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Review

Advances in Deformation and Permeability Evolution during Creep of Rocks

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Abstract: The goal of this paper is to review the research advances in deformation and permeability evolution during the creep of rocks in geoengineering problems through aspects of experiments, models, and methods. On the experimental side, we reviewed the reports related to creep-permeability evolution in resolving real geoengineering problems. In the section on the constitutive model, we summarized the equations of the relationship between creep deformation and permeability evolution in reproducing the interaction mechanism of creep-permeability. In addition, in the section on the numerical modeling method, we examined the modelling methods able to apply the mechanism of creep-permeability evolution as a real problem. Our report concludes that it is important to conduct experiments to demonstrate the deformation and permeability evolution during the creep of heterogeneous rocks in multi physics fields (Thermal-Mechanics-Hydraulic-Chemical). Additionally, we confirm that it is necessary to improve the proposed equation of permeability evolution by considering strain and damage. Finally, this paper suggests that the DEM (Discrete Element Method) is available to evaluate the influence of the heterogeneousness of rocks on deformation and permeability evolution.

Keywords: rock mechanics; creep; permeability; deformation; hydro-mechanical coupling

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1. Introduction

The progress of creep-seepage can lead to serious deformation and the failure of the geo-framework during long operation. On the other hand, the creep-seepage process, because of a fixed load, often can affect the normal operation and stability of deep-underground structures. In order to reduce the influence of creep-seepage action on long-term safety and to keep normal operation, it is necessary to have an adequate knowledge of the mechanism of deformation and permeability evolution during the creep of rocks [1–4].

Creep-seepage is commonly a very complex process, which involves a multitude of hydraulic, thermal, and chemical, as well as mechanical and material properties. Thus, the deformation and creep permeability due to change deviator stress and confined pressure have been the main points for a long time in the creep-seepage experiment [5]. The characteristics of permeability evolution depend on the mechanical and chemical parameters of rocks, such as initial porosity and fracture, mineral composition, and density [6,7], which influence the mechanical state of environmental conditions including stress, damage, confined pressure, and pore pressure [8–10].

Research in this area has recently come to rise as strong interest. There are also many publish to show the mechanism of the deformation and permeability evolution during the creep of rock [5,11,12]. However, it is necessary to research more creep-seepage induced by deformation and permeability evolution during the creep of rocks. Because this discipline has a few problems. For example, the effect of material properties on the permeability evolution during creep deformation is still not clear. Also, the mechanisms of creep deformation and permeability evolution under multi physical fields (Thermal-Mechanic-Hydro-Chemical) require more research.

In order to explore the issues of future work, this paper reviews previous studies related to the creep-seepage process related to experiments. Equations for creep-permeability evolution and modeling method are also summarized.

2. Experimental Research on Creep-Permeability Evolution

Experiments are a useful means of studying creep-seepage. For this reason, there are many experimental results that concern it found in previous research. In this section, we comprehensively review the experimental results associated with creep-seepage associated with the deformation and permeability evolution during the creep of rocks.

A lot of creep-seepage tests consider the deviator stress level under certain confined pressure [3,5,11,13]. These experiments adopted a step-loading method in the mode of axial stress, considering long-term strength, where the permeability was measured using water or gas under unchanged pore pressure. In these experiments, the entire test process kept the pore pressure state and humidity unchanged. Results showed the permeability evolution with an increase in deviator stress. Not only that, it also revealed that the confined pressure affects permeability evolution [14]. However, from analyzing the results, we recognized that material properties, including porosity, microstructure, density, and heterogeneousness, are key factors in altering the behavior of permeability evolution. For example, the initial permeability of some rocks increased with the stress level [13], but that of another decreased with it [11,15]. Particularly, because it is microstructure specific, the permeability evolution of clastic rock during creep deformation is different with others, and thus requires consideration of its microstructure [5,15].

Some scholars used AE (acoustic emission) technology to evaluate the change in microstructure during the creep-seepage of rock [16,17]. Their experiment results illustrated accumulative AE hits can reflect volumetric strain and permeability evolution. The experiment is evidence that the AE technology is useful for picking up characteristics of deformation and permeability during the creep of rock. Meanwhile, it proves the requirement of the method of quantitative assessment for creep damage using accumulated AE hits.

Many published experiments have pointed to chemical erosion of rock by reactive solution [18,19]. These experiments have motivated research on chemical erosion of rock during the creep deformation process. An experiment of creep-seepage of granite in an acid-alkaline environment contributed to illustrate the influence of chemical solutions on deformation and permeability during the creep of rock [20], while the reaction between acid solution and feldspar was an important issue in hydro-mechanical-chemical behavior.

Many researchers have proved thermal influence on the mechanical and physical properties of rock. They have emphasized the thermal effects on short-term strength, long-term strength, permeability evolution, and damage [21–24]. Their results pointed out that the mechanism of the thermal effect on deformation and permeability evolution is the thermal damage with a change in microstructure, including thermal expansion, initiation, and propagation of cracks. Based on the experimental result of some articles [24,25], we recognized it is necessary to focus on the permeability evolution during creep deformation under a certain temperature.

The effect of pore pressure (or seepage pressure) should be considered in research about deformation and permeability during the creep of rocks. It can affect the creep-seepage process in three aspects [1,5,26,27]. The long-term strength decreases with an increase in pore pressure, while the deformation rate and permeability of the tertiary creep stage increases. Despite investigation into the effect of pore pressure, there is a need to enhance the theoretical research by considering the damage mechanism due to pore pressure. In addition, it is also necessary to focus on the effect of pore pressure under a certain temperature.

