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Research Article

Status and Analysis of Rock Rheological Fracture Mechanics Research

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Abstract In fact, the rock rheology is a rheologic and fractured process that the rock crack initiates, creep and evolves, perforates and the rock mass fails at last. This process is very complicated which is related to time, stress level and other influencing factor. The rheologic fracture effects of rock is an important cause for the rock mass instability. With the economy development, more and more engineering include slope, underground powerhouse, nuclear waste repository, hydropower station and so on should been considered the rock rheologic fracture effects. In this paper, the research of status and analysis for rock rheology, rock crack propagation and rheological fracture property, failure criterion and failure model were discussed. The further research directions of rock's rheologic fracture were pointed out. The research results show the study of rock rheologic fracture will be a hotspot for rock mechanics and will made greater progress with the development of the theories, experiment means and calculation methods for rock rheologic fracture, even though it is very difficult to study.

Keywords rock rheology; rock crack propagation; rock rheologic fracture

Introduction

The rock rheology is an important reason for the failure and large deformation of rock underground engineering, building foundation and rock slope. Because of the rock rheology, the wallrock maximum deformation of Tanem road tunnel in Austria achieves 120 cm and the maximum rate of deformation achieves 20 cm/day. Many cracks and collapse happen on the left dam abutment and upriver slope of Longtan hydropower station in China for the rock creep. The creep deformation appears on the northern slope of Fushun mine every year in the flood season and it causes the immense influence on the mine's safety production and building regular service.

Sun [1] has pointed out the rheological behaviors of rock and soil are not only related to the compression strength and shear strength of the geomaterials, but also related to the stress value of the geomaterials. On the condition of high ground stress, Even the moderate intensity rock or hard rock with joint, when the rockmass stress value reach or exceeds the lower limit of rheology, the rheologic effects will happen. With the development of the economy, the embedded depth of rock engineering is doper and deeper, the high ground stress and the high permeation pressure leads to more remarkable rheological behavior, so the rock rheologic effects should been fully considered in the design and construction process for these rock engineering. The rock rheologic destructive process is the crack initiates, extends, perforates and the rock mass is destroyed at last. So, the rock rheology process is essential a rheologic and fractured process and it is a complicated process that the rock crack initiates, creep and evolves, perforates and the rockmass fails which is related to time. The rheology and fracture problem universally exists in rock engineering [2].

The rheologic fracture theory is the basis for rock rheologic fracture study. Because the theories, experiment means and calculation methods for rheologic fracture are very imperfect, the research findings are very lacking. The study of rock rheologic fracture characteristic is very difficult for the following reasons.

(1)The rock microcosmic characteristic is very difficult to measure and quantize. Based on the microcosmic failure mechanism, the rock macroscopic rheological behaviors are derived from the evolution law of rock microcosmic structure is an important way. But, limited to the research means and test equipment, the rheologic characteristic of microcosmic crack is very difficult to measure and quantize in the rheologic fracture process.
(2)The quantitative relationship between the rock microcosmic characteristic and the macroscopic measurable indexes is very difficult to build. The rock rheologic fracture is a memonic and nonreversible thermodynamics process [3]. The nonlinearity of rheologic behavior, the nonlinearity between the generalized force and generalized flow and the nonreversibility of thermo-mechanical coupling are the substantive characteristics for the rheology. It is very difficult to build the relationship between the rock microcosmic characteristic and the macroscopic measurable indexes by mathematical methods.

2. Status and analysis of rock rheology research

In 1979, professor Lnager expounded the fundamental conception, research methods, characteristic and the rheologic problems of rock engineering on the fourth international conference of rock mechanics. Since then, the rock rheology has made significant progress in rheologic characteristic, test facility, test method, constitutive model, and parameter identification of rheological model [1,4]. The experimental investigation focus of rheologic characteristic has been transferred to hard rock [5] from soft rock [6]. The test facility research has been transferred to import equipment [7] from autonomous developments [8]. The test means have been transferred to creep test under unloading confining pressure [9] or different stress path [10] from the uniaxial [11] or triaxial compression test [12], and have been transferred to the shear rheology from the compressionrheology [13]. The test methods have been transferred to CT scanning [14] and scanning electron microscopy [15] from the macroscopical mechanics experiment.
The rheologic constitutive models are studied from experiential models to rheologic element models, from linear element models to nonlinear element models [16]. The rheologic models parametric inversion is studied from indoor test [17] and field experiment to back analysis [18]. The back analysis has been developed into inverse method, direct method, perturbation method, and neural network method from analysis method [19]. Although the rock rheology has made significant progress, there are many problems and they are embodied in the followings:

(1) The rheologic experimental investigation are focused on the uniaxial compression test. The triaxial compression test is few and the study emphasis is the relationship between axial deformation and time for soft rock which rarely consider the relationship between lateral deformation, volumetric deformation and time.

(2) The rheologic characteristic of rock is mainly studied from its macroscopical mechanical property, rarely from its microcosmic property. The microcosmic and rheologic property of rock is focused on the microcosmic analysis under uniaxial creep deformation and the analysis
is only qualitatively described.

(3) The study of rock rheologic models stay on seeking the empirical model or theoretical mode through rheologic test results and these models can't consider the acceleration stage. Even though some nonlinearity rheologic models can consider the acceleration stage, they are very difficult to practical application because of their complexity.

(4) In fact, the rock rheology is a rheologic fracture process and the research findings are very few by applying rheologic fracture theory to solve the rock rheologic problems.

3. Status and analysis of rock crack propagation

For fractured rock mass, because of the geologic environment action and construction perturbation, the crack propagation and transfixion of rock adjacent cracks are the main failure model. In fracture mechanics theory, the crack initiation and propagation is judged by the stress intensity factor of crack forehead's stress and strain fields. Horii H. et al [20] calculated the interaction of multiple cracks adopted the pseudo tension method in infinite plate, but this method can't analyzed the close cracks. Based on the principle of superimposed stresses, Kachanov [21] put forward a simple method which could calculate the interaction multiple cracks and could estimate the equivalent elastic parameters and analyze the stress and strain fields of cracking body. LI et al [22] and H. Qing et al [23] improved the Kachanov method and Basista et al [24] applied this method to the interaction of multiple compressive-shear crack of brittle body. The Kachanov method and its revised methods are only valid when the load act in the distance [25]. ZHOU et al [26] revealed the transfixion mechanism ofjointed rockusing the Dugdale-Barenblatt model. ZHOU et al [27] built two fracture criterions and got the initial angle of crack with the minimum J2 rule under compression shear state. C.A. Tang and R.H.C. Wong [28-29] had systematically analyzed and simulated the transfixion and failure of rock cracks.

For the past few years, many scholars at home and abroad have studied the water-rock mechanical action with fracture mechanics and have made some progress. HUANG et al [30] researched the crack propagation mechanism under water pressure by the principle of effective stress. TANG et al [31-32] got the critical stress intensity factor and expanded angle under watered and waterless state for mixed mode crack. Vandamme et al [33] put forward the couple solution of hydrofracturing. Douranary et al [34] investigated the fluid-structure interaction of hydrofracturing in the process of crack initiation, expantion and closing. ZHUANG [35] studied the laws of crack initiation and expantion in coupling of seepage process from micromechanics using PFC software. SUN et al [36] analyzed the crack propagation rules with the element-free method, considered the coupling effect of seepage field and stress field. LI et al [37] built the damage and fracture model and evolution equation of stress intensity factor for rock containing pre-existing crack under seepage field and compression shear field and regarded the stress intensity factor of crack foreside as the initiation criterion. ZHAO et al [38]compiled analysis coupling program of seepage and fracture for fractured rock mass through the FISH computer language based on the FIAC3D, built the coupling mechanism of seepage and fracture and applied the theory of seepage and fracture to the high-head tunnel.

