DEVELOPMENT OF A VERY WEAK ANALOG SANDSTONE FOR BRITTLE INSTABILITY MODELLING IN UNDERGROUND EXCAVATION

MinesGRADS
Graduate Research And Discovery Symposium @ MINES
Connecting students to ideas

Doandy Y. Wibisono | Ph.D. Candidate, Civil and Environmental Engineering

Advisor: Dr. Marte Gutierrez | James R. Paden Chair and Distinguished Professor, Civil and Environmental Engineering

KEY HIGHLIGHTS

- An unusually very weak (ISRM, 1981) brittle analog sandstone is developed.
- Brittle analog sandstone specimens are prepared, conforming to mortar mixing terminology.
- Base mix constituents used are Type I/II Portland cement, F-75 Ottawa sand, and distilled water.
- The developed sedimentary rock is isotropic, homogenous, and densely compacted.
- Engineering treatments to the mixture were found to improve the brittleness.

MOTIVATION

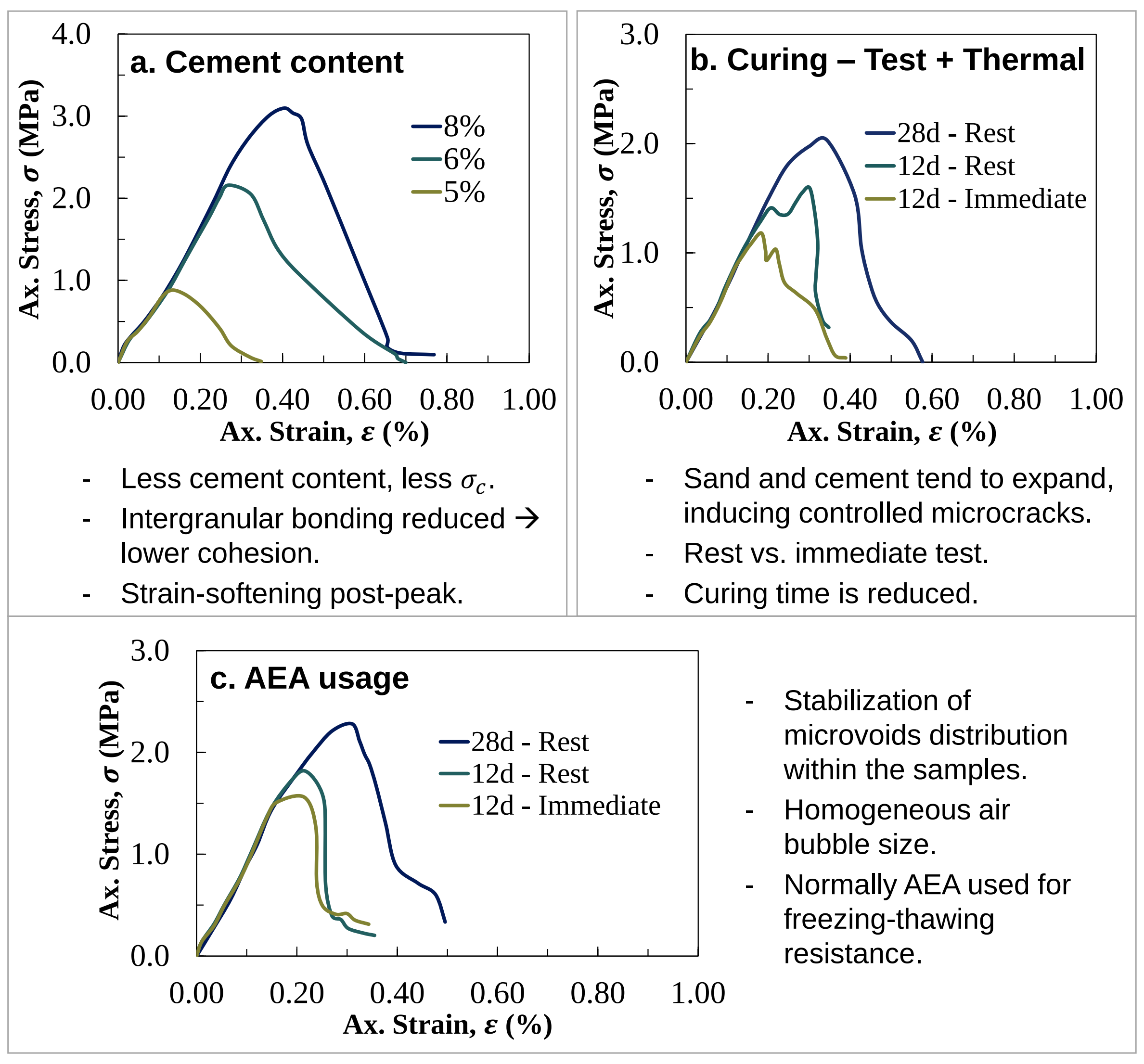
- Brittle instabilities pose a safety hazard during tunneling operations, and often cause violent and uncontrolled failure (i.e., spalling, rockburst). This has also occurred in sedimentary rocks lithology (Naji et al. 2019; Rivières and Goodman, 2023).
- Further physical modelling to a scaled-down tunneling operation by drilling and loading a cubical specimen (300 × 300 × 300 mm^3) using a miniature TBM and a true-triaxial cell, respectively (Wibisono et al. 2023a).
- Analog rock development allows controlled range of flexible properties to capture brittle instability (Johnston and Choi, 1986; Wibisono et al. 2023b).