Table 1 sums up the results reviewed above. Based on review described above, we realized that the future work needs more detailed research on creep-seepage.

Table 1. Summarization of experimental research for creep-permeability.

Literature	Experimental Material	Experimental Method	Result Analysis	Saturated/Unsaturated	Gas or Liquid	Duration of Creep Deformation	Project	Experiment Equipment
[13]	Coal	MS-TCCT CP; 2, 6 MPa PP; 1.5 MPa	Curve of "ε_a-t", "ε_v-t", "ε_a-ε_v", "k-t", "k-ε_a"	Unsaturated	N2	25 h/step	dynamic disaster and water damage prevention and control of gas in coal mine	CSCG-160-type gravity hydraulic constant load creep seepage test system developed by China University of Mining & Technology (Beijing)
[12]	Argillite	SS-TCCT CP: 6 MPa PP; 1 MPa	Curve of "ε_a-t, ε_v-t, k-t", "σ-ε_a"	Unsaturated (RH; 59% (NaBr))	N2	340 h/step	Disposal of radioactive waste	Auto-compensated hydro-auto-servo testing device designed at LML Scanning electron microscopy (SEM)
[11]	COx claystone	MS-TCCT CP; 6 MPa PP; 1 MPa	Curve of "σ-ε_a", "k-ε_a"	Unsaturated (RH;59% (NaBr))	N2	300 h/step	Disposal of radioactive waste	Auto-compensated hydro-auto-servo testing device designed at LML
[3]	COx claystone	MS-TCCT CP (2, 6, 12 MPa), PP; 1 MPa	"ε_a-t, k-t" Power law of creep rate with time	Unsaturated (RH;59%(NaBr))	N2	140 h or 170 h/step	Disposal of radioactive waste	Auto-compensated hydro-auto-servo testing device designed at LML
[27]	Coal	HM&MSCT-TCCT CP; 2, 3, 4, 5 MPa PP; 0.2, 0,4, 0.8, 1.2 MPa Creep Test (CP; 2 MPa, PP; 0.4 MPa)	"k-CP(PP)", "k-ε_a, σ-ε_a", "ε_a-t, k-t"	Gas-saturated	methane gas	4 h/step	safe production of coal underground and efficient exploitation of coalbed methane	adsorption-desorption-seepage experimental system

Table 1. *Cont.*

Literature	Experimental Material	Experimental Method	Result Analysis	Saturated/Unsaturated	Gas or Liquid	Duration of Creep Deformation	Project	Experiment Equipment
[28]	Coal	MSCT-TCCT-(URS) Initial CP; 25 MPa PP; 2 MPa	"ε_a-t, ε_r-t, "k-t", "ε_r-ε_a", ""k-ε_v"	Natural sate	N2	10~20 h/step	to characterize the timeliness of simultaneous exploitation of coal and gas at depth.	a servo-controlled triaxial rheology equipment
[29]	Red sandstone (single fissure)	MSCT-TCCT (Loading-Unloading) CP; 30 MPa PP; 3 MPa	"ε_a-t, k-t"	Natural sate	Gas	48 h/step	Geoscience research and energy resource.	Rock triaxial rheological testing device
[15]	Clastic rock	MS-TCCT CP; 1.5, 2.0, 2.5 MPa PP; 0.25 MPa	Curve of "ε_a-t, k-t", "σ-ε_a, k-ε_a",	Wi: 6.6%	water	48~50/step	a hydropower station	Scanning electron microscopy (SEM), triaxial creep testing device
[14]	Volcanic breccia	MS-TCCT CP; 2, 6 MPa PP; 1.5 MPa	Curve of "ε_a-t, ε_r-t", "ε_a-t, dε_c-t", "ε_r-t, dε_c-t", "k-t"	Saturated	water	50 h/step	Huangdeng Hydropower Project	Rock servo-controlled triaxial rheology equipment, developed by LML
[5]	Cataclastic sandstone	MS-TCCT CP;1.0, 1.5, 20 MPa PP;0.25, 0.35 MPa	Curve of "ε-T-t", "k-t", "ε_c-t"	Wi: 4.61–7.70%	water	48~50/step	dam foundation of a hydropower station	
[1]	Granite gneiss	MS-TCCT CP;4 MPa PP; 1, 2, 3 MPa	Curve of "ε_a-t", "k-t", "σ-ε_a, k- ε_a", "k-PP"	Saturated	Water	72 h/step	underground oil storage cavern	
[16]	Granite	MS-TCCT CP (3, 6, 9 MPa) GB/T50266-99, China	"ε-t", "k-t", "AE hits-step"	saturated	water	12 h/step	high-level radioactive waste (HLW)	MTS815, a three-dimensional AE system