The rock crack propagation and transfixion is close related to the rock's microstructure, so many researchers make attempt to reveal the mechanism of rock crack propagation from the rock's microstructure. GE [14] introduced the principle and method of CT scanning and pointed out the CT scanning technique was a new means for rock and soil mechanics which contacted the macrographic mechanical property with the evolvement of microstructure. ZHU et al [39] obtained the density distribution and its statistical characteristic of rock inside by dint of CT scanning under uniaxial compression process, they distinguished the microfissuring action through the density change of the same point and described the evolved behavior of microfissuring

Through the fractal index, XIE et al [40] studied the fractured characteristic (Ⅱ model) and microcosmic mechanism of brittle rock under high temperature adopted the scanning electron microscope. ZHU et al [41] carried out the triaxial compression tests of griotte in complete stress strain path under high water pressure, high confining pressure and low confining pressure and analyzed the microcosmic characteristic by the scanning electron microscope. ZHANG [15] found out the long-term strength of diabase was dependent on the cementation of mineral by the scanning electron microscope. LI et al [42] studied the damage property of rock pore structure under the freezing and thawing cycle with the nuclear magnetic resonance (NMR) and revealed the pore propagation mechanism according to the extent of porosity and T2 spectrum.

Although research findings of rock crack propagation have been acquired, these findings can't consider the rheologic effects. The real-time observation of the failure models, peak strength prediction and failure process of multiple cracks rock just stay in starting stage. The rock crack propagation research has entered into the meso-level by the CT scanning, the scanning electron microscope and the nuclear magnetic resonance (NMR), but the quantitative relationships between the macrographic mechanics parameters and the microcosmic mechanics effects of crack haven't been built.

4. Status and analysis of rheological fracture property, failure criterion and failure model

4.1 Status and analysis of rheological fracture property, failure criterion

Kranz [43] found out the crack of Barre granite started to creep at the 87 percent of rupture strength, the quantity and length of cracks were increased with time and the crack's interaction were more violent with tome. In the acceleration creep stage, the connection and merger of cracks was more important than the single crack propagation. Korzenrowsik [44] studied the whole process from the cranny creep, evolvement, rupture, partial failure to holistic failure because of the environmental condition worsening. After comparative studies from macroscopy and microscopic view using experiment means, DENG et al [45] gained the relationship between the strength weakening of fractured rock mass and cracks propagation. Regarded sandstone as an example, CHEN [46] carried out the three point bending tests in order to study the rock crack initiation and propagation, and brought out the creep rupture criterion and crack propagation mechanism. From the principle of least energy dissipation, YANG et al [47] deduced the crack creep criterion and applied the criterion of strain energy density in the linear elasticity fracture theory to the viscoelasticity state. XU et al [48] deduced the expressions of the bulk relaxation module for fractured rock mass and pointed out the interaction of cracks would lead to the increase of relaxation modulus and the stress intensity factor of crack would increase with the crack's radius. YUAN et al [49] gained the laws of viscoelastic plasticity for ore-rock after creep test, imported the stress intensity factor of rheologic fracture and built the uniform rheologic fracture criterion of rock. ZHAO et al [50] carried out the rheologic fracture test and fracture toughness test of rock crack under compression shear state, and built the three transfixion models of rheologic fracture which included the model between the winged cracks, the model between the winged crack and the protogenous crack and the model among the winged crack, the protogenous crack and the sheared crack.

Under the high stress in deep underground engineering, hard rock present the rheological behavior and it has been confirmed in deep mining in South African [51]. In the past few years, some scholars started to study the properties of rock rheologic fracture under high stress [52-59]. ZUO et al [55] built the yield criterion of deep rock under the coupling of temperature and pressure according to the principle of least energy dissipation. They thought the rock would failed when the plastic dissipative energy and dissipative energy of temperature gradient reached the threshold value. WANG et al [56] got the creep equation of deep soft rock under high geostress and built the quantitative relationship among the creep, time and stress. They thought the difference value of geostress was the major factor for creep. The overseas study of deep rock's rheologic fracture are focused on the stability of storage shed for nuclear waste. Kwon S. et al [57] pointed out the rock strength near storage shed for nuclear waste would markedly decreased under the longtime groundwater corrosiveness and tiny rending effect. Munson D. E [58] put forward the multifactorial deformation model of rheology for storage shed's rock mass considering the coupling of cutting forces and heat. Their model's predicted results were verified by the long-term observed results. Based on the international cooperative project named DECOVALEX, Jing L.*et al* [59] studied the rheologic properties and the long-term stability of storage shed for nuclear waste under the coupling of heat-water –force.

