Thermomechanical effects in different geomaterials in limiting behavior of cyclic loading

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Abstract. The authors discuss feasibility of acquisition of information on mechanical processes in geomaterials in post-limiting elastic deformation by variations in infrared radiation rate. Experimental recording of heat emission of rock salt and concrete samples in the limiting behavior of cyclical loading under uniaxial compression is described. Records of mechanical parameters appear qualitatively identical to heat emission variations which characterize the change in the stress–strain behavior of the test geomaterials. The differences in the thermomechanical effects in concrete and rock salt in the described deformation mode are found.

1. Introduction
It is known [1, 2] that mechanical behavior of geomaterials considerably changes in cyclical loading, and these changes are identified in the stress–strain curves obtained in different loading cycles. In different geomaterials, these changes have distinctive features [1–4]. Furthermore, the changes in the mechanical behavior of geomaterials are mirrored in the changes in correlations of parameters of physical fields in the course of deformation.

One of the progressing methods of nondestructive testing of the mechanical behaviors in rocks is infrared radiometry which is noncontact evaluation of variation in infrared emission from the surface of geomaterials subjected to deformation [5–10]. Interpretation of thermal IR radiation measurements is based on the description of the known thermodynamic effects: change in the temperature of a solid under adiabatic deformation (thermoelastic and thermoplastic effects [11]) and temperature dependence of IR radiation rate [12].

This study aims to analyze the specified effects in geomaterials having different physical and mechanical properties and subjected to multiple repeated loading–unloading cycles using the IR radiation measurements.

2. Laboratory test results
The tests were carried out on cylindrical specimens made of rock salt (\(d = 35\) mm and \(h = 70\) mm) and concrete (\(d = 50\) mm and \(h = 100\) mm). Measurements were taken on the testing machine Instron 150LX using automated equipment for synchronous recording of mechanical and thermal emission parameters [7, 8]. In the tests, the rate of change in axial strains \(\varepsilon_1\) in the branches of loading and unloading was maintained constant in absolute value \(|d\varepsilon_1/dt| = \text{const.}\)
The uniaxial compression strength $\sigma_c$ of rock salt in multiple cyclic tests, with regard to the strength of the same samples in the single cycle tests, was assumed as 20 MPa. For concrete specimens, $\sigma_c$ was assumed as 32 MPa from the same reasoning.

In the tests, in each loading–unloading cycle, the load was increased up to $\sigma_{\text{max}} \approx 0.9\sigma_c$, and then unloading was performed down to $\sigma = \sigma_{\text{min}} \approx 0.1$ MPa.

Figure 1 shows the typical time dependences of the axial stress $\sigma_1(t)$, longitudinal strain $\varepsilon_1(t)$ and IR radiation rate $V(t)$ in repeated loading of rock salt and sample (Figures 1a and 1b, respectively).

**Figure 1.** Functions $\sigma_1(t)$, $\varepsilon_1(t)$ and $V(t)$ for (a) rock salt in testing at $|d\varepsilon_1/dt| = \text{const} = 3$ mm/min and (b) concrete in testing at $|d\varepsilon_1/dt| = \text{const} = 3.6$ mm/min.

**Figure 2.** Graphs $\sigma_1(\varepsilon_1)$ and $V(\varepsilon_1)$ (a), (b) for rock salt and (c), (d) for concrete, respectively.
The functions $\sigma_1(\varepsilon_1)$ and $V(\varepsilon_1)$ in Figure 2 depict in more details the change on the mechanical behavior of specimens in cyclical deformation. The diagrams $\sigma_1(\varepsilon_1)$ for rock salt and concrete have a standard shape and contain features typical of diagrams describing similar loading conditions in geomaterials [3, 4].

To analyze differences in $\sigma_1(\varepsilon_1)$ and $V(\varepsilon_1)$ for rock salt and concrete, Figure 3 shows these functions obtained in different cycles of loading–unloading.

