$w = M_w / M_s \quad (1)$$

where

M_w = mass of pore water

M_s = mass of grain (solid component of the specimen)

"Water absorption" (A_w), also known as "absorption" or "total water absorption", is given in ASTM (2001) as

$$A_w = (M_{sat} - M_{dry}) / M_{dry} \times 100\% \quad (2)$$

where

M_{sat} = mass of saturated-surface-dried test sample in air

M_{dry} = mass of oven-dry test sample in air

2 Results – some comparisons

"Water absorption capacity" (*WA*) is used as a measure of the amount of water absorbed by a rock immersed in water for a specific time (Cooke 1979) and is defined below.

$$WA = (W_3 - W_0) / (W_2 - W_1) \times 100\% \quad (4)$$

where

W_0 = dry weight of sample after tests

W_3 = weight of sample that is first dried (overnight or for 24 hours in an oven at 105°C then cooled) then saturated by water poured over the sample and left in water for 24 hours, wiped and then weighed in air.

2 Results – some comparisons

"Water absorption by capacity" is defined by Borrelli (1999) as the maximum quantity of water absorbed by a material at room temperature and pressure under conditions of saturation, again expressed as a percentage of the dry mass of the sample."

$$WAC = (M_{max} - M_d) / M_d \times 100\% \qquad (5)$$

where
M_{max} = mass of the sample at maximum water absorption
M_d = mass of the sample after re-drying at the end of the test

Siegesmund & Snethlage (2010)

"Water absorption under atmospheric pressure condition" (W_{atm}), also known as "freely or unforced water absorption"

"Water absorption under vacuum condition" (W_{vac}), also called "forced water absorption"

2 Results – some comparisons

Degree of saturation

=

Saturation coefficient?

2 Results – some comparisons

"Degree of saturation" (S_r) is defined in the ISRM suggested methods (1981)

$$S_r = V_w / V_v \times 100\% \qquad (8)$$

where
V_w = volume of pore water
V_v = volume of pore (voids)

"saturation coefficient" (S_r) is defined. It is expressed as the quotient of the freely or unforced water absorption and the forced water absorption (Hirschwald 1912; Siegesmund & Snethlage 2010), as shown in Eq. (10).

$$\boldsymbol{S_r} = W_{atm} / W_{vac} \times 100\% \qquad (10)$$

where
W_{atm} = the water absorption under atmospheric pressure, see Eq. (6)
W_{vac} = the water absorption under vacuum, see Eq. (7)

Further info

"Water absorption under atmospheric pressure condition" (W_{atm}), which is also known as "freely or unforced water absorption", is defined by Siegesmund & Snethlage (2010) as

$$W_{atm} = (M_{wet} - M_{dry}) / M_{dry} \times 100\% \qquad (6)$$

where

- M_{wet} = wet mass of the sample immersed in water for 48 hours
- M_{dry} = dry mass of the sample

"Water absorption under vacuum condition" (W_{vac}), which is also called "forced water absorption", is defined by Siegesmund & Snethlage (2010) as

$$W_{vac} = (M_n - M_t) / M_t \qquad (7)$$

where

- M_n = mass of the sample after forced water absorption
- M_t = dry mass of the sample

2 Results – some comparisons

"Water absorption coefficient" (w_{coe}, kg/ $m^2h^{0.5}$), which takes the surface area of the sample and the time of the sample immersed in water into account (Eq. (11)), is used to describe the capillary water absorption (Siegesmund & Snethlage 2010).

$$w_{coe} = m_w / t^{1/2} \quad (11)$$

where
m_w = the surface-related water absorption, kg/m^2
t = the absorption time, hour

Practical application?

time

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3 Relationship between water content and related parameters

Based on the above discussion, degree of saturation (S_r), water absorption by weight (A_w), dry density (ρ_{dry}) and effective porosity (ϕ_e) can be related by the following equations.

$$A_w = \rho_w \phi_e / \rho_{dry} \qquad (15)$$

Saturated!!

$$S_r = w / A_w \qquad (16)$$

If the rock is assumed to be fully saturated, i.e. $S_r = 100\%$

➔ water content is able to reach its maximum possible value, *max*(*w*), by filling up all the accessible void by water.

➔ *max*(*w*) is equivalent to water absorption by weight (A_w) as shown in Eq. (17).

➔ ϕ_e is then calculated from Eq. (15).

$$max(w) = A_w \qquad (17)$$

$$\max(\rho_{bulk}) = \rho_{sat} = (1 + A_w)\,\rho_{dry} \qquad (18)$$

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4 Case studies

- Published data from three sources are analyzed to highlight such any obscure usage of water absorption, water content and degree of water saturation.