RESEARCH OBJECTIVES

- Develop an analog rock design with very weak uniaxial compressive strength (UCS) with brittle characteristics.
- Improve the brittle failure understanding through laboratory characterization of the analog rock.

DEVELOPMENT PROCESS

- General **mixing method**:
  - Pre-mixing of solids.
  - Adding water and mixing for at least four minutes (40 RPM).
  - Casting the sample in three layers, with a tamping for compaction and ~10 mm disturbance to facilitate interconnection.
  - Curing the sample properly following ASTM C192 (ASTM 2021).
- Effect of **cement content**, **poorly-graded fine aggregate**, **curing time**, **thermal**, and **air-entrainment agent (AEA)**



- Less cement content, less σ_c.
- Intergranular bonding reduced → lower cohesion.
- Strain-softening post-peak.

- Sand and cement tend to expand, inducing controlled microcracks.
- Rest vs. immediate test.
- Curing time is reduced.

- Stabilization of microvoids distribution within the samples.
- Homogeneous air bubble size.
- Normally AEA used for freezing-thawing resistance.

Fig. 1. Development process summary with engineering treatment applied and stress-strain curves record as follows: (a) cement content variation, (b) thermal exposure, and (c) air-entraining admixture (AEA) usage. For (b) and (c), tested specimens contain 4% cement content.

