Static and dynamic mechanical properties of sedimentary rock after freeze-thaw or thermal shock weathering

Peng Wang ^{a,*}, Jinyu Xu ^{a,b}, Shi Liu ^a, Haoyu Wang ^a, Shaohe Liu ^a

^a Department of Airfield and Building Engineering, Air Force Engineering University, Xi'an, Shaanxi, China

^b College of Mechanics and Civil Architecture, Northwest Polytechnic University, Xi'an, Shaanxi, China

Abstract:

Rocks in engineering works and as building materials are always suffering freeze-thaw (F-T) and thermal shock (TS) weathering, and engineering rocks usually involve responses to impact loads from blasting operation, mechanized construction and seismic oscillation. Sedimentary rock distributes extensively and is important for engineering geological and hydrogeological works. For a deeper understanding of the F-T and TS effects on the rock behaviors, physical tests, static compressions and dynamic impacts were carried out on red-sandstone free from and after artificial F-T or TS cycles in this work. Laboratory tests show the significant physic-mechanical deterioration of red-sandstone after F-T or TS weathering. Compared to fresh specimens, red-sandstone after 10 F-T or TS cycles performs poorly in both the static compression and SHPB impact tests, and F-T/ TS induced decreases of UCS and modulus are more remarkable under dynamic impacts than under static loads. Dynamic mechanical behaviors of both fresh and F-T/ TS weathered red-sandstone have distinguishable strain rate effects, and water content significantly affects the strain rate effects on mechanical behaviors. Water and temperature variation play important roles in the rock weathering process. In this work, water effects during the rock weathering process were summarized as solvent effect and medium effect, while temperature variation damaged red-sandstone mainly in two ways, non-uniform thermal deformation of mineral grains and phase-transition of water.

* Corresponding author. P. Wang
E-mail address: wpsuai@126.com

Keywords:

Weathering; rock impact dynamics; freeze-thaw; thermal shock; the SHPB; deterioration

1. Introduction

Exposed to the atmosphere and water, as well as artificial disturbances during engineering construction, rocks are always suffering various kinds of weathering (Alavi Nezhad Khalil Abad et al., 2014; Ercoli et al., 2014; Alavi Nezhad Khalil Abad et al., 2015a,b). Due to the significant effects on engineering properties of rock mass, rock weathering is crucial in the whole design, construction and maintenance stages of geotechnical works (Shen, 2004; Alavi Nezhad Khalil Abad et al., 2016).

Cycling freeze-thaw (F-T) and thermal shock (TS) are typical weathering processes and have strong impacts on the physico-mechanical behaviors of rock. Repeated F-T is common and damaging in cold region (Fatih, 2012), where the environment temperature floats up and down the freezing point of water. The frequent freezing and thawing of pore water inside rock expands the cracks and pores and promotes the development of new micro-fractures and thus does great damage to rock engineering (Sousa et al., 2005; Park et al., 2015). Generated by sudden changes in temperature, TS is ‘catastrophic fracture under most conditions of high heat transfer and/or rapid environmental temperature variations’ (Hasselman, 1969). Rock is naturally a three phase system of air-water-solid, and water behavior is affected by temperature variation during the F-T or TS process, which in turn affects the heat transmission and rock properties. Thus, the F-T and TS weathering of rock are typical coupled hydro-thermal-rock interaction processes.

Besides, because of the widely existed blasting operation, mechanized construction and seismic oscillation, rock engineering disasters often involve rock responses to stress pulses or impact loads, and the corresponding prevention and cure researches come down to the analyses on dynamic mechanical properties of rock-like materials (Zhang and Zhao, 2014; Huang and Xia, 2015;). Due to the rate sensitivity, mechanical

