**Cementing under High Temperature and High Pressure (HTHP) Conditions: a Fully Coupled Porothermoelastic Solution Using P&A as Case Studies**

1. Introduction

Properly designed and executed cementing operations is important as it is widely applied across the various earth Science-related geotechnical applications, such as radioactive waste disposal, deep-well plug and abandonment (P&A), drilling and completion in unconventional reservoir and Enhanced Geothermal (EGS) reservoir, and carbon capture, utilization and storage (CCUS)(Gruber et al., 2021; Hargis et al., 2021; Koťátková et al., 2017; Olson et al., 2015; Vrålstad et al., 2019). A successful cementing job will avoid the unnecessary deficiencies during the life circle of each project which will make the project more environment friendly and improve the system efficiency. Despite the advancements in technological development of cementing materials over the last several decades, the problems of cementing still persists due to the harsh environments where cementing is placed (Ahmed et al., 2020; Allahvirdizadeh, 2020; Kiran et al., 2017). Taking the P&A as an example, over the years and across companies, the upper range of the reservoir’s pressure and temperature have been pushing up to 40000 psi and 600 F (DeBruijn et al., 2008; Khalifeh et al., 2020). The cement is originally designed for low temperature and low pressure conditions. However, under such harsh conditions, its stability over an extended period of time is unknown. To leverage this problem, extensively pioneering researches have being focusing on reinforcing the cement by adding various additives, which is aiming for providing a better mechanical properties and hydraulic properties thus hoping for maintain the system integrity under the extreme conditions (Cai et al., 2022; Ge et al., 2018; Katende et al., 2020; Krakowiak et al., 2018; Massion et al., 2021; Massion et al., 2022; Qin et al., 2021; Samarakoon et al., 2022).

However, known as the cementitious saturated porous material with permeability ranges from mili-darcy to nano-darcy (Banthia et al., 1989; Goto et al., 1981; Meng et al., 2021; Picandet et al., 2011), the cement’s behavior can be heavily influenced by the thermo-hydraulic-mechanical (THM) coupling in the porous space, especially when it is experiencing a large temperature and pressure variations. Within the permeability range mentioned above, a very lager pore pressure could be induced by the THM coupling and the pore pressure will be progressively reestablished over the time, which will also lead to the changing of the effective stress and increase the possibility of shear failure, hydraulic fracturing or even tensile failure (Ghabezloo et al., 2010). While THM coupling phenomena in the porous media has been studied by considerable researchers, their applications have been mainly focusing on the wellbore stability during drilling and fluid injection into borehole (Detournay et al., 1988; Gao et al., 2017; Song et al., 2019; Tao et al., 2010; Zhou et al., 2009). The THM coupling effect in the cementing designs and operations has rarely been properly considered and fully investigated under the HTHP conditions, which could result in jeopardizing the cementing integrity and lead to many serious consequences.

To include these mutual interactions between thermal, hydraulic and mechanical systems in the non-isothermal conditions, Biot (Biot, 1977) firstly extended the tradition theory of poromechanics and include the uncoupled thermal effects by incorporating the thermos-molecular diffusion and dynamic forces using the variational Lagrangian thermodynamics approach. Later on, the thermal diffusion process was coupled in solid and fluid deformation by Derski (1979), as well as others (Bear et al., 1981; Kurashige, 1989; Smith et al., 1993). The abovementioned porothermoelastic analytical solutions are obtained by neglecting the non-linear term associated with connective heat transfer thus it is called as linear porothermoelastic model that is especially prevailing for the low permeability material (Chen et al., 2005; Delaney, 1982; Gomar et al., 2014; Wang et al., 2003). Within the framework of linear porothermoelasticity, substantial studies have been performed for coupled THM behavior of isotropic porous media to understand the mechanism of relative cases, but most of the work are assuming the fluid flux and heat flux are dominated by the pore pressure gradient and thermal gradient, respectively (Ghassemi et al., 2002; Ghassemi et al., 2009; Valov et al., 2022). That is to say, as shown in Eq.1 and Eq.2, the thermo-osmosis (fluid flex generated by thermal gradient denoted by ) and mechano-caloric effects (heat flux generated by pore pressure gradient denoted by and also known as thermal filtration effect (Cheng, 2016) are neglected. However, as for porous material with low permeability, these two effects actually play important roles (Gonçalvès et al., 2010; Roshan et al., 2015; Trémosa et al., 2010). For example, Carnahan (1983) has shown that the thermos-osmosis flow through kaolinite can be two orders of magnitude higher than Darcy’s flow near the nuclear waste repository. Thus, when designing the cementing under the HTHP conditions, both the thermos-osmosis and mechano-caloric effects should be taken into considerations. To our best knowledge, under the HTHP conditions, their influences on the cement integrity are still unclear (is denoting for the fluid flux and is the heat flux).