COLORADO SCHOOL OF MINES
@150 | 1874-2024

- Effect of **water-saturation** and **frost exposure.**

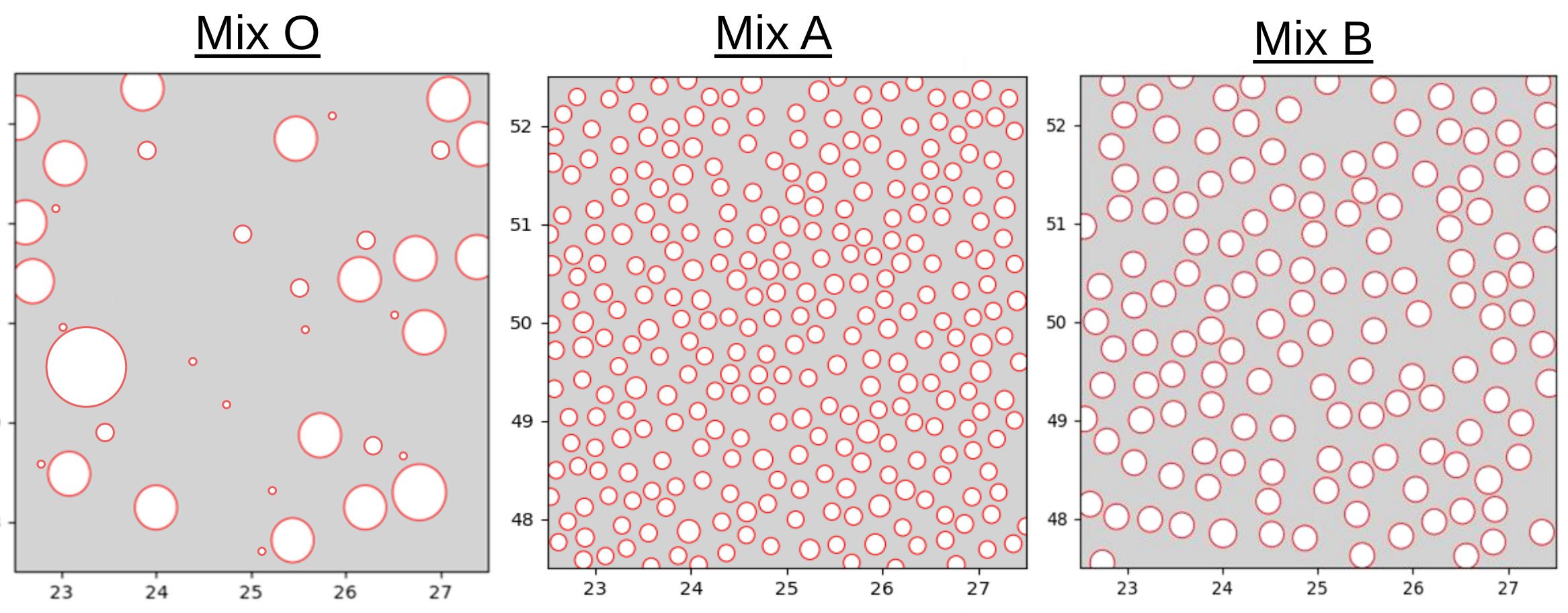


Fig. 2. Visual representation of perceived alterations in the entrained micropores, as affected by the application of different engineering treatments.

RESULTS AND DISCUSSIONS

• Mix Properties

Table 1. Summary of mix treatment and laboratory test results.

Properties	Mix O	Mix A	Mix B
Treatment remarks	*28 days curing*	*12d curing, AEA, therm*	*12d, AEA, sat-frost, therm*
Cement content, C	8%	4%	4%
Porosity, n	11.51%	29.71%	30.59%
$\overline{\sigma_c}$ (MPa)	3.07	1.82	1.68
$\overline{E_{50}}$ (GPa)	0.94	0.81	0.76
$\overline{\sigma}_t$ (MPa)	0.45	0.22	0.19
Hoek-Brown constant, m_i	4.89	19.93	20.58

• Brittleness assessment

Table 2. Summary of analog rock mix with rock bursting criteria. Note for burst-prone range, H and M denotes high and moderate proneness, respectively.

Brittleness assessment	Source	Burst-prone range	Mix O	Mix A	Mix B
Strength brittleness index, $B_1 = \sigma_c/\sigma_t$	Hucka and Das (1974)	<14.5 (H)	7.36	8.27	**8.84**
Brittleness index modified, $BIM = A_2/A_1$	Goodman (1989)	1.0 - 1.2 (H), 1.2 - 1.5 (M)	1.18	1.38	**1.11**
Burst energy coefficient, $R = W_E/W_P$	Aubertin et al. (1994)	> 1.0 (M-H)	1.3	1.56	**2.50**