4.2 Status and analysis of rheological fracture model

From the single crack rheological-damage microcosmic mechanism to considering the rheologic effects, considering the transmission force effects of crack leading end, the crack surface transmission force effects and three-dimensional effects, YAN et al [60] gained the semi-analytical formulas of the three-dimensional crack propagation under rheological-damage action and applied the model to the excavation analysis of rock slope. Chan K S et al [61] proposed a creep-damage-fracture coupling model of salt rock. YANG [62] derived the nonlinearity rheological equation from the crack rheologic fracture process of the underground powerhouse rock mass and compared with the observed displacement. Costin. L. S [63] studied the brittle rock's ageing deformation and failure characteristics and pointed out the creep had a stress threshold with the fracture mechanics and damage mechanics. XIAO et al [64] derived the crack rheologic fracture formulas of Sanxia granite under compression state from the scanning electron microscope test and double-torsion specimens test and built the damage-rheology-fracture propagation model of fractured rock mass. Based on the equivalent strain in damage mechanics, CHEN et al [65] built the elastic-plasticity creep model of fracture-damage coupling with viscoelastic theory and finite element method. They revealed the mechanism of crack creep, evolution and failure.

5. Further research directions of rock's rheologic fracture

Although the rock's rheologic fracture studied make great strides in recent decades, many problems in theory, test and practical engineering are worth to further research. These further directions of rock's rheologic fracture are shown in the following.

(1) The rheology-damage theory and the rheology-fracture theory can been applied to the rock failure characteristic in what situations and what degree is a worthy pronlem.

(2) The rock mass is in complicated stress state. Based on the existing research findings, the further study of rheologic fracture properties under the compression-shear state or tension-shear state is very significant.

(3) The relationship between the rheologic fracture toughness and the specimen size and shape also is a research direction.

(4) The interaction of multiple cracks is a governing factor to the stability of rock engineering. It is worth to study the multiple cracks propagation and connection on the condition of rock creep.

(5) The rock fracture and damage is indivisible for jointed rock and they interact in the creep process. The combinations of the rheology, fracture and damage theories are propitious to reveal the failure laws of jointed rock mass.

(6) The deep rock engineering is more and more and the fluid-solid coupling, rheologic fracture and abrupt failure are their characteristic. The microcosmic mechanism and failure criterion of deep fractured rock mass also are important research frontiers.

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References

[1]. SUN Jun. Rock rheological mechanics and its advance in engineering application [J]. Chinese Journal of Rock Mechanics and Engineering, 2007, 26(6):1081-1106.

[2]. YANG T.H., XU T., Rui R.Q., et al. Deformation mechanism of bedding creep slope and associated stability assessments [J]. International Journal of Rock Mechanics and Mining Sciences, 2004, 41(3):525.

[3]. YUAN Longwei. The theoretical basis of rheological fracture-thermorheological material response and thermos-mechanical balance requirements [J]. Journal of Xiangtan University, 1980,(2):31-49.

[4]. YANG Shengqi. Study on rheological mechanical properties of rock and its engineering application [D]. Nanjing: Hohai University, 2006.

[5]. LI liangquan, XU Weiya, WANG Wei, et al. Estimation of long-term strength for XiangJiaBa sandstone baesd on creep tests [J]. Engineering Mechanics, 2010, 27(11):127-136.

[6]. CHEN Weizhong, Tan Xianjun, LU Senpeng, et al. Research on large-scale triaxial compressive rheological test of soft rock in depth and its constitutive model [J]. Chinese Journal of Rock Mechanics and Engineering, 2009, 28(9):1735-1744.

[7]. WANG Rubin, XU Weiya, WANG Wei, et al. Experimental investigation on creep behaviors of hard rock in dam foundation and its seepage laws during complete process of rock creep [J]. Chinese Journal of Rock Mechanics and Engineering, 2010, 29(5):960-969.

[8]. CHEN Yuanjiang, PAN Changliang, WANG Wenxing. A new test method for soft rock rheology [J]. mechanics in Engineering, 2002, 24(4):42-45.