Table 1. *Cont.*

Literature	Experimental Material	Experimental Method	Result Analysis	Saturated/Unsaturated	Gas or Liquid	Duration of Creep Deformation	Project	Experiment Equipment
[20]	Cracked granite	SS-TCCT CP; 2, 5, 10 MPa PP; 1 MPa pH; 2, 12	Curve of "ε_a-t, ε_r-t", "dε_a-t, dε_c-t", "ε_r-t, dε_c-t", "k-t with pH&CP"	Saturated	Water (pH; 2, 12)	300/h, 2700/h	EGS, conventional and unconventional gas, and oil	thermal-hydrological-mechanical-reactive flow coupling testing system
[21]	Red sandstone	MSCT-TCCT (Loading-Unloading) CP; 25 MPa PP; 1 MPa T; 25, 300, 700, 1000 °C	"ε_a-t, dε_a-t (T °C)" "ε_a-t, k-t" (T °C)	Saturated	water	Loading 90 h, unloading 20 h/step		to characterize the timeliness of simultaneous exploitation of coal and gas at depth.
[26]	Coal measures sandstone	MSCT-TCCT CP; 1, 2, 3, 4 MPa PP; 0.5, 1.5, 2.5, 3.5 MPa (CP; 4 MPa)	"ε_a-t", "dε_c-t", "k-t (PP; 0.5, 1.5, 2.5, 3.5 MPa)"	Saturated/unsaturated	water	4 h/step	stability control of roadway surrounding rock in water-rich areas	Electro-hydraulic servo rock mechanics test system of MTS816

MS-TCCT; Multi step triaxial compressive creep test, SS-TCCT; single step triaxial compressive creep test, EGS; enhanced geothermal systems, MSCT-TCC; Multi Stage Cycle loading-unloading with Temperature Triaxial Compressive Creep Test, HM and MSCT-TCCT; Hydraulic-mechanic and Multi step triaxial compressive creep test. CP (confining pressure), PP (pore pressure), φ—Porosity. RH—relative humidity, Dim—dimension of specimen, C_f—compression strength (conventional uniaxial compression test), W_i; initial water content, ε_a; axial strain, ε_T; total strain, ε_v; volumetric strain, ε_c; creep strain, ε_r; radial strain, dε_c; creep rate.

First, the future work should establish the technique for evaluating micro-damage inside of sample during creep-seepage experiments. For example, it can quantify the change in microstructure and micro-damage by using AE (acoustic emission) technology. This technique could be a means of illustrating the mechanism of the deformation and permeability evolution during the creep process of rock, which has complicated properties, such as inhomogeneous and anisotropy. Moreover, its result can support the improving of a constitutive model for creep-permeability.

In addition, we suggest it is important to research more detail about the effect of hydraulic pressure. This work covers researching the influence of its initial properties, such as porosity and fissure, on the sensitivity of pore pressure to affect rock softening.

Finally, we emphasize the important of considering the thermal and chemical effects, because thermal and chemical action are key issues of micro-damage in the creep-seepage process.

3. Permeability Evolution Model

As described above, it is recognized that the change in permeability in the coupled hydro-mechanic field relates to several factors, including porosity, stress level, damage scale, strain rate, and so on. Based on the relationship between these parameters, several permeability evolution models of porous and fracture media are developed through theoretical investigations and laboratory tests by pioneers.

3.1. Relationship between Permeability and Porosity

From laboratory experiments, changes in porosity and permeability are characterized by a few theories to propose the permeability evolution model for describing the relationship between these parameters, which are divided into two classes, the exponential and power function, respectively.

The Kozeny-Carman (KC) model and the other conventional models are used to describe the simple power laws of relationship between permeability and porosity [8,30,31]. From the models presented by the previous paper as described above, a common model can be expressed, as follows:

$$K = \alpha \frac{\phi^{\gamma}}{(1-\phi)^{\beta}} \tag{1}$$

where α is a coefficient related to the initial porosity phase or geometry structure, β is a coefficient associated with a solid phase of porous media, and γ is a constant of the power law.

The parameters in the Kozeny-Carman model can be deduced from the characteristics of pore space in fracture-porous media [32]. While the advanced KC model in considering Darcy's law and the general Poiseuille equation [33], in a straight channel with the generic cross-sectional area, deduced as follows

$$K = \alpha_{KC} \frac{\phi^{3}}{(1-\phi)^{2}} \tag{2}$$

where $\alpha_{KC} = c/\left(8a_v^2\tau\right)$, and a_v is the specific surface area. From the above model, an advanced model can be deduced for considering the channel cross-sectional area with the dimension Ds of the fractal embed in 3D space [32].

$$K = \alpha_{C} \frac{\phi^{\beta}}{(1-\phi)} \tag{3}$$

where α_C is a factor similar KC model, and β is an Archie exponent.

While the relationship K-p (permeability and porosity) induced by [34] could reproduce the experiment result for glass and natural fabric materials:

$$K = \frac{1}{C}\frac{\phi^{1+m}}{(1-\phi)^m} \tag{4}$$

where C and m are empirical parameters.

An empirical power law obtained by using a single transient test can reproduce the permeability evolution under the creep of low permeable material [35].

$$\frac{K}{K_0} = \left(\frac{\phi}{\phi_0}\right)^{\alpha} \tag{5}$$

where α is the porosity sensitive parameter related to the material properties and the evolution process.

The threshold percolation theory can make another power function of the permeability-porosity relationship:

$$K = c(\phi - \phi_{cr})^{\alpha} \tag{6}$$

Previous articles reveal this model has several disadvantages in applying it. For instance, it needs several tests for calibrating the model parameters, and depends on measuring the features of cracks in porous-fracture matrix. Moreover, the parameters obtained from the experiment data of one matrix system, cannot be adopted to another matrix, but it is still preferable to apply to engineering problems [36,37].