responses of rocks after F-T/TS weathering to dynamic loads differ from those to static loads. Literature reviews show that investigations about the F-T/TS weathering are concentrated on physical and static mechanical properties of rock (Tuğrul, A., 2004; Yavuz et al., 2006; Basu et al., 2009; Basu et al., 2012; Ghobadi and Babazadeh, 2015), while only a few published works studies on the dynamic mechanical behaviors of F-T/TS weathered rock. Wen et al. (2015) obtained the relationship between the dynamic strength with the freeze-thaw cycles according to numerical simulations and experiments. Zhou et al. (2015) obtained the microscopic damage characteristics and dynamic mechanical parameters of sandstone after freeze-thaw from the nuclear magnetic resonance (NMR) tests and impact loading tests. Investigations about the effects of water and temperature on rock dynamic mechanical properties during the weathering process are far from enough.

Sedimentary rock distributes extensively in the superficial lithosphere, of which the distribution area is the main provider of minerals and the main place for engineering geological and hydrogeological works. For a deeper understanding of the F-T and TS weathering effects on the static and dynamic mechanical properties, static and dynamic compressive tests on sedimentary rock free from and after cycling F-T or TS were carried out and the results were analyzed in this work. Red-sandstone, a common sedimentary rock, was selected as the test object in this paper. Totally four groups of specimens were prepared for static compressive tests and dynamic impact tests respectively, of which one group was free from weathering treatments and tested in dried state, one group was also free from weathering treatments but tested in water-saturated state, one group was saturated and weathered by 10 F-T cycles and tested in saturated state, the last group was saturated and weathered by 10 TS cycles and then dried before loading tests. Impact loading tests were carried out using the split Hopkinson pressure bar (SHPB) system (Xia and Yao, 2015), with the impact condition set at three incident pulse intensity grades.

2. Material and methods

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prepared, free from or after F-T/ TS weathering. Water absorption and cycling F-T/ TS tests followed the DL/T 5368-2007 (National Development and Reform Commission of the People's Republic of China, 2007).

Two groups of specimens were prepared free from F-T and TS cycles for comparative analyses, named as dried specimens and saturated specimens respectively. The specific preparing process was: 1). Dried specimens were made by drying in an oven at 107°C for 48-hours. 2). Saturated specimens were made by submerging the dried specimens in water at room temperature for 48-hours and then submerging in boiling water for 6-hours.

Another two groups of specimens were made by artificial weathering tests, one for 10 F-T cycles and one for 10 TS cycles.

Fig.2. Temperature-time schematic diagrams of accelerated weathering: (a) freeze-thaw cycles; (b) thermal shock cycles

An automatic freeze-thaw cycle machine was used for accelerated F-T weathering, with one F-T cycle procedure set as follows: 4-hours freezing in air after the test chamber temperature reaching -20°C, followed by a 4-hours thawing in water at 20°C. In this paper, 10 F-T cycles were carried out on red-sandstone specimens saturated beforehand. An electric thermostat-box and a thermostatic water bath were used for accelerated TS weathering. For one TS cycle, specimens were heated inside the air-ventilated thermostat-box at 200°C for 4-hours (exclusive of the heating up time), then the specimens at 200°C were taken out of the box and immediately immersed in water at 20°C for 6-hours. In this paper, 10 TS cycles were carried out on

99 saturated red-sandstone specimens as well. Since Newton's Law of Heating and Cooling applied to those F-T
 100 or TS cycles, the temperature change followed almost the same path during each cycle for F-T or TS tests
 101 respectively (see Fig.2) (Mutlutürk et al., 2004). Specimens after 10 F-T cycles were kept underwater till
 102 loaded in mechanical tests, except for a short time for physical determination. TS weathering tests differed.
 103 Samples after 10 TS cycles were dried in an oven at 107°C for 48-hours and then cooled to room temperature.
 104 In other words, the F-T weathered specimens remained almost saturated while the TS weathered specimens
 105 were dried for the mechanical tests.

106 Red-sandstone specimens were significantly damaged after 10 cycles of F-T or TS, clear from the visible
 107 macro-cracks and mineral loss on the specimen surfaces as shown in Fig.3.