[9]. XIA Caichu, YAN Zijian, WANG Xiaodong, et al. Research on elasto-viscopastic constitutive relation of marble under unloading condition [J]. Chinese Journal of Rock Mechanics and Engineering, 2009, 25(3):459-466.

[10]. YANG Chunhe, BAI Shiwei, WU Yiming. Stress level and loading path effect on time dependent properties of salt rock [J]. Chinese Journal of Rock Mechanics and Engineering, 2000, 19(03):270-275.

[11]. Tsai L S, Hsieh Y M, Weng M C, et al. Time-dependent deformation behaviors of weak sandstones[J]. International Journal of Rock Mechanics and Mining Sciences. 2008, 45(2):144-154.

[12]. GUO Chenye, XIAN Xuefu, JIANG Yongdong, et al. Experimental research on creep of fractured sandstone [J]. Chinese Journal of Rock Mechanics and Engineering, 2010, 29(5):990-995.

[13]. FU Bin, JIANG Haifei, FU Xinli, et al. Analysis of shear rheological mechanical properties of fuchsia mudstone [J]. 2010, Chinese Journal of Rock Mechanics and Engineering, 2012, 31(S1):2796-2802.

[14]. GE Xiurun. Deformation control law of rock fatigue failure, real-time X-ray CT scan of geotechnical testing, and new method of stability analysis of slopes and dam foundations [J]. Chinese Journal of Geotechnical Engineering, 2008, 30(1):1-20.

[15]. ZHANG Qiangyong, YUAN Wendong, CHEN Fang, et al. Long-term strength and microscopic failure mechanism of hard brittle rocks [J]. Chinese Journal of Geotechnical Engineering, 2011, 33(12):1910-1918.

[16]. XIONG Liangxiao, YANG Linde. Viscoelasto-plastic rheological model for brittle hard rock [J]. Journal of Tongji University, 2010, 38(2):188-193.

[17]. XIA Caichu, WANG Xiaodong, XU Chongbang, et al. Method to identify rheological models by unified rheological model theory and case study [J]. Chinese Journal of Rock Mechanics and Engineering, 2008, 27(8):1594-1600.

[18]. Yang Zhi-fa,Wang Zhi-ying. Back analysis of viscoelastic displacement in a soft road tunnel [J]. Int. J. Rock Mechanics and Mining Sciences, 2001, 38:331-341.

[19]. Feng Xia-ting, Wang Yong-jia, Yao Jian-guo. A neural network model on real-time prediction of roof pressure in coal mines [J]. International Journal of Rock Mechanics and Mining Sciences, 1996, 33(6):647-653.

[20]. Horii H., Nemat-Nasser S. Compression-induced micro-crack growth in brittle solids axial splitting and shear failure [J]. Journal of Geophysical Research, 1985, 90(B4):3105-3125.

[21]. Mark Kachanov. On the problems of crack interactions and crack coalescence [J]. International Journal of Fracture, 2003(120):537–543.

[22]. LI Yinping, YANG Chunhe. Asymptotic analysis of interaction of closely-spaced cracks [J].Chinese Journal of Theoretical and Applied Mechanics, 2005, 37 (5):600-605.

[23]. H. Qing, W. Yang. Characterization of strongly interacted multiple cracks in an infinite plate [J]. Theoretical and Applied Fracture Mechanics, 2006, (46):209-216.

[24]. M. Basista, D. Gross. A note on crack interactions under compression [J]. International Journal of Fracture, 2000(102):L67-L72.

[25]. CHEN Yizhou. Integral equation methods for multiole crack problems and related topics [J]. Advances in Mechanics, 2008, 38(3):358-387.

[26]. ZHOU Xiaoping, WANG Jianhua, HA Qiuling. Failure analysis of intermittent jointed rocks under compression-shear stress [J]. Chinese Journal of Rock Mechanics and Engineering, 2003, 22(9):1437-1440.

[27]. Zhou Jiawen, XU Weiya, SHI Chong. Investigation on compression-shear fracture criterion of rock based on failure criteria [J]. Chinese Journal of Rock Mechanics and Engineering, 2007, 26(6):1194-1201.