Another class of the PPR (permeability-porosity relationship) is an exponent form, and those are commonly obtained with empirical forms by calibrating the experiment data in describing a linear relationship between the porosity and log of permeability:

$$\ln K = \alpha_c\phi + C \tag{7}$$

where the coefficients α_c and C can be obtained by regressing laboratory data for the fracture and porous matrix [38–40].

Yang et al. [7] proposed a significantly more complex formulation of the permeability-porosity relationship, and it is possible to reproduce the permeability-porosity relationship in a whole range of porosity in mudstone.

$$\ln K = a_{c1} + a_{c2}e + a_{c3}e^{0.5} \tag{8}$$

where e is the void ratio, and a_{c1}, a_{c2}, a_{c3} are the coefficients (m^2), depending on the clay content.

According to studies described above, the KC class of models has the capability for describing the permeability evolution. However, the class has disadvantages for an analysis of the mechanical or geometrical aspects, which make it impossible to use without modification. Despite this, empirical models are still useful for the analysis of engineering problems, because they are simple to calibrate and include a few parameters. The KC class of models is quite flexible. The mechanical parameters or geometrical parameters that are associated with the fundamental properties of material, can add into the model. Previous studies show that the KC class of models can become a cure to deduce the more complicated evolution model of permeability under various environmental conditions. Thus, it is necessary to select one of the KC models, fitted with the permeability evolution under the creep of rock, and improve it.

3.2. Permeability-Stress Relationship

Stress covered on rock matrix is a factor of permeability evolution. The permeability-stress relationship can be divided into two classes, respectively: direct relationship and indirect relationship. As described above, permeability is a function of porosity, and porosity can be changed under stress load. So, to consider porosity change due to stress means to evaluate the indirect relationship between permeability and stress. Thus, it needs to focus on the porosity change due to stress. Many articles have shown the influence of stress on porosity by inducing the stress-porosity relationship with an exponential form.

$$\phi = \phi_0 \exp(-\chi \sigma_e) \tag{9}$$

where σ_e is effective stress, and χ is a material constant [41].

Some researchers have proposed an advanced empirical model to contribute to a better understanding of the stress-porosity relationship with considering "residual porosity" [42,43]:

$$\phi = \phi_r + (\phi_0 - \phi_r) \exp(-\chi \sigma) \tag{10}$$

This equation, because of adding a parameter ϕ (residual porosity), can describe the stress-porosity relationship.

Many previous studies have investigated a directive stress-permeability relationship to describe the influence of stress on permeability evolution. The directive stress permeability relationship includes an exponential law and a power law. According to previous investigations, the general formula of the stress-permeability relationship is an exponential function of the current stress and reference stress, describing the ratio of initial permeability and current permeability, as follows [42–44]:

$$\ln\left(\frac{K}{K_0}\right) = f(\sigma, \sigma_0) \text{ or } \frac{K}{K_0} = \exp(f(\sigma, \sigma_0)) \tag{11}$$

Several works have used the power function of stress-permeability to represent the change in permeability because of effective stress [45,46].

$$K = \psi \sigma_e^{-\chi} \tag{12}$$

where ψ and χ are material constants, which can be obtained by fitting a curve of permeability-effective stress from the experimental results, and σ_e is effective stress.

When the studies investigated the influence of effective stress on the fluid flow in one direction of Wilcox shale [47], researchers used the cubic expression of effective stress-permeability to describe the permeability evolution with effective stress.

$$K = K_0 \left[1 - (\sigma_e / \sigma_r)^m\right]^3 \tag{13}$$

where σ_r and m are the reference effective stress and material constant (0 and 1), respectively. The power law of the stress-permeability relationship can represent their relationship at a certain low-effective stress range. However, it might be an infinite value, because the effective stress equals zero and a negative value when effective stress is larger than a certain threshold.

Considering the power law of the porosity-permeability relationship, Zheng et al. [46] developed an advanced stress-permeability model by adopting the concept of a two part-Hooke model (PHM). It could contribute to improving a physically reasonable stress-permeability relationship in low-permeability sedimentary rock.

$$K = K_{e,0} \exp(-\beta C_e \phi_{e,0} \sigma) + \alpha \left[\gamma_t \exp\left(-\frac{\sigma}{K_t}\right)\right]^m \tag{14}$$

where $K_{e,0}$ is the initial value of the hard part permeability, β, α, and m are material constants, C_e is the compressibility for the hard part fraction of pore space, and K_t is the elastic moduli of soft part.

The permeability resistance parameter could refer to the influence of tortuosity due to shear deformation and the fissures' closure because of compaction. So, it was introduced to establish the unified permeability evolution model. The model can describe permeability change induced by stress, and the model used the conventional permeability-porosity power function in order to calculate permeability [48].

$$K = K_0 \left(\frac{\varphi}{\varphi_0} \right)^z \left(\frac{1}{\tau} \right)^\kappa \tag{15}$$

where φ_0 is the reference porosity, z is the parameter of permeability-porosity power function, κ is the power parameter of the permeability resistance, and τ is the permeability resistance with tortuosity resistance due to shear deformation and the context of the fissures' closure because of compaction.

$$\tau = \alpha \left(\frac{\sigma_m{}'}{\sigma_m} \right)^\psi + \beta \left(\varepsilon_q \right)^\xi \tag{16}$$

where α is the fissures' closure-induced resistance parameter, σ_m' is the current mean effective stress, σ_m is the reference value of mean effective stress, ψ is the parameter for the mean effective stress, α is the resistance parameter for the fissures' closure, β is the resistance parameter for the fissures' tortuosity, ξ the parameter for the total shear strain, and ε_q is the total shear strain in conventional triaxial test.