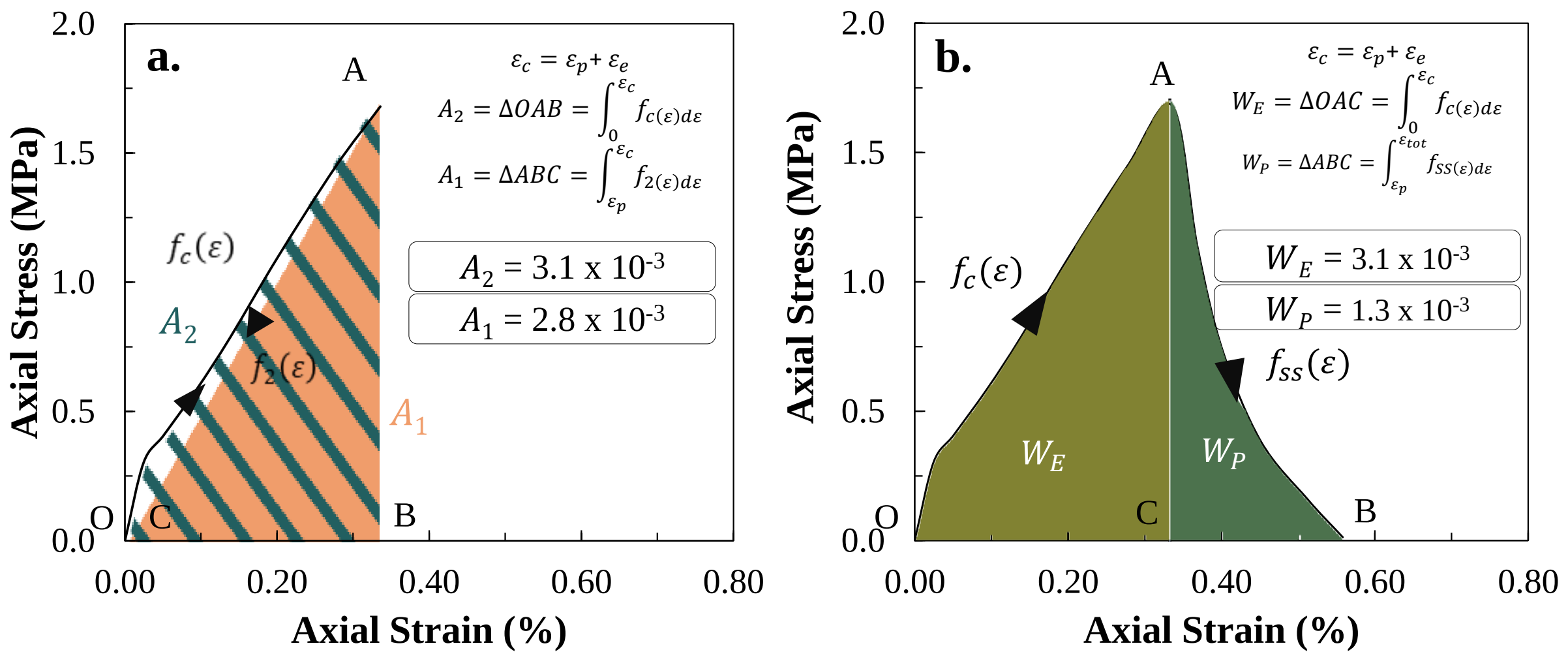


Fig. 3. Brittleness assessment using stress-strain curve from UCT; (a) brittleness index modified BIM and (b) burst energy coefficient R. Shown plots are for Mix B.