108 **Fig.3.** Typical superficial morphologies of red-sandstone specimens after 10 F-T or TS cycles: (a) Upper surface, after 10 F-T cycles;
 109 (b) Upper surface, after 10 TS cycles; (c) Cracks at edge, after 10 F-T cycles; (d) Cracks at edge, after 10 TS cycles.

111 2.3. Physical property determination

112 Dry density (ρ_{dry}) and saturated density (ρ_{sat}) of red-sandstone were measured as Eq.(1) and applied to
 113 at least 48 specimens in dried or saturated state respectively in this work, obtaining the dry density and
 114 saturated density being 2.21 g/cm³ and 2.39 g/cm³ in average.

$$115 \quad \rho_{dry} = \frac{M_{dry}}{V_{dry}} \quad ; \quad \rho_{sat} = \frac{M_{sat}}{V_{sat}} \quad (1)$$

116 where M_{dry} and V_{dry} represent mass and block volume of oven-dried sample; M_{sat} and V_{sat} stand for mass

and block volume of saturated-surface-wiped sample.

Water absorption (A_w) defined by ASTM (2001) as Eq.(2) and total porosity (ϕ) determined using buoyancy techniques by ISRM (1981) as Eq.(3) were measured in this work. Calculated results of A_w and ϕ were averaged in Table 1.

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

$$\phi = \frac{M_{sat} - M_{dry}}{M_{sat} - M_w} \times 100\% \quad (3)$$

where M_w is the saturated-submerged weight measured with the saturated specimen immersed in water; M_{dry} and M_{sat} are of the same meanings as in Eq.(1).

Table 1 Averages of water absorption and total porosity free from and after 10 F-T or TS cycles

Red-sandstone specimens	Water absorption, A_w (%)			Total porosity, ϕ (%)		
	Free from	After 10	After 10	Free from	After 10	After 10
	F-T and TS	F-T cycles	TS cycles	F-T and TS	F-T cycles	TS cycles
Static specimens ($\Phi 50 \times 100$ mm)	7.54	9.08	8.56	16.92	19.37	18.54
Impact specimens ($\Phi 96 \times 48$ mm)	7.42	8.95	8.44	16.44	18.84	18.04

*Notes: A_w and ϕ of red-sandstone free from F-T/ TS are average values from 12 static specimens and 36 impact specimens tested before weathering process; A_w and ϕ of red-sandstone after 10 F-T cycles are average values from 6 static and 6 impact specimens suffered from 10 F-T cycles and free from loading tests; A_w and ϕ of red-sandstone after 10 TS cycles are average values from 6 static and 6 impact specimens suffered from 10 TS cycles and free from loading tests.

2.4. Ultrasonic and SEM tests

Ultrasonic test was applied on specimens both prior to and after F-T/ TS. Direct method (Kahraman, 2002) was adopted and a nonmetal supersonic test meter with two transducers of 50 KHz was used to detect the P-wave velocity. Vaseline was distributed at the sample-header interface as the ultrasonic coupling fluid. Test results of P-wave velocity were averaged in Table 2.

Table 2 P-wave velocities of red-sandstone specimens before or after artificial weathering

Sandstone specimens	Specimens for static compression		Specimens for impact compression	
	P-wave velocity (m/s)	Relative change (%)	P-wave velocity (m/s)	Relative change (%)
Before TS cycles (dried)	2671.5	-17.1%	2672.8	-14.6%
After 10 TS cycles (dried)	2213.6		2283.6	
Before F-T cycles (saturated)	2967.3	-25.2%	2843.3	-24.1%
After 10 F-T cycles (saturated)	2220.1		2159.3	

*Notes: P-wave velocity values are average values of 3 static specimens and 9 impact specimens respectively.

Scanning electron microscopy (SEM) was carried out to visualize the microscopic changes of red-sandstone after F-T or TS cycles. Micro-cracks and surface micro-structure of red-sandstone specimens before or after accelerated weathering were clear from SEM images as shown in Fig.4.