- Some parameters are re-calculated, which are then compared with the values presented in the original references.

2 cases presented below

4 Case studies – case 1 (Shakoor & Barefield, 2009)

Sandstone	ρ_{dry} *1 (g/cm^3)	A_w(%)	ϕ_e (%)	ρ_{sat} *2 (g/cm^3)	RECALCUATED ρ_{sat} *3 (g/cm^3)
Lower Freeport	2.149	4.33	9.31	2.27	?
Berea A	2.160	5.42	11.72	2.29	?
Homewood	2.443	2.95	7.23	2.52	?
Juniata	2.520	1.63	4.12	2.57	?
Berea B	2.096	6.06	12.72	2.24	?
Sharon	2.126	5.53	11.77	2.26	?
Lower Mahoning	2.206	3.62	8.00	2.30	?
Cow Run	2.066	6.05	12.51	2.22	?
Black Hand	2.131	5.41	11.54	2.26	?

Note:
*1: Values were originally reported in unit of pcf. Numbers in SI units shown here are converted from pcf (1pcf = 0.016 g/cm^3) by retaining the same number of significant numbers
*2: Values obtained by multiplying the originally reported specific gravity values by water density (1g/cm^3)
*3: Re-calculate based on (ρ_{dry}, 2nd column) and (A_w, 3rd column)

4 Case studies – case 1

$\max(\rho_{bulk}) = \rho_{sat} = (1 + A_w)\,\rho_{dry}$ (18)

$\rho_{sat} = (1+0.0433) \times 2.149 = 2.24$ g/cm³

Sandstone	ρ_{dry} *1 (g/cm³)	A_w(%)	ϕ_e (%)	ρ_{sat} *2 (g/cm³)	RECALCUATED ρ_{sat} *3 (g/cm³)
Lower Freeport	2.149	4.33	9.31	2.27	
Berea A	2.160	5.42	11.72	2.29	
…	…	…	…	…	…

the ratio of the oven-dried weight of the core to its volume

calculated from bulk specific gravity at saturated surface-dried condition

using the phase relations by dividing the maximum volume of water absorbed by the core during 24-hour saturation by the total core volume given by Holtz & Kovacs (1981)

the cores were assumed to reach a 100 percent saturation after being submerged in water for 24 hours.

4 Case studies – case 2 (Erguler & Ulusay, 2009)

*rock specimens were considered to reach a **fully saturated state** after immersing them in water in a vacuum for a period between 24 and 48 hours.*

No.	Rock	ρ_{dry} (g/cm³)	ϕ (%)	A_w (%)	Recalculated ϕ_e (%)
L1-1	Siltstone	2.28	14.1	6.2	
L10-1	Tuff	1.36	33.6	19.6	

$\phi_e = A_w\,(\rho_{dry}/\rho_w) = 6.2 \times 2.28 = 14.1$

$\phi_e = A_w\,(\rho_{dry}/\rho_w) = 19.6 \times 1.36 = 26.6$

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5 Conclusions – Part 1

KEY FINDINGS

- Summarized definitions of various terminologies for characterizing the amount of water present in a rock specimen.
- For a particular term, such as water absorption, more than one definition is available, although the rationale behind various definitions is the same.

5 Conclusions – Part 1 (continued)

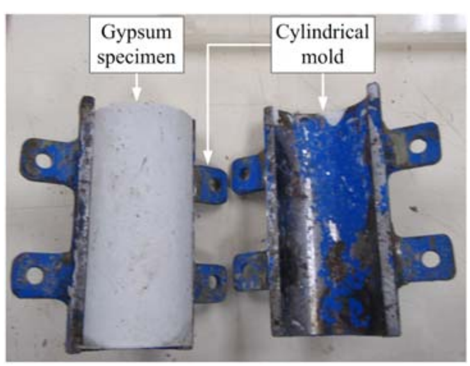
- Discrepancies are associated with procedures to obtain dry mass, wet mass, and duration of water saturation.
  - ✓ Always provide clear definitions for all the terms used in assessing the amount of water in rocks
  - ✓ Should be aware of the relevant definitions while using and comparing data in the literature
  - ✓ Beware of invalid assumption of "full saturation" in reported studies

Wong, L.N.Y.*, Maruvanchery, V. and Liu, G. (available online) "Water effects on rock strength and stiffness degradation", Acta Geotechnica.