• Sample failure morphology

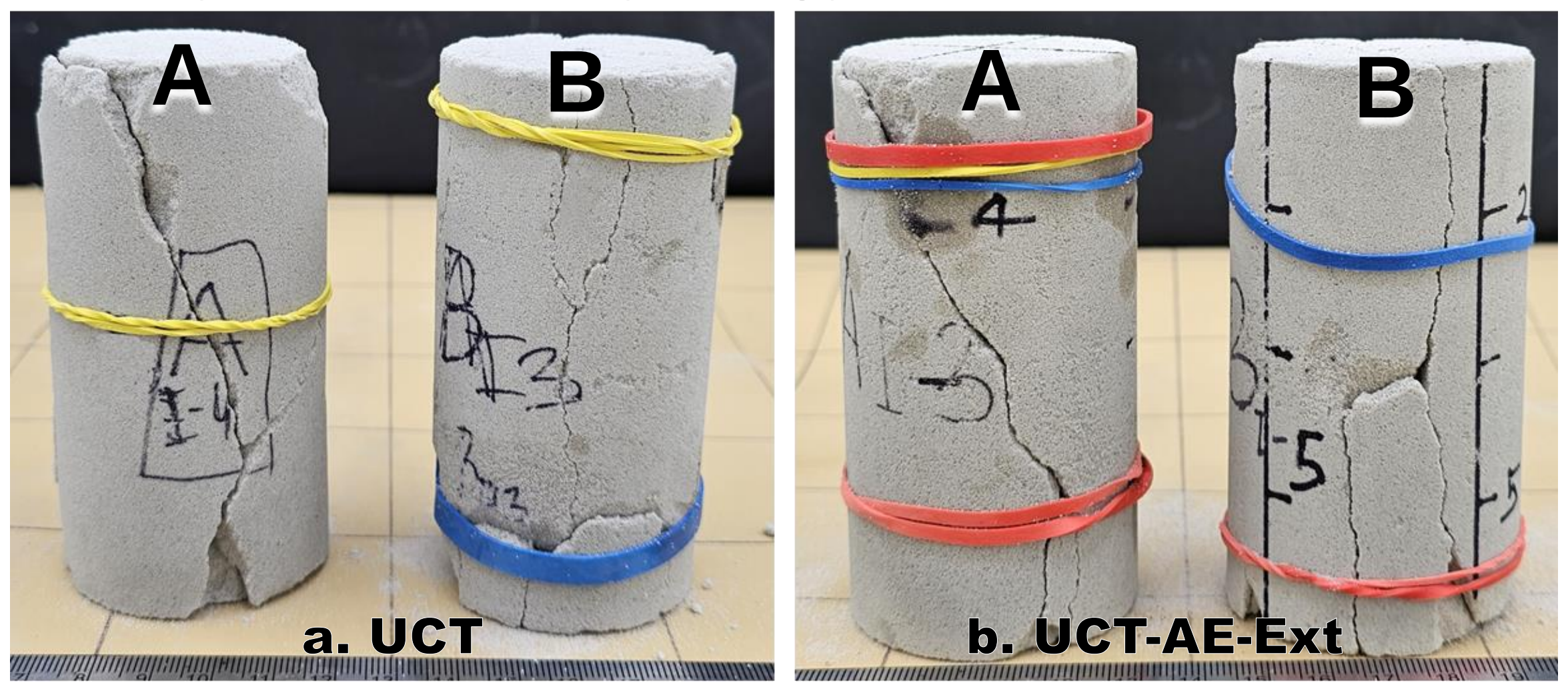


Fig. 4. The specimens of both Mix A and B after unconfined compression tests: (a) UCT and (b) UCT-AE-Ext. Mix B specimens exhibited failure characterized by more sub-vertical fractures, parallel to major principal stress extensional fractures, in contrast to Mix A.

• Brittle-ductile (B-D) transition

- Mix B with the largest Hoek-Brown constant m_i (Table 1) expected to have higher threshold of B-D transition (Rahjoo, 2019) as follows:

$$\frac{\sigma_3^*}{\sigma_c} = \left(\frac{m_i + \sqrt{m_i^2 + 4d^2}}{2d^2}\right) \qquad (1)$$