[28]. Tang C.A., Lina P., Wong R. H. C., et al. Analysis of crack coalescence in rock-like materials containing three flaws Part II-numerical approach [J]. International Journal of Rock Mechanics and Mining Science, 2001, 38(5):925-939.

[29]. Wong R.H.C., Tang C.A., Chaua K.T., et al. Splitting failure in brittle rocks containing pre-existing flaws under uniaxial compression[J].Engineering Fracture Mechanics,2002, 69(17):1853-1871.

[30]. HUANG Runqiu, WANG Xianneng, CHEN Longseng. Hydro-splitting off analysis on underground water in deep-lying tunnels and its effect on water gushing out [J]. Chinese Journal of Rock Mechanics and Engineering, 2000, 19(5):573-576.

[31]. TANG Liansheng, ZHANG Pengchen, WANG Yang. Propagation of the complex cracks in rocks without water pressure [J]. Acta Scientiarum Naturlium Universities Sunyatseni, 2002, 41(6):83-85.

[32]. TANG Liansheng, ZHANG Pengchen, WANG Yang. Propagation of the complex cracks in rocks Ⅱ. Under water pressure and chemical damage [J]. Acta Scientiarum Naturlium Universities Sunyatseni, 2003, 42(1):90-49.

[33]. Vandamme M., Roegiers J.C. Poroelasticity in hydraulic fracturing simulators [J]. JPT, 1990: 1199-1203.

[34]. Douranary E., Mclennan. Prelatic concepts explain some of the hydraulic fracturing mechanism [J]. SPE, 1990: 152-162.
[35]. ZHANG Ning. Propagation rile of crack rock mass and its mathematics model research under the seepage-stress coupling [D]. Shanghai: Tongji University,2006
[36]. SUN Yuelin, SHEN Zhenzhong, WU Yuejian, et al. Analytic model for tracing crack propagation under coupled mechanical-hydrological environment [J]. Chinese Journal of Geotechnical Engineering, 2008, 30(2):199-204.
[37]. LI Xibing, HE Xianqun, CHEN Hongjiang. Crack initiation characteristics of openling-mode crack embedded in rock-like material under seepage pressure [J]. Chinese Journal of Rock Mechanics and Engineering, 2012, 31(7):1317-1324.
[38]. ZHAO Yanlin, WANG Wei-jun, WAN Wen, et al. Coupling mechanism of seepage-fracture in fractured rock mass and its application [J]. Chinese Journal of Geotechnical Engineering, 2012, 34(4):677-685.
[39]. ZHU Hongguang, XIE Heping, YI Cheng, LIU Zheng, et al. CT identification of microcracka evolution for rock materials [J]. Chinese Journal of Rock Mechanics and Engineering, 2011, 30(6):1230-1238.
[40]. XIE Haifeng, RAO Qiuhua, XIE Qiang, et al. Plane shear (model Ⅱ) fracture experiment analysis of brittle rock at high temperature [J]. The Chinese Journal of Nonferrous Metals [J]. 2008, 18(8):1534-1540.
[41]. ZHU Zhende, ZHANG Yong, XU Weiya, et al. Experimental studies and microcosmic mechanics analysis on marble rupture under high confining pressure and high hydraulic pressure [J]. Chinese Journal of Rock Mechanics and Engineering, 2005, 24(1):44-51.
[42]. LI Jielin, ZHOU Keping, ZHANG Yamin, et al. Experimental study of rock porous structure damage characteristic under condition of freezing-thawing cycles based on nuclear magnetic resonance technique [J]. Chinese Journal of Rock Mechanics and Engineering, 2012, 31(6):1208-1214.
[43]. Kranz R L. Crack growth and development during creep of Barre granite[J]. Int. J. Rock Mech.Min.Sci and Geomech.Absrtact, 1979, 16(1):23-35.
[44]. Korzniowski.W. Rheological model of llard rock pillave [J]. Rock Mech.Rock Eng., 1991(24):155-166.
[45]. DENG Guangzhe, ZHU Weishen. An experiment research on the crack propagation in rockmass [J]. Journal of experimental mechanics, 2002, 17(2):177-183.
[46]. CHEN Youliang. The experimental study on creep fracture of rock [J]. Acta Mechanica Sinica, 2003, 35(4):480-483.
[47]. YANG Songlin, XU Weiya, ZHANG Guijin. Stability criterion for fracture creep [J]. Rock and Soil Mechanics, 2003, 24(3):423-427.
[48]. XU Weiya, YANG Songlin. Analysis of relaxation moduli of fissured rock mass [J].Journal of Hohai University (Natural Sciences), 2003, 31(3):295-298.
[49]. YUAN Haiping, CAO Ping, WAN Wen, et al. Study on creep rules of soft and intricate ore-rock under step load and unload [J]. Chinese Journal of Rock Mechanics and Engineering, 2006, 25(8):1575-1581.
[50]. ZHAO Yanlin, WAN Wen, et al. Compressive-shear rheological fracture of rock-like cracks and subcritical crack propagation test and fracture mechanism [J]. Chinese Journal of Geotechnical Engineering, 2012, 34(6):1050-1059.
[51]. Mala D. F. Simulation of the time-dependent behavior of excavations in hard rock [J]. Rock Mech Rock Eng., 2002, 35(4):225-254.
[52]. Hudson J.A., Stephansson O., Andersson J. et al. Coupled T-H-M issues relating to radioactive waste repository design and performance [J]. Int. J. Rock Mech Min. Sci, 2001, 38:143-161.
[53]. Rehbinder G. Analytical solution of stationary coupled thermo-hydro-mechanical problems [J]. Int. J.Rock Mech Min. Sci. Geomech Abstr, 1995, 32:453-463.
[54]. Hou Z. Mechanical and hydraulic behavior of rock salt in the excavation disturbed zone around underground facilities [J]. Int. J. Rock Mech Min. Sci., 2003, 40:725-738.