The previous permeability-stress models help to understand the influence of stress change on the permeability, but it is difficult to describe the change in permeability evolution during the creep of rock. So, this section of review reveals the need to improve the permeability evolution model.

3.3. Permeability-Damage Relationship

In a lot of previous studies, it is well known that the description of the permeability-stress relationships is difficult, with only stress being larger than a certain value. In order to explain the reason for the permeability shift, it is essential to apply the concept of damage to permeability evolution.

A new damage mechanical model can evaluate to the effect of Thermal-Hydrological-Mechanic (THM) to thermal the cracking problem of geothermal extraction. Pogacnik et al. [49] established an advanced permeability model to reproduce the permeability evolution as a function of damage. While introducing the sigmoidal functions for capturing permeability change with damage, the model was written as follows:

$$\mathbf{K}(\mathbf{D}) = \mathbf{K}_0 + \kappa_1^i(\mathbf{D})\mathbf{I} - \kappa_2^i(\mathbf{D})\mathbf{I} \tag{17}$$

where $\mathbf{K}_0$ is the initial permeability, and κ_1^i and κ_2^i are the sigmoidal functions as follows:

$$\kappa_1^i = \frac{K_{\max} - K_0}{1 + \exp\left[-\nu_1 \left(D^i - D_1 \right) \right]} \tag{18}$$

$$\kappa_2^i = \frac{K_{\max} - K_f}{1 + \exp\left[-\nu_2 \left(D^i - D_2 \right) \right]} \tag{19}$$

$K_{\max}$, K_0, K_f, ν_1, ν_2, D_1, and D_2 are the parameters fitted through the experimental data.

Some articles deduced the behavior of permeability evolution induced to damage from analysis of previous experimental results [50]. From the report, after the percolation threshold, the relationship between permeability and damage showed a power function, as follows:

$$\mathbf{K} = a \left(\mathbf{D}_{mic} \right)^b \tag{20}$$

where $\mathbf{K}$ is the permeability tensor's trace and $\mathbf{D}_{mic}$ is the trace of micro-damage tensor, and a is the parameter presented as the maximum value of permeability at full damage phase ($\mathbf{D}_{mic} = 1$).

From the experimental result of gas permeability on three concrete specimens subjected to the axial compressive load, a relationship between mechanical damage and permeability evolution shows as an exponential function, as follows [51]:

$$K(D) = K_0 \exp\left(\alpha D^{\beta}\right) \tag{21}$$

where K_0 is the initial permeability, and α and β are constants got by regression of experimental data.

The degree of accumulating damage plays a significant role in the criteria that separate the stress-permeability evolution phase along with the increase in effective stress. For this reason, Yang et al. [9] proposed the stress-permeability evolution model with the reference of accumulating damage, as follows:

$$\begin{cases} K = K_0 e^{-\beta(\sigma_{ii} - \alpha p)} & D = 0 \\ K = \xi K_0 e^{-\beta(\sigma_{ii} - \alpha p)} & 0 < D < 1 \\ K = \xi K_0 e^{-\beta(\sigma_{ii} - p)} & D = 1 \end{cases} \tag{22}$$

The above reviews reveal that damage is one of important factors related to the change in permeability under the hydro-mechanical environment. The damage-permeability evolution model is available to represent the permeability change during the damage process. The previous studies considered the stress-induced damage-permeability relationship, but they were not focused on the permeability change due to creep damage. From this point of view, future investigations need to establish the advanced permeability evolution model by considering creep damage.

3.4. Permeability and Strain

A basic strain-permeability relationship can be established from the theoretical definition of initial porosity and volumetric strain by using the Kozeny-Carman permeability and porosity formula [10].

$$K = \frac{K_0}{1 + \varepsilon_v}\left(1 + \frac{\varepsilon_v}{\varphi_0}\right)^3 \tag{23}$$

where ε_v is the volumetric strain, and φ_0 is the initial porosity.

Some articles have proposed the permeability-strain relationship constitutive model with the tensile strain as instead of damage state [52].

$$\begin{cases} \log\left(\frac{K}{K_0}\right) = C\left(\frac{\varepsilon_t}{\varepsilon_t^c} - \frac{\varepsilon_t^s}{\varepsilon_t^c}\right), \ \frac{\varepsilon_t}{\varepsilon_t^c} > \frac{\varepsilon_t^s}{\varepsilon_t^c} \\ K = K_0, \ \frac{\varepsilon_t}{\varepsilon_t^c} \le \frac{\varepsilon_t^s}{\varepsilon_t^c} \end{cases} \tag{24}$$

where C is the constant of material rock, ε_t^c is the principal tensile strain, and ε_t^s is the reference of tensile strain.