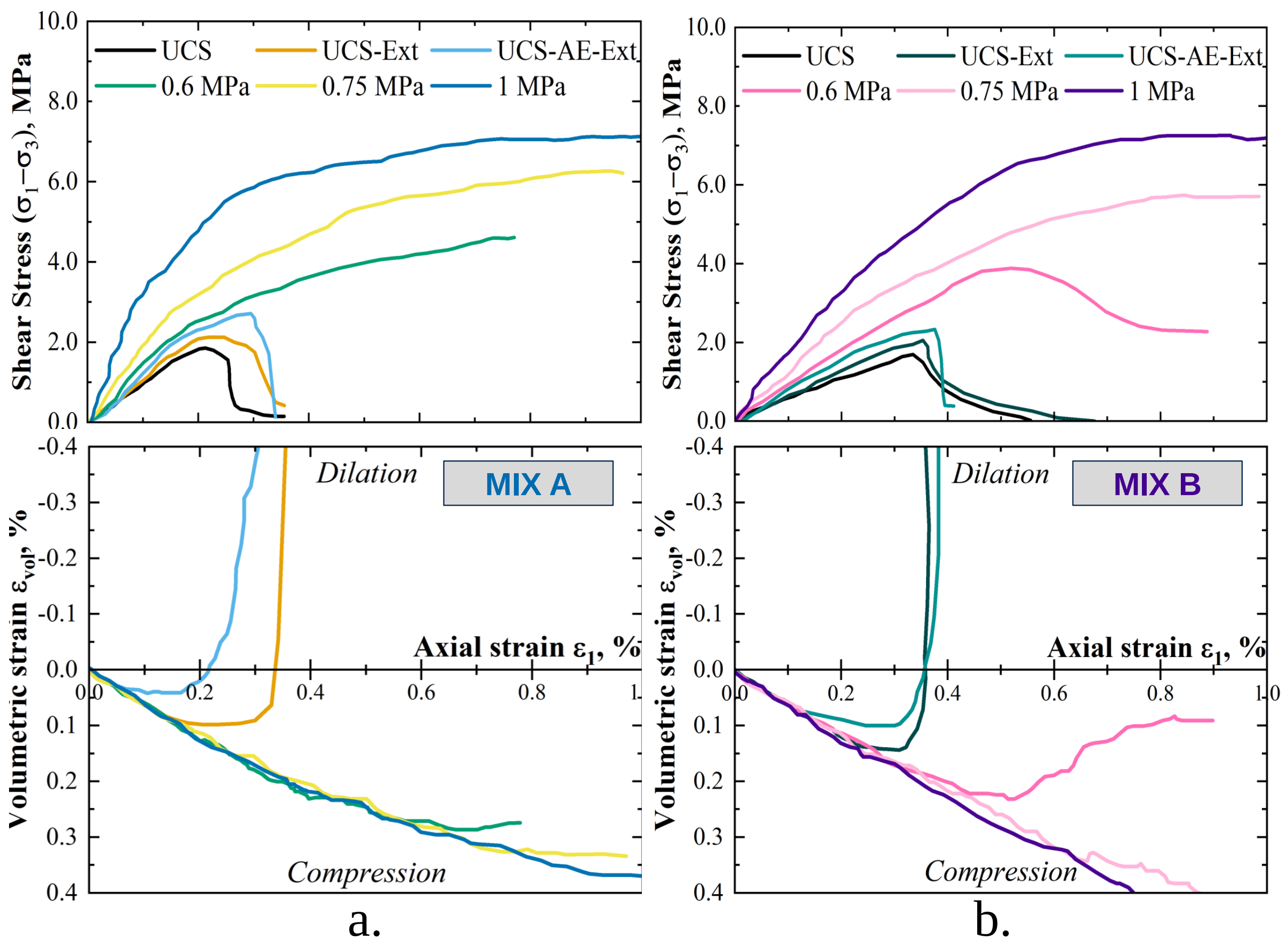


Fig. 5. Full stress-strain (upper) and volumetric strain curves (lower) associated with compression tests for a) Mix A—only saturation and thermal exposure, and b) Mix B—with additional frost exposure.