[55]. ZUO Jianping, XIE Heping, ZHOU Hongwei. Study on failure behavior of rock under coupling effects of temperature and confining pressure [J]. Chinese Journal of Rock Mechanics and Engineering, 2005, 24(16):2917-2921.
[56]. WANG Yongyan, WEI Jia, QI jun, et al. Study on prediction for nonlinear creep deformation of deep rocks [J]. Journal of China Coal Society, 2005, 30(4):409-413.
[57]. Kwon S., Park B.Y, Kang C.H. Structural stability analysis for a high-level underground nuclear waste repository in granite [A]. Girard J., Liedman M., Brecs C. Proceedings of 4th North American Rock Mechanics Symposium[C]. Rotterdam: A. A. Balkema, 2000, 1279-1285.
[58]. Munson D. E. Constitutive model of creep in rock salt applied to underground room closure [J]. Int. J. Rock Mech Min. Sci, 1997, 34:233-247.
[59]. Jing L., Tsang C.F, Stephasson O. DECOVALEX- an international cooperative research on mathematical models of coupled THM processes for safety analysis of radioactive repositories [J]. Int. J. Rock Mech Min. Sci. Geomech Abstr., 1995, 32(5):389-398.
[60]. YAN Gongrui, ZHOU Weiyuan, YANG Ruoqiong. The micro damage rheological mechanics model for rock and concrete and its application [J]. Shuili Xuebao, 1997, 10:33-38.
[61]. Chan K S, Munson D E, Bodner S R. Creep deformation and fracture in rock salt [A]. Aliabadi M H.Fracture of Rock[C]. Boston: Southampton WIT gress, 1999.
[62]. YANG Yanyi. The underlying relationship between nonlinear rheological property of fissured rocks and damage development [J]. Engineering Mechanics, 1994, 11(2):81-89.
[63]. Costin.L.S. Time-dependent damage and creep of brittle rock [A]. Damage Mechanics and Continuum Modeling[C]. ASCE, New York, 1985:25-38.
[64]. XIAO Hongtian, QIANG Tianchi, ZHOU Weiyuan. Rheologic damage study of three gorges shiplock high slope and analysis on in-situ measured deformation [J]. Chinese Journal of Rock Mechanics and Engineering, 1999, 18(5):512-515.
[65]. CHEN Weizhong, ZHU Weishen. Rheology and fracture damage-coupled model for rock mass and its application [J]. Shuili Xuebao, 1999, (12):33-37.