Fig.4. Micro-cracks and surface micro-structure of red-sandstone specimens: (a) Dried specimen; (b) Saturated specimen; (c) Specimen after 10 F-T cycles; (d) Specimen after 10 TS cycles.

Thermal deformation of mineral grains and phase-transition of water occurred during those weathering processes, leading to various degrees of damages of red-sandstone after 10 F-T or TS cycles. Significant as Fig.4 that microstructures of F-T and TS weathered specimens had some changes in common, with pores

150 becoming more and bigger, cements between mineral grains losing seriously, mineral granules getting more
151 separate from each other and cohesion between them getting weaker. From comparison of Fig.4 (c) and (d),
152 differences were also obvious between F-T and TS induced damages that cracks crossed the mineral grains of
153 specimens after 10 F-T cycles which had rarely been found from specimens after 10 TS cycles.

154 2.5. Mechanical experiments

155 Both static and dynamic compressive tests were applied on red-sandstone specimens of four groups.

156 2.5.1. Static compressive tests

157 Static uniaxial compressive tests were done by hydraulic servo material testing system, with the stress
158 rate between 0.16 and 0.18 MPa/s. Static tests were carried out on three specimens for each group, and the
159 averaging results were displayed in Fig.9 and Fig13. In this paper, the uniaxial compression strength (UCS),
160 i.e. peak stress (σ_p), was the maximum axial stress of specimen during the compression and critical strain
161 (ε_c) was the corresponding axial strain at that moment. Definitions of modulus are various (Wang et al., 2015)
162 due to the nonlinear deformation of rock. In this paper, both elastic modulus (E_e) and deformation modulus
163 (E_d) were calculated, as Eq.(4):

$$164 \quad E_e = \frac{\sigma_{0.6} - \sigma_{0.4}}{\varepsilon_{0.6} - \varepsilon_{0.4}}, \quad E_d = \frac{\sigma_p}{\varepsilon_c} \quad (4)$$

165 where $\sigma_{0.6}$ and $\varepsilon_{0.6}$ represent respectively the stress and strain values at the pre-peak point of 0.6 times peak
166 stress; $\sigma_{0.4}$ and $\varepsilon_{0.4}$ stand respectively for the stress and strain values at the pre-peak point of 0.4 times peak
167 stress.

168 2.5.2. Impact compressive tests

169 The $\Phi 100\text{mm}$ split Hopkinson pressure bar (SHPB) system was applied to the uniaxial impact
170 compressive tests, with the basic principles displayed in Fig.5. To ensure dynamic equilibrium and deform

171 uniformity, pulse shaping technique was adopted and a circular annealed T2 copper pulse shaper, 1.0 mm in
 172 thick and 15-35mm in diameter, was placed on the impact surface of the incident bar (Frew et al., 2002).

173
 174 **Fig.5.** Schematic diagram of the Φ100mm SHPB system

175 In SHPB impact tests, incident wave generated by the strike of projectile against incident bar propagated
 176 along the incident bar, reflected and transmitted at the “bar-specimen-bar” interface, during which the signals
 177 of incident wave, reflected wave and transmitted wave were collected by strain gages, as shown in Fig.6.

178
 179 **Fig.6.** Impact pulse waves in the SHPB impact compression tests

180 Clear from Fig.6 that sum of the incident wave and reflected wave agreed well with the transmitted wave,
 181 reflecting the stress equilibrium of specimens during impact process. The incident wave intensity (I_i), as
 182 identified in Fig.6, greatly affected the dynamic mechanical behaviors of rock specimen and was selected as
 183 the main control factor in the tests. For each specimen group, impact tests of three I_i levels, 350MPa,
 184 440MPa and 630MPa, were carried out.

Based on the recorded wave signals, incident wave, reflected wave and transmitted wave, the dynamic stress-strain relation of specimen can be calculated through three-wave analysis (Zhou et al., 2012; Zou and Wong, 2014). Three specimens were impacted under each I_i level for each specimen group in this work, from which the stress-strain relations were calculated and typical curves were displayed in Fig.10 and Fig.14.