Moreover, some articles have shown that dilatancy due to shear/tensile stress induces a change in porosity and permeability in mudstone. They used the percolation bond model, which has the probability of any bond in its percolation bond network, and connectivity C, which reflects interconnectivity in the fracture network, to establish the permeability evolution model [53].

$$K = AK_p[1 - \exp(-\varepsilon_1/\varepsilon_{ci}) - p_{ci}]^2 \tag{25}$$

where K_p is a permeation peak value, ε_1 is the axial strain, ε_{ci} is the Weibull distribution parameter, and p_{ci} the percolation threshold, while, if permeability reaches to the permeation peak value, that is, $K = K_p$, A is a constant;

$$A = 1/[1 - \exp(-\varepsilon_1/\varepsilon_{ci}) - p_{ci}]^2 \tag{26}$$

From many experimental results, it was well-known that volumetric strain reflected permeability change in steady-state and transient creep deformation phases. Based on the knowledge, Zhou et al. [16] proposed an advanced relationship between creep strain and permeability evolution. The model introduced Hagen-Poiseuille's law and Darcy's law to calculate volume flow rate, as follows:

$$K = K_0 + \frac{n^2(\varepsilon_m - \varepsilon_a)^2}{8\pi} \tag{27}$$

where n is the coefficient of micro-crack connectivity, ε_m is the volumetric strain, and ε_a is the axial strain.

Analyzing the experimental result of granite gneiss triaxial creep test revealed the permeability-strain relationship. From analysis of it, Liu et al., proposed another permeability-strain model to contribute in describing creep-permeability evolution [1].

$$K = \begin{cases} a_i \exp(-b_i \varepsilon_v) + c_i & t < t_s \\ c_s & t_s < t < t_f \\ a_f \exp\left[b_f\left(\varepsilon_v^f - \varepsilon_v\right)\right] + c_f & t \geq t_f \end{cases} \tag{28}$$

where t_s is the time of starting stable state, t_f is the time of starting volumetric dilation, ε_v is the volumetric strain, ε_v^f is the volumetric strain at point of starting volumetric dilation, and the other denotes are constant parameter fitted by permeability-strain curve.

The strain-permeability model contributed to explain the phenomena of permeability change under hydro-mechanical deformation. Particularly, the change in volumetric strain agrees well with the change in permeability. However, the strain-permeability model is unable to describe the permeability evolution with time under the creep deformation of rock. For example, it cannot reflect the permeability evolution due to creep damage and healing effects.

As above described, the relationship between creep and permeability help to understand the permeability evolution under creep. Many researchers have proposed models of permeability evolution in the mechanical field, and there has been a lot of successful research regarding the characteristics of the mechanic-hydro field. Our review has enabled the recognition of a change in porosity to be the basic point for permeability change. So, the porosity formulations are the theoretical basis for estimating permeability. However, it is impossible to represent the change in permeability under creep deformation because the proposed models had not considered a few of the factors that influenced the permeability evolution under creep deformation.

There are several research articles considering several factors that impact the change in permeability. The relationship between permeability and stress, for instance, was considered by using the exponential function and power function. It enables the stress-permeability relation formulation to be applied to estimate the porosity change under certain stress conditions; however, its form cannot reflect the evolution of permeability under creep deformation.

A few articles have shown that damage was an important factor regarding the permeability change and have proposed many formulations for estimating the influence of the damage on its permeability change. They considered the permeability change due to stress damage, but not creep damage. The damage-permeability evolution model cannot reproduce the permeability change under creep deformation.

The strain-permeability evolution model can reproduce the characteristics of permeability evolution. It reflects the principle of strain-porosity-permeability. It is necessary to consider two problems: when the strain-permeability evolution model is used, what is the relationship between permeability and porosity?; and the characteristics of strain evolution. It is convenient to use the strain-permeability evolution model to represent the creep-permeability evolution, because the strain model can include the creep strain as a component of the model. The disadvantage is that the model cannot reproduce the effect of micro-damage on the permeability evolution.

It needs to develop the advanced creep-permeability evolution model to meet the requirements based on the analysis of above review, as follows.

First, it is necessary to develop the creep-permeability evolution model, based on the strain-permeability evolution model, including the creep deformation.

Second, the model can represent the mechanism of permeability change; the change in porosity and initiation and propagation of micro-fractures induced by micro-damage.

In conclusion, it needs to establish the model based on the progressive course; a certain stress condition →the strain included creep deformation and creep damage ($\varepsilon(\sigma, D(\sigma, t), t)$) →the strain induced to change the porosity and crack ($\phi(\varepsilon)$) →the permeability is estimated by the porosity.

4. Method of Simulation for Creep-Permeable Process

There are many methods of simulation for hydraulic-mechanical properties of rock material, including the finite element method (FEM) [54], the discrete element method (DEM) [55], the extended finite element method (XFEM) [56], the combined finite element method, and discrete element method (FDEM), etc. This paper focused on three methods of numerical simulation using FEM and DEM.

4.1. FEM Models

The FEM has been widely used for a few decades in the analysis of rock mechanic problems. The FEM still plays an important role in hydro-mechanical analysis. In particular, several articles, in recent decades, have been published to contribute to the achievements for predicting the situation of the hydro-mechanical field. Many researchers focus on the improvement of the method for simulating the permeability evolution under different mechanical environment conditions [57–59].

The creep behavior of rock means a load-induced time dependent deformation process. Time effect is a primary key. Some scholars proposed the numerical simulation method to represent the creep deformation process under various mechanical environment conditions [60,61]. Similarly, a paper considered the effect of water on the creep damage of rock, but not the effect on the permeability evolution [62].

The research of creep–permeability includes the understanding of the interaction between the creep-induced hydraulic field and the mechanical field permeability evolution, so it focuses on the variation in the hydro-mechanical field with time. For this reason, we review the reports associated with the hydro-mechanical field and creep deformation.