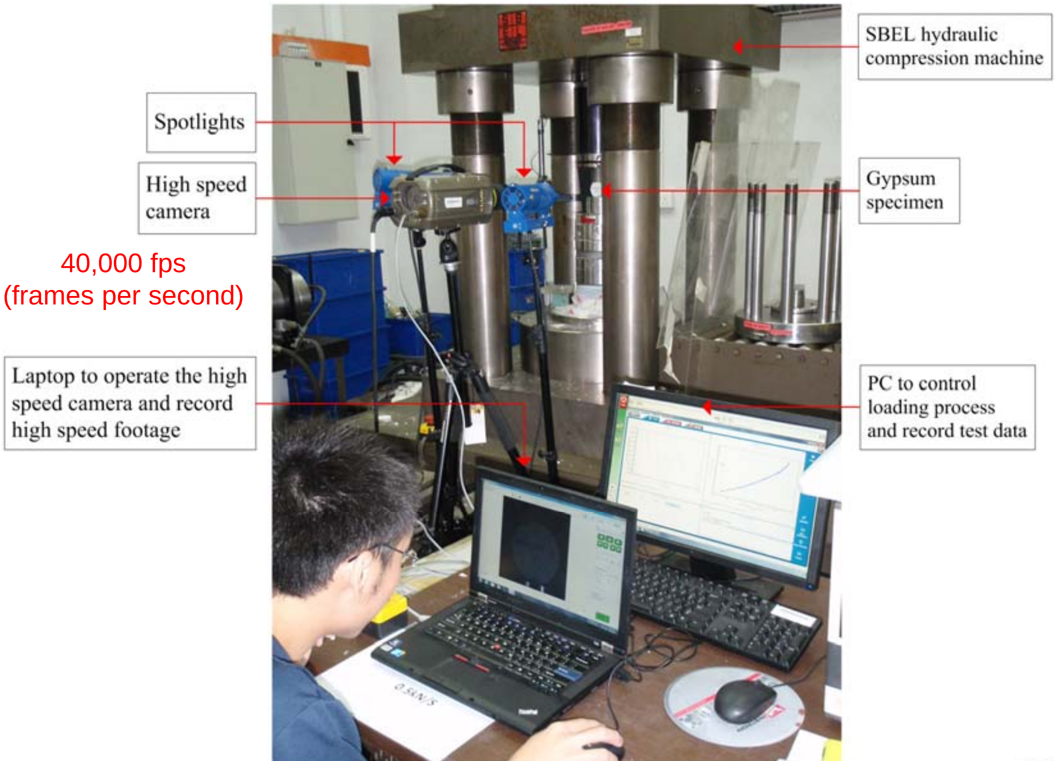
Wong, L.N.Y. and Liu, G. (2012) "Discussion of water content and related physical properties of rock", EUROCK 2012, Stockholm, 28-30 May, 2012.

6 Experiment

- Water weakening effect on the Brazilian tensile strength + fracturing behavior
- Artificially molded Hydrocal B-11 gypsum
- Dry specimens are oven-dried
- Wet specimens are prepared by soaking in water for 1, 3, and 10 weeks



6 Experiment

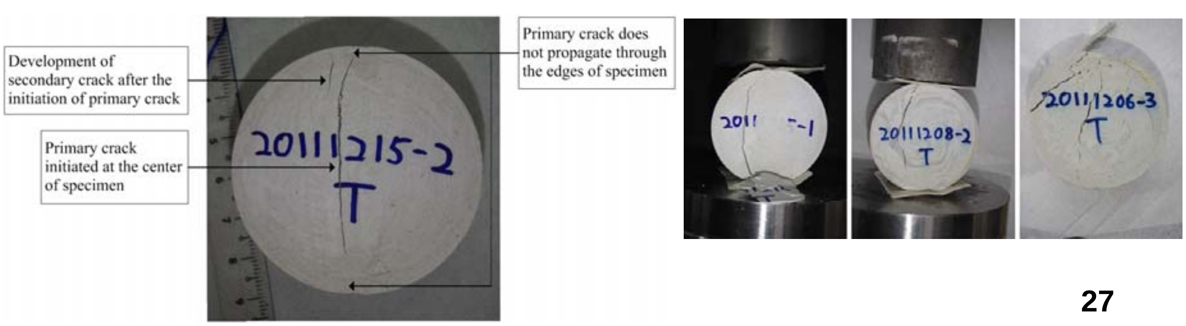


40,000 fps
(frames per second)