3. Results and analyses

Repeating F-T/ TS weathering led to deteriorations of red-sandstone. Changes of micro-structures influenced the mechanical responses to loads. F-T/ TS induced softening in mineral grains and inter-granular cements led to decreased loading capability and deformation-resistance capacity.

3.1. Cycling F-T weathering

In this paper, comparisons were done between specimens free from and after 10 F-T cycles, from which F-T effects on the physical, static mechanical and dynamic mechanical properties were analyzed.

3.1.1. F-T effects on physical properties

Relative physical parameter variations of red-sandstone after 10 F-T cycles were presented in Fig.7, including the mass, block volume, density, water absorption, total porosity, and P-wave velocity.

Fig.7. Relative variations of physical properties after 10 F-T cycles, measured in saturated state

Parameters including mass, block volume and density changed slightly (no more than 3%) after 10 F-T

cycles, for both static and dynamic specimens. In contrast, obvious variations occurred to water absorption and total porosity, increasing by about 20% and 15% respectively. Most remarkable decrease appeared with the P-wave velocity, dropping by 25.17% and 26.76% respectively for static and dynamic specimens respectively. Delicate differences between measured values from specimens for static and dynamic tests, $\Phi 50 \times 100 \text{mm}$ and $\Phi 96 \times 48 \text{mm}$ respectively, might result from size effects.

3.1.2. F-T effects on static mechanical properties

Typical axial static stress-strain curves of red-sandstone specimens free from or after 10 F-T/ TS cycles were drawn in Fig.8.

Fig.8. Static stress-strain curves of red-sandstone specimens free from or after F-T/ TS weathering: (a) unweathered dried specimen; (b) unweathered saturated specimen; (c) saturated specimens after 10 F-T cycles; (d) 10 TS cycles-weathered and then dried specimen.

As clear in Fig.8, F-T weathered specimens performed worse than saturated specimen, with a lower load-bearing capacity and bigger deformation under static compression. Changes of the strength and moduli after 10 cycles of F-T were drawn in Fig.9. Compared to saturated specimens (free from F-T weathering), samples after 10 F-T cycles had a 23.6% drop in static UCS, falling from 38.13MPa to 29.13MPa, and a 47.2% drop in static elastic modulus, from 3.38GPa down to 1.79GPa, and a 32.8% drop in static deformation moduli, from 1.91GPa to 1.28GPa.

Fig.9. Static strength and moduli of specimens free from or after 10 F-T cycles

3.1.3. F-T effects on dynamic mechanical properties

Impact compressive tests were carried out on both the saturated specimens and F-T weathered specimens with the I_i controlled at three levels. Typical axial dynamic stress-strain curves were presented in Fig.10.

Fig.10. Dynamic stress-strain curves of red-sandstone specimens free from or after F-T weathering: (a) unweathered saturated specimen; (b) saturated specimens after 10 F-T cycles.

Water-softening effects resulted to the nonlinearity and elastic-plastic features of stress-strain curves for both saturated and F-T weathered specimens. Yield platforms presented during the pre-peak stage of saturated specimens under I_i of 342.3 and 432.9 MPa, and F-T weathered specimens of 630.6MPa.

Dynamic mechanical parameters of specimens free from or after 10 F-T cycles, including dynamic strength and deformation modulus, were averaged from three specimens for each I_i grade and drawn in Fig.11 versus strain rate ($\dot{\epsilon}$). Static strength and modulus were also taken into consideration for comparison.

Fig.11 presented the obvious decrease of strength and deformation modulus of red-sandstone after 10 F-T cycles. Relationships between UCS, E_d and $\dot{\epsilon}$ were exponentially fitted, with the fitted curves drawn in Fig.11. Influenced by strain rate, the F-T-caused strength decrease of red-sandstone under impact compression was bigger than that under static compression. In contrast, the absolute variation of deformation modulus was less affected by strain rate, as the $E_d - \dot{\epsilon}$ regression line of specimens after F-T cycles was nearly parallel to that of specimens free from F-T.