It is important to model the stress–seepage coupled field for roadway construction processes [53]. They used a finite element model in the commercial software ABAQUS for evaluating the distributed zone of rock damage and pore pressure during roadway construction process. The paper established the method for analyzing the change in damage and permeability with time after excavation, but was not interested in the effect of stress redistribution due to creep deformation in the stress-seepage field.

The FEM method established by using the subroutine UMAT of ABAQUS [63,64], used an elasto-viscoplastic (EVP) model to model the hydraulic-mechanical field in the creep process of clayey rock. The result of modeling the area of the nuclear waste repository evaluated the zone distributed creep deformation, stress damage, and pore pressure for providing the significant information on its stability. The method used an advanced MC-EVP model and an empirical creep model. The empirical model could not include the full creep-stages. So, it was difficult to simulate the creep-permeability evolution under lower pressure and long-term strength condition.

Deformation and permeability during the creep of rock in the foundation of hydropower station is also significant [54]. The scholars established the permeability evolution model derived as a function of damage. Specifically, they developed the damage function based on the relationship between energy dissipation and viscous-plastic displacement.

According to the review as above described, the FEM has an advantage in applying flexibly to the investigation of various problems. The reason is that it can use the user-defined subroutine through developing a constitutive model and improving parameters. There is, however, a lack of studies about deformation and permeability under the creep of rocks. Despite some scholars emphasizing that the heterogeneousness of rock is an important issue in the study of hydro-mechanical properties [65,66], there are few articles that have discussed its heterogeneousness during the creep deformation process. Moreover, there is a lack of modeling on the deformation and permeability of creep-seepage under the multi-physical field (Thermal-Hydraulic-Mechanical-Chemical).

4.2. DEM Models

The DEM that was used was smaller than those of FEM in the analysis of hydro-mechanical field. There are many achievements to estimate the stress–strain evolution of the rock material during the fracture and failure process for the problems of geoengineering, such as the safety of underground tunnels and high-level radioactive disposal, and the stability of the rock slope using DEM. A few of the published articles have contributed to the understanding of creep deformation of rock material, and the initiation and propagation of hydraulic fractures due to water injection, in recent years.

It is useful to consider the micro-scale mechanical, as creep behavior is related to a change in microstructure. There are many reports, for this reason, to establish the DEM approach for research work on creep behavior of geological material.

It was possible to simulate a creep behavior in a mechanical experiment, by introducing the Burgers model in a DEM approach [67,68].

Wang et al. (2014) proposed the mode to change the Hertz-Mindlin contact model between some particles into the Burgers contact model [67]. This mode can reproduce the three stages of deformation under various loading conditions in the creep test of sand. Li et al. (2017) proposed an advanced hybrid numerical model for simulating the creep process of salt rock during a triaxial compressive test to estimate the influence of temperature and confining pressure on creep deformation. The researchers used the Burgers model as a contact model between particles to reproduce the creep behavior of salt rock. There was not the research work, however, for the investigation of the change in microstructure in the validation process of its model. The change in porosity in the temperature-induced creep process was also not researched.

In many research articles, the proposal numerical method with the Burgers model could not reproduce the tertiary creep stage [68–70].

Some articles, however, have proposed a DEM approach to simulating the tertiary stage of creep deformation of slate rock in a Uniaxial Compression Multi-stage Creep Test with coupling to the Rate Process theory (RPT) [71,72]. The paper contributed to develop the DEM approach for reproducing the tertiary creep stage, but there are a few things lacking. First, with focus on the aspects of reviewing the creep-permeability evolution, the variation in porosity because of the change in the micro-mechanics field was not considered, and, ultimately, there were no research works on permeability evolution during creep deformation. Secondly, the microstructure evolution under compression creep deformation was not focused, despite DEM being particularly useful for reproducing the micro-mechanics properties when compared to the other methods.

In fact, there are only a few articles that achieve success in illustrating the creep-permeability evolution in the hydro-mechanical research field. However, some previous reports have shown that the DEM approach has a capability for demonstrating the interaction relationship between hydraulic behavior and mechanics properties, such as porous and crack rock and soil.

Some articles have contributed to show the effect of microstructure evolution on the permeability of rock through simulating the hydro-mechanical field by using DEM [55,73,74].

A discrete element method coupled a bonded particle model (BPM) and a pore-scale finite volume model (PFVM) [55]. The method can reproduce the permeability evolution of the cracked low-permeability rock during triaxial compressive tests. The research results illustrated the permeability change process controlled by stress-induced shear deformation. Moreover, it represents the relationship between the crack density and permeability, and post-failure mean residual stress and permeability evolution.

Krzaczek et al. [74] used a fully coupled DEM/CFP approach to simulate the characterization of hydro-fracture in rock. In the research article, it was the primary task to explain the characteristics of hydro-fracture under fluid injection at high-pressure. The research work focused on the several factors, such as the initial porosity of rock, the dynamic viscosity of fluid, the strength of rock, and pre-existing fracture. The report, however, did not include the research work for demonstrating the effects of the heterogeneousness of rock, such as on the permeability and the investigation for the creep deformation.

A review of the DEM shows that the DEM has the potential ability to represent the creep–permeability evolution. It also has an advantage compared with the FEM approach, but it is necessary to research deeply several problems.

The first problem is to establish a DEM approach to reproduce the creep-seepage coupling model in order to model fully the deformation and permeability evolution under the creep of rock.