In this paper, we will use primary cementing in P&A as case studies to introduce so-called fully-coupled porothermoelastic model by incorporating both of the thermos-osmosis and the mechano-caloric effects, dubbed here as “porothermoelastic-osmosis-filtration” (PTEOF). The motivations of creating the PTEOF model is to have a comprehensive understanding of the cement’s behaviors under the HTHP and build up a general framework and solutions for future cementing studies and analysis. Drawing on the important contributions of Sarout et al. (2011) on modifying the theory of linear chemo-poroelasticity into a convenient form whereby the interpretations of the phenomenological parameters can be clarified, this paper will not only include a detailed parametric studies of each parameters in PTEOF, but also it will include a discussion of the implications of these results for future HTHP cementing design and operations.

conclusions:

2. Model Basics

Following the sign convention in Detournay et al. (1988), the positive stress is considered to be tensile within the present work. Following the pioneering work of Cheng (2016) and Wang (2017), the constitutive equations for linear porothermoelasticity are written as follows:

 where 

whereandis volumetric strain tensor and total stress tensor, respectively. is the variation of fluid content per unit reference volume, is entropy density,is pore pressure change and is temperature change from the reference temperature. The material constants include the drained bulk modulus tensor, Biot effective stress coefficient, Skempton pore pressure coefficient, coefficient of volumetric thermal expansion of porous media frame , coefficient of volumetric thermal expansion of variations in fluid content in the solid-fluid system, and represents the specific heat of the porous medium at the reference temperature. From the constitutive equations, it shows that the deformation of the solid frame is caused by the effective stress and the temperature change. The fluid phase in the porous medium is not only deforming with the solid frame, but at the same time, driven by pore pressure gradient and thermal forces, causing the pore fluid entering or leaving the solid frame of unit volume. Last, the stress and temperature change will cause the change of the entropy of the porous system based on the generalized-energy relation. The entropy density is therefore becoming a function of volumetric strain of the solid frame and fluid content and the change of temperature. Thus, the constitutive equations relate and couple volumetric strain, fluid content and energy variables  with total stress, pore stress and temperature variables with the materials constant. Noted that one of these volumetric response that Eq. 3 shows can also be contraction on Eq. 4.







Based on quasi-static equilibrium (Eq.5) and the strain-displacement relations (Eq.6) and by substituting both transport laws (Eq. 1 and Eq. 2) into the mass balance equations (Eq.7 and Eq.8), the fully coupled diffusion equations (Eq. 9 and Eq. 10) could be obtained. These two diffusion equations indicate that both fluid flux and heat flux are not only dominated by the Darcy’s law and Fourier’s law, but also they are influenced by the thermal osmosis effect and thermal filtration effect. This is also where porothermoelastic-osmosis-filtration (PTEOF) so called fully coupled model roots in. One of the motivations to build up these fully coupled model is to facilitate the further studies and analysis. For example, under some circumstances where thermal osmosis or thermal filtration is not considered important, it can always take the corresponding coefficient to zero to simplify the model.









3. PTEOF solution for the primary cementing in P&A

3.1 Problem descriptions and boundary conditions

In light of the presenting work will showcase the PTEOF model by using the primary cementing in P&A cases where the length of the primary plug is usually 50 to 100 times larger than its diameter (Eshraghi, 2013), it is appropriate to apply the generalized plain-strain assumption where the pore pressure and thermal diffusions only appear in the isotropic plane that perpendicular to the length axis of the plug. In line with the loading decomposition scheme proposed by Detournay et al. (1988) in the poroelasticity, the PTEOF model could be decomposed into three sub-loading cases to simplify the analysis, i.e. pore pressure loading (), temperature loading () and isotropic far-field stress loading (), where the superscript i is denoting by the stress field that induced by the loading mode j. Thus, the boundary conditions at the outside surface of the primary cement plug for each of the loading modes can be written as follows (the subscript f is denoting by formation, subscript c is denoting by cement). Since the PTEOF model is linear, the principle of superposition will be used as final step to obtain the final solution.

* Mode 1: , and 
* Mode 2: , and 
* Mode 3: , and 

3.2 Solution to the fully coupled diffusion equations

The solution method starts with obtaining a general solution of the fully coupled diffusion equations (Eq.9 and Eq.10). Noting that the plain-strain assumption will lead to the conclusion that fluid and thermal transport will be only directed along the radial direction only in the cylindrical coordinates system. Then the first step is to eliminate  and in the diffusion equation Eq.9 and Eq.10 by substituting the constitute equations (Eq.3), this results in a new form of coupled diffusion equations could be expressed by Eq.11 and Eq.12.