Fig.11. Mechanical indexes of specimens free from or after 10 F-T cycles: (a) UCS; (b) deformation modulus

3.2. Cycling TS weathering

In this paper, contrastive analyses were also carried out between specimens free from and after 10 TS cycles. Variations of physico-mechanical characteristics, as drawn in Fig.12-15, expounded the damage effects of TS weathering on red-sandstone specimens.

3.2.1. TS effects on physical properties

Compared with 10 F-T cycles, smaller variations of physical properties were caused by 10 TS cycles except for mass loss, including the block volume, density, water absorption, total porosity and P-wave velocity, as presented in Fig.12. All variations of the mass, block volume, and density after 10 TS cycles were less than 2 percent. Besides, water absorption and total porosity of red-sandstone increased by about 13.5 and 9.5 percent respectively. Biggest decrease also occurred to P-wave velocity, dropping by 16.84% and 15.05 % for static and

dynamic specimens respectively. Slight differences resulting from size effect also existed between static and dynamic specimens.

Fig.12. Relative variation of physical properties after 10 TS cycles, measured in dried state

3.2.2. TS effects on static mechanical properties

Static stress-strain curves of the unweathered dried specimens, as well as of the 10 TS cycles-weathered and then dried specimens were also drawn in Fig.8. Clear in Fig.8 that 10 TS cycles did not change the curve mode significantly, but changed the static UCS and moduli obviously.

Fig.13. Static strength and moduli of specimens free from or after 10 TS cycles

Fig.13 displayed variations of static UCS and moduli after 10 TS cycles, which were slighter than those after 10 F-T cycles. In contrast with the dried specimens (free from TS), red-sandstone specimens after 10 TS cycles fell from 77.37MPa to 69.35MPa in static UCS, a drop of 10.4%. For static deformation indexes, elastic and deformation moduli went respectively from 6.42 and 3.96GPa down to 5.46 and 3.33GPa, about

265 15.0 and 16.0 percent respectively.

266 3.2.3. TS effects on dynamic mechanical properties

267 Impact compressive tests were also carried out on both the dried specimens and TS weathered specimens,
268 with the typical dynamical axial stress-strain curves presented in Fig.14. From the strain-strain curve
269 morphologies, ductility of red-sandstone during the impact failure process got better after 10 TS cycles. All
270 tested in dried state, red-sandstone specimens after 10 TS cycles had a relative slower stress growth rate in
271 pre-peak phase and also a slower reduction rate in the post-peak phase with the adding up of strain.

272
273 **Fig.14.** Dynamic stress-strain curves of red-sandstone specimens free from or after TS weathering: (a) unweathered dried specimen; (b)
274 10 TS cycles-weathered and then dried specimen.

275 Dynamic mechanical characteristics of specimens free from and after 10 TS cycles were drawn in Fig.15
276 versus strain rate ($\dot{\epsilon}$), including dynamic strength and deformation modulus. Static strength and modulus
277 were also taken into consideration for comparison. Exponential equations were adopted to fit relationships
278 between UCS, E_d and $\dot{\epsilon}$ of dried specimens and TS weathered specimens, with the fitted curves drawn in
279 Fig.15. TS-caused decreases of UCS and E_d were clear from the separation distances between the fitted
280 curves. Influenced by strain rate, the TS-caused decrease of dynamic strength was slightly bigger than static
281 strength. Similarly, decrease of deformation modulus was also got larger with the increase of strain rate.

Fig.15. Mechanical indexes of specimens free from or after 10 TS cycles: (a) UCS; (b) deformation modulus

3.3. Water effects on mechanical properties

Obvious from the above analyses of F-T/ TS effects that water greatly affected the rock behaviors, and therefore analyses of water effects on rock mechanics are necessary for studies on the F-T and TS weathering. Sandstone, as a typical sedimentary rock, is generally more likely to be affected by water content on its mechanical properties (Wong et al., 2015). For red-sandstone material tested in this work, pronounced water effects were clear from the contrasts of mechanical characteristics between dried specimens and saturated specimens, as showed in Fig.8, Fig.10(a) and Fig.14(a).