• Comparisons to literature and natural sandstone

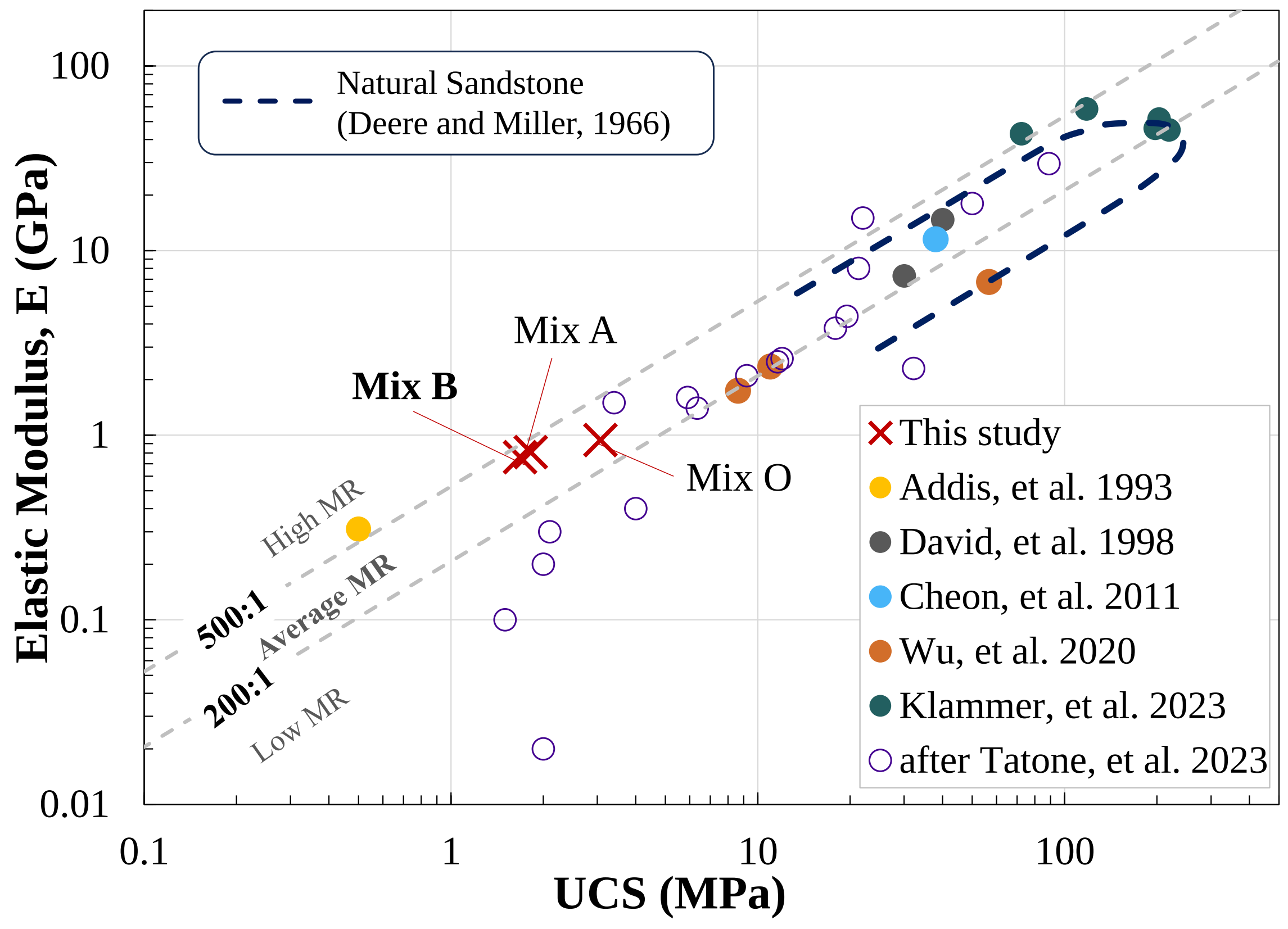


Fig. 6. Comparative plot depicting the elastic modulus and UCS of very weak analog sedimentary rocks developed in this study, alongside data collected from previous studies on sandstone and rock-like materials.

CONCLUSIONS

i. An analog sandstone with brittle characteristics was developed using mortar terminology.
ii. The post-peak behavior of strain softening was improved during the development process, indicating a more brittle failure.
iii. The entrained and enlargened micropores treatment allowed faster crack propagation.
iv. The brittle-ductile transition was expanded to a larger range, as confirmed by the triaxial test.
v. The developed analog sandstone can be used for further experiments to gain a deeper understanding of brittle failure in underground excavations.

ACKNOWLEDGMENT

The present study is financially supported by the University Transportation Center for Underground Transportation Infrastructure (UTC-UTI) at the Colorado School of Mines under Grant No. 69A3551747118 from the US Department of Transportation (DOT). The opinions expressed in this paper are those of the authors and not of the DOT.

REFERENCES

ASTM. ASTM Standard C192/C192M – 19 Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. Book of Standards, vol. 04.01, 2021b.

ISRM. Suggested methods for determining tensile strength of rock materials. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts 1978;15:99–103.

Johnston IW, Choi SK. A synthetic soft rock for laboratory model studies.

Naji AM, Emad MZ, Rehman H, Yoo H. Geological and geomechanical heterogeneity in deep hydropower tunnels: A rock burst failure case study. Tunnelling and Underground Space Technology 2019;84:507–21.

Rahjoo M. Directional and 3-D confinement-dependent fracturing, strength and dilation mobilization in brittle rocks 2019.

Rivières J-L des, Goodman R. Acclimatization: Adapting Conventional Tunnel Lining Techniques to Overstress Rock Conditions. RETC 2023, 2023, p. 422–34.

Tatone BSA, Abdelaziz A, Grasselli G. Example framework for evaluation of synthetic rock-like materials as applied to a commercial gypsum cement. International Journal of Rock Mechanics and Mining Sciences, 2023

Wibisono, D. Y., Arora, K., Majumder, D., & Gutierrez, M. Laboratory-Scale Rockburst Physical Model Testing Using a True-Triaxial Cell. IOP Conference Series: Earth and Environmental Science, 1124(1), 12039, 2023a

Wibisono, D. Y., Gutierrez, M., Majumder, D., & Gautam, P. K. Development of a Weak But Brittle Analog Sediment Rock for Experimental Study. 57th US Rock Mechanics/Geomechanics Symposium, 2023b

Contact of presenting author:
dwibisono@mines.edu