6 Experiment

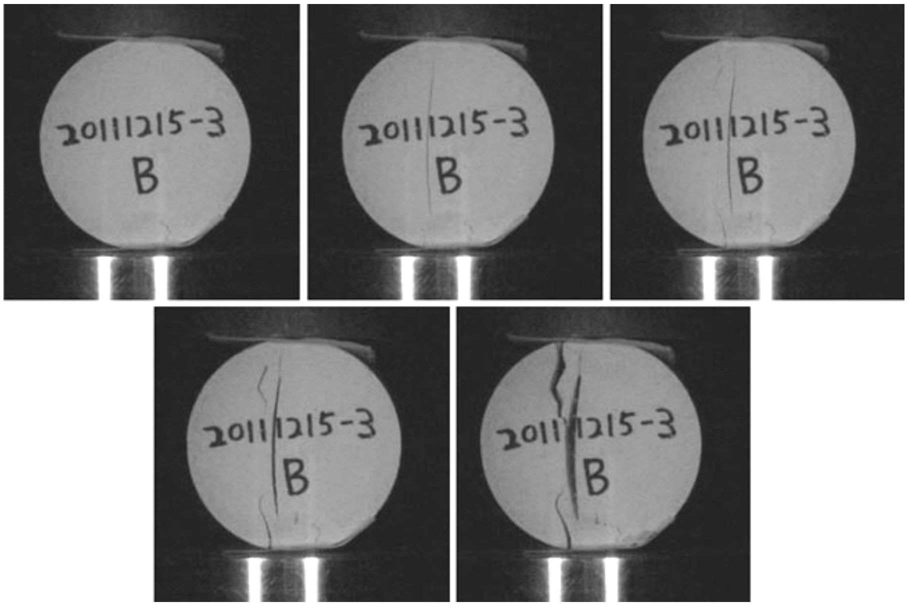
Immersion Time	Dry
No. of specimens tested	15
No. of invalid test results discarded	5
No. of valid test results	10
Average water content*	0%
Average tensile strength*	**4.50MPa**
Standard deviation*	0.41MPa
Reduction in tensile strength	-

Wet…



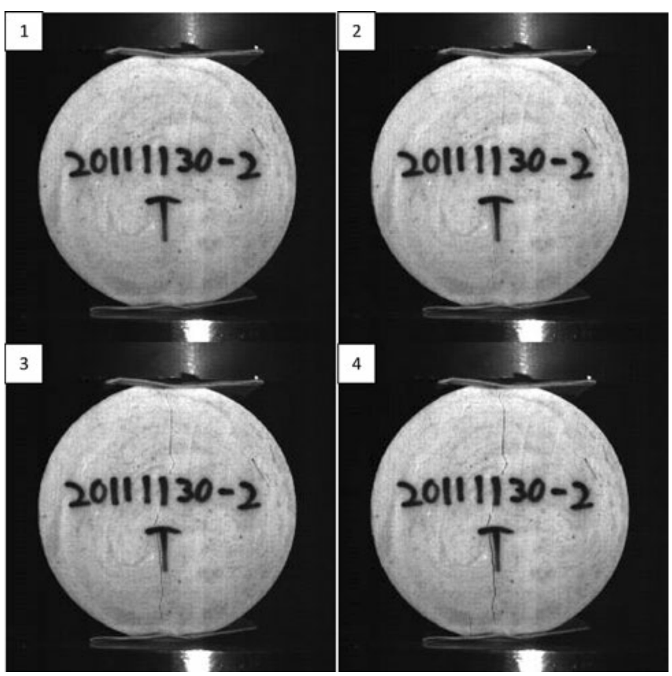
6 Experiment

High-speed video analysis - cracking processes (DRY)



6 Experiment

High-speed video analysis - cracking processes (WET)



6 Experiment

High-speed video analysis - cracking processes (40,000 fps)

	Dry	Wet
Primary crack to propagate from center to edges	1 to 3 frames of time	5 to 10 frames of time
Cracking style	a single dominant crack propagating through the specimen	❑ >one crack initiates in the specimen ❑ these cracks coalesce to form the primary diametrical crack

Wong, L.N.Y.* and Jong, M.C. (2014) "Water saturation effects on the Brazilian tensile strength of gypsum and assessment of cracking processes using high-speed video" Rock Mechanics and Rock Engineering. 47(4), 1103-1115

7 Conclusions – Part 2

KEY FINDINGS

- ❑ Wetting no only affects the rock strength
- ❑ Wetting also affects the cracking processes

Thank you

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