3.3.1. Water effects on strength

As a judging method of water effects on rock, the softening coefficient (K) is often used in rock engineering, as the static UCS ratio of saturated specimen to dried specimen. According to the static compressive test results, K of red-sandstone in this paper was calculated as 0.49, showing a great decrease of static UCS after saturated.

Considering the rate sensitivity, Fig.16 was drawn to analyze the water effects under different strain rates. Compared with in dry state, red-sandstone performed poorly in both static and dynamic compressive tests after water-saturated. From the fitting equations and concave convex properties of fitted curves, differences of strain rate influences on the strength were found between dried and saturated specimens. UCS increase speed

of dried specimens got slower with the adding up of strain rate, while that of saturated specimens got faster.

Fig.16. Static and dynamic UCS of dried and saturated red-sandstone versus strain rate

3.3.2. Water effects on deformation property

Besides strength, attention was also paid to water effects on deformation characteristics of rock. Elastic modulus (E_e) and deformation modulus (E_d) of both dried and saturated specimens were drawn in Fig.17.

Fig.17. Elastic modulus (E_e) and deformation modulus (E_d) of dried and saturated red-sandstone versus strain rate

Various degrees of decrease occurred to both E_e and E_d of red-sandstone after saturated, clear in Fig.17. Deformation modulus generally added up with the increase of strain rate for both dried and saturated specimens, while the increasing mode was affected by water content. For dried specimens, increase speed of E_d got slower with the adding up of $\dot{\epsilon}$, while for saturated specimens the increase got faster.

312 Non-monotonic changes occurred to E_e versus $\dot{\varepsilon}$ due in part to its definition in this paper. Method of Eq.(4)
313 perfectly met the linear sections of static stress-strain curves, but failed to meet the linear sections of dynamic
314 curves on account of the high nonlinearity of curves. This was also the main reason that E_d exceeded E_e
315 for saturated specimens at strain rate of 405.9 s^{-1} .

316 **4. Mechanisms of F-T/ TS weathering**

317 Test results both in this work and of other researches (Yavuz et al., 2006; Fatih, 2012; Wen et al., 2015;
318 Zhou et al., 2015; Ghobadi and Babazadeh, 2015) confirmed the serious damages of cycling F-T and TS
319 weathering on physico-mechanical properties of rock. Synthesizing weathering experiment results, water and
320 temperature variation played important roles in F-T/ TS weathering process. Comparative analyses of SEM
321 images (Fig.4) clearly revealed the microscopic changes of red-sandstone, interpreting the changing rules of
322 physico-mechanical properties after F-T or TS weathering.

323 **4.1. Mechanism of water effects during F-T/ TS process**

324 Water effects on physico-mechanical properties of red-sandstone were simply summarized as solvent
325 effect and medium effect in this paper.

326 On the one hand, many minerals are hydrophilic and soluble to some extent and unstable during the
327 water-absorption of red-sandstone. Water dissolution effect leads to the corrosion of unstable cement minerals,
328 weakening of the cement cohesion between mineral granules as well as the softening of mineral grains
329 themselves, which all together promotes the reduce of physico-mechanical properties of red-sandstone during
330 the weathering process. The biggish solution holes and clearer grain boundaries of saturated or weathered
331 samples under SEM observation, clear in Fig.4, apparently present those changes.

332 On the other hand, water is an important transmission medium of both matter and energy inside rock.

Free water in cracks is the outflow medium of soluble minerals and the water erosion accelerates dissolution of mineral grains and cements. Water is also the transmission medium of compressive stress which is well known as pore water pressure (Oshita and Tanabe, 2000). When saturated specimen is compressed, the initial fracture develops into winged crack and the inside water spreads to the wing crack tips as the load increases, producing wedging effect on the crack surfaces under the pore water pressure, which promotes the expansion of winged crack due to its extruding winged crack outwards (Steif, 1984; Li et al., 2007).