Second, the future work requires the development of an advanced theoretical model. As above described, the Burgers model and RPT (Rate Process Theory) have the capability for simulating the creep evolution of rock, but they have difficulty in reproducing the full creep stage (not including the tertiary creep phase in the Burgers model) and have not determined the influence of RPT parameters on the simulating result of the creep deformation. So, the development of the theoretical model that can represent the rock creep is a significant issue in an advanced DEM.

5. Conclusions

In this paper, we summarized the advance of deformation and permeability under the creep of rocks. We focused on three disciplines, respectively, experiment research on creep-induced permeability evolution, the permeability evolution model based on hydro-mechanics, and the method of simulation for deformation and permeability evolution.

From our review, we confirmed that there are a few issues to enhance. The first issue is to consider the effect of multi-physics fields. The research articles show that it is a fact that deformation and permeability evolution induced, by coupling, the Thermal, Mechanical, Hydraulic, and Chemical fields under in situ conditions. As we can see from Figure 1 and Table 2, the mechanism of interaction between the thermal, mechanical, hydraulic, and chemical fields is well known, and it is true that the TMHC coupled field to influence creep–permeability. Despite this, there is a lack of research regarding the deformation and permeability under multi-physics fields (Thermal–Mechanical–Hydraulic–Chemical). Thus, we suggest it is necessary to conduct further experiments on the deformation and permeability evolution during the creep of rocks under coupled TMHC. Moreover, the method of modeling the creep–permeability under TMHC coupled condition is also required.

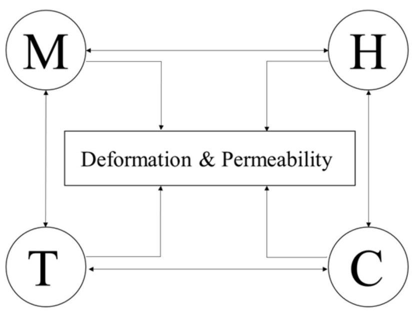

Figure 1. Interaction between TMHC fields and influence on deformation–permeability (TMHC; Thermal-Mechanical-Hydro-Chemical).

Table 2. Interaction between multi-physical fields.

	T	M	H	C
T		Change porosity and mechanical properties by thermal damage	Change in fluid flow Permeability change by thermal damage	Reaction rate change due to change in temperature
M	Change temperature distribution		Pore pressure change, permeability change	Change in flow channel, reactive rate
H	Temperature distribution change due to porosity and fluid flow	Hydraulic damage and permeability change		Change in chemical concentration due to hydraulic field
C	Change in thermal conductivity by chemical process	Microstructure change by chemical damage	Change in permeability induced by chemical damage	

Second, results of our review reveal that it is necessary to focus on the heterogeneity and microstructure. Many rocks are inhomogeneous and anisotropic, but those properties of rock were not considered most times. Moreover, the significant role of damage in creep deformation and permeability evolution, is evidence of the need to consider the microstructure of rock. The change in microstructure is a means of evaluating the damage during the creep of rock, and can contribute to quantify the influence of damage on the deformation and permeability evolution. Its result can be also introduced to establish the creep–permeability model by considering damage and strain as reviewed in Section 3.

Third, we discussed the method of modeling the deformation and permeability during the creep of rocks. Although there are few articles that take into account modeling creep–permeability evolution with using DEM, the result of the review shows that DEM is available to model creep–permeability evolution. In particular, as above described, DEM has the capability to reproduce the deformation and permeability evolution during the creep of rocks as considered by the change in damage and microstructure. Finally, we recommend the research procedure, as in Figure 2. Primarily, the experiment would like be conducted considering the TMHC condition. The results contribute to determining the classic macro-mechanic behavior of rock. At same time, the characteristic of damage and microstructure change can be taken account. The next step includes research in establishing the creep–permeability model, and it needs to estimate the macro-behavior with an increase or decrease in heterogeneousness with the DEM. The result of a DEM modeling stage would be introduced to the stage of the FEM model for estimating the deformation and permeability evolution during the creep of rocks.

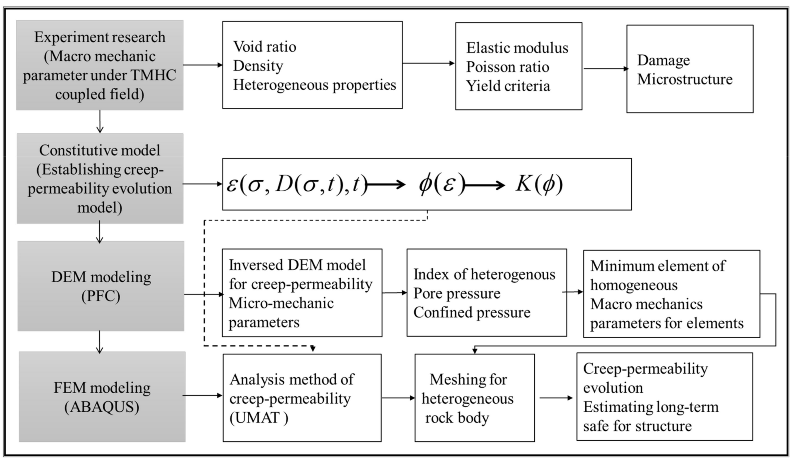

Figure 2. Algorithm and task for the investigation of the creep-permeability field.

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