![Figure 3](image)

**Figure 3.** Functions $\sigma_1(\varepsilon_1)$ and $V(\varepsilon_1)$ in (a), (b) the sized deformation cycle in rock salt and (c), (d) the third deformation cycle in concrete, respectively.

As seen from the function $\sigma_1(\varepsilon_1)$ in Figure 3a, deformation of rock salt in the stage of loading follows a ‘slower’ trajectory as compared with the trajectory of unloading in this cycle. This fact is reflected in Figure 3b as faster cooldown of the rock salt specimen as against its heating in loading. The functions $\sigma_1(\varepsilon_1)$ and $V(\varepsilon_1)$ are highly identical. The same conclusions can also be drawn in the analysis of the functions $\sigma_1(\varepsilon_1)$ and $V(\varepsilon_1)$ plotted for the other deformation cycles in rock salt specimens.

The functions $\sigma_1(\varepsilon_1)$ and $V(\varepsilon_1)$ correlate differently in concrete. In the plot of $V(\varepsilon_1)$ in Figure 3d, in the branch of unloading, it is distinct that IR radiation rate and, accordingly, temperature, has higher values as compared with the rates in the branch of loading. This behavior of the function $V(\varepsilon_1)$ in concrete can probably be explained by the known feature of concrete deformation: the unloading branch of the diagram $\sigma_1(\varepsilon_1)$ is a more bowed curve than the cure in the loading branch [4, 10].

3. Conclusions

The qualitative dependence of the functions $\sigma_1(\varepsilon_1)$ and $V(\varepsilon_1)$ allows concluding on applicability of thermal IR radiation measurements in identification of deformation features in different geomaterials under high-amplitude cyclic loading.
References

[1] Mokhnachev MP 1979 Fatigue of Rocks Moscow: Nauka (in Russian)
[2] Voznesensky EA 1999 Dynamic Instability of Soil Moscow: Editorial URSS (in Russian)
[3] Fuenkajorn K and Phueakphum D 2010 Effects of cyclic loading on mechanical properties of Maha Sarakham salt Engineering Geology Vol 112 No 1 pp 43–52
[4] Eryshev VA and Toshin DS 2005 Diagram of concrete deformation under few repeated loads Izv. Vuzov. Stroitelstvo No 10 pp 109–114
[5] Sheinin VI, Levin BV, Blokhin DI and Favorov AV 2003 Identification of nonstationary changes in stress state of geomaterials by infrared radiometry data Journal of Mining Science Vol 39 No 5 pp 431–437
[6] Wu L, Liu S, Wu Y and Wang C 2006 Precursors for fracturing and failure, Part II: IRR T-curve abnormalities Int. J. Rock Mech. Min. Sci. Vol 43 No 3 pp 483–493
[7] Sheinin VI and Blokhin DI 2012 Features of thermomechanical effects in rock salt samples under uniaxial compression Journal of Mining Science Vol 48 No 1 pp 39–45
[8] Sheinin VI, Blokhin DI, Maksimovich IB and Sarana EP 2016 Experimental research into thermomechanical effects at linear and nonlinear deformation stages in rock salt specimens under cyclic loading Journal of Mining Science Vol 52 No 6 pp 1039–1046
[9] Ma L, Sun H, Zhang Y, Zhou T, Li K and Guo J 2016 Characteristics of infrared radiation of coal specimens under uniaxial loading Rock Mechanics and Rock Engineering Vol 49 Issue 4 pp 1567–1572
[10] Lou Q and He X 2018 Experimental study on infrared radiation temperature field of concrete uniaxial compression Infrared Physics & Technology Vol 90 pp 20–30
[11] Nadai A 1963 Theory of Flow and Fracture of Solids New York: McGraw-Hill
[12] Kriksunov LZ 1978 Reference Book on Basics of Infrared Mechanics Moscow: Sov. Radio (in Russian)