4.2. Mechanism of temperature variation effects during F-T/ TS process

During F-T/ TS process, temperature variation damages red-sandstone mainly in two ways, non-uniform thermal deformation and phase-transition of water, significant from Fig. 3 in macro and Fig.4 in micro.

Firstly, non-uniform thermal deformation, among different mineralogical components and between the interior and exterior portion of specimens, is thought to be one important reason of F-T/ TS damages. On macroscopic level, rapid temperature variation during weathering process creates sharp thermal gradients along the depth direction of specimens. In this study, tensional fissures were observed in most of the weathered red-sandstone specimens (Fig.3). On microscopic level, uncoordinated deformation occurs among different minerals because of the various thermal expansion coefficients. During the temperature changing periods of F-T/ TS cycles, thermal stresses resulting from incoordination deformation combine to generate tensile strain sufficient for micro-fracturing to occur (Ghobadi and Babazadeh, 2015), as shown in Fig.4.

Secondly, water-ice or water-gas phase-transformation occurs frequently to water inside red-sandstone during cycling F-T or TS, resulting from which the volume change and migration effects affect greatly on fracture development. For F-T weathering, expansive force of water during the freezing period leads to the crack extending, while water-migration effect leads to transfer of the around free water toward the freezing crack tips and further crack expansion. During the melting period, ice in cracks melts and deciduous cement

minerals transfer easily by means of water. Cycling F-T brings great damages to red-sandstone. For TS weathering, pore water expands on vaporizing and produces steam pressure towards the internal surfaces of fractures. Steam splitting effect is an important acceleration for the fracture development and void communication (Hettema et al., 1998). Greatly affected by the impermeability of pores, splitting effect of pore steams is much more notable inside the specimens instead of the surficial layer.

5. Conclusions

Physico-mechanical characteristics of red-sandstone free from and after artificial F-T or TS weathering were tested in this work, indicating the coupled weathering effects of temperature variation and water. The following conclusions can be drawn from this study:

(1) Both cyclic F-T and TS weathering deteriorate red-sandstone significantly. Contrasted to specimens free from F-T and TS, red-sandstone specimens performed poorly in most tested physical and mechanical categories after 10 F-T or TS cycles. Generally, deterioration degree of red-sandstone after 10 F-T cycles was greater than after 10 TS cycles.

(2) Strain rate effects were obvious for dynamic mechanical behaviors of both fresh and F-T/ TS weathered red-sandstone. F-T/ TS induced decreases of UCS and modulus were more remarkable under dynamic impacts than under static loads. Growth trend of dynamic mechanical indexes of red-sandstone tested in dried state was different with those tested in saturated state.

(3) Cycling F-T and TS are typical rock weathering processes, during which water and temperature variation play important roles. Water effects during the rock weathering process could be summarized as solvent effect and medium effect, while temperature variation damages red-sandstone meanly in two ways, non-uniform thermal deformation and phase-transition of water.

(4) Considering significant damages of F-T/ TS weathering on rock performances, weathering deterioration of

rock should be concerned during all of the design, construction and maintenance of rock engineering and constructions. Methods should be taken to evaluate and reduce the F-T/ TS induced physical/ mechanical property deterioration (Ozcelik et al., 2012; Gratchev and Kim, 2016; Jamshidi et al., 2016; Alavi Nezhad Khalil Abad et al., 2016). Before the design and construction of geo-engineering, field or laboratory experiments should be taken to evaluate the residual physico-mechanical properties of rock suffered from freeze-thaw or thermal shock weathering. Empirical or statistical functions obtained from experiments are also beneficial for the prediction and decision-making in rock engineering.

Acknowledgments

The authors acknowledge the financial support of the National Science Foundation of China (No.51378497).

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