Next by combining the Eq.4 to Eq.6 and taking the body force to zero, an extended form of the classical Naiver equations about be obtained:



Drawing on the important contributions of Sarout et al. (2011) on modifying the theory of linear chemoporoelasticity into a convenient form whereby the interpretations of the phenomenological parameters can be clarified, we herein by using the irrotational field assumptions to simplify the process of solve the Navier equations. When displacement field is irrotational, i.e. is the gradient of a scaler, one can integrate Eq. 13 to obtain



Where  and 

Wheredoes not depend on the spatial coordinates and it is a spatially uniform function that is often taking to zero for infinite or semi-infinite domain (Detournay et al., 1993). In the case of the primary cementing in P&A, thewill not be taking as zero here. Next, by substituting Eq. 14 into Eq. 11 and Eq. 12, thecould be eliminated and it could have the coupled diffusion equations in other form as shown in Eq. 15.



Where















The diffusion equations shown in Eq.15 are coupled in terms of T and p, which can be transformed into uncoupled problems in terms of  and by using the eigen decomposition approach developed by Sarout and Detournay (Sarout et al., 2011). This methodology is starting with obtaining two eigenvalues  and  of matrix. Then the eigen-decomposition theorem (Weisstein, 2002) will allow us to define a transition matrix which is composed of eigenvalues and eigenvectors of . So temperature and pore pressure can be expressed as follows



Where





This transition leads directly to an uncoupled system of diffusion equations for the given by

 where 

Then by applying the Laplace transform to the Eigen function , i.e., in Eq.17, it becomes an ordinary differential equation in terms of variable , where the is function of the coordinators in cylindrical system ρ, and the Laplace parameter s and the ’s eigenvalue

 where 

Therefore, the original coupled diffusion equations (Eq.15) has been lead to the zeroth-order modified Bessel equation with the general solution as (Eq.19), where and  are unknowns that will be determined based on the boundary conditions. and are the zeroth-order modified Bessel functions of the first and second kinds, respectively.



The symmetry conditions of the primary cementing in P&A will ensure the equals to zero, thus the pore pressure and temperature profile in Laplace domain could be expressed as follows:





Within the framework of plain-strain conditions and irrotational field, the displacement  could be obtained by integrate the Eq.14. At the same time, the strain-displacement relationship could be expressed as follows:



where  and 

Up to now, there are totally three unknowns , i=1,2,3 in the system. The first two unknown  and are coming from the coefficient of zeroth-order modified Bessel functions of the first and the third unknown is coming from the spatially uniform function from Eq.14 in Laplace domain. In the process of deriving the above expressions for the pore pressure, temperature and radial total stress boundary conditions in Laplace domain, we have three equations for these three unknowns (shown in Eq.23).



Where















So that given a value of s, thecan be readily computed, thus the solution then can be numerically inverted to the time domain using Stehfest’s method, which has been proved to be efficient in poroelastic problems. For a given function p with Laplace transform, Stehfest’s method can be expressed as, taking pore pressure for example:



Where the coefficient are given by



3. Numerical Analysis and Discussion

The input parameter for modeling results for this section are listed in Table 1. All of their values obtained from the previous literature and the temperature difference between the formation and cement is assigned as. In this section, we will discuss firstly discuss the pore pressure profile, temperature profile and effective stress profile that induced by three different loads, respectively. Lastly, the superposition results will be discussed.

3.1 Pore pressure file in three loadings

Considering the boundary conditions that defined in the last sections, the influence of the factors of interest on the pore pressure will be conducted to illustrate different thermoporoelastic modes in the section.

In the most of classical poromechanics analysis, the evolution of pore pressure in response to different loadings is calculated and interpreted. It is therefore of interest to plot and understand the evolution of pore pressure under different loading modes.





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**Figure 1**

Figure 1 illustrates the evolution of pore pressure profile inside the primary cement plug in response to mode 1 loading (temperature loading) and mode 2 loading (pore pressure loading). Under the pore pressure loading, it is similar to the classical diffusion process, the pore pressure near the surface is instantly raised to the level to pore pressure loading and then the pressure is gradually diffusing towards in the center of the specimen. However, in contrast of gradual and smooth diffusion process, the temperature induced pore pressure firstly peaks near the surface area. At the surface, the pore pressure returns to zero due to the boundary conditions. The pore pressure, however, decreases toward the inner core hence a peak profile is developed. As time progresses, the pore pressure peak declines due to fluid diffusion, and at the same time, the inner core becomes heated as well and so the peak is moving toward to the center. At even larger time, when the entire specimen is heated but the pore pressure is not yet dissipated due to the small fluid diffusivity. As time further increases, the entire pore pressure dissipated and return to zero everywhere. For the pore pressure that induced by the mode 3 (isotropic far-field stress), it is firstly arrives the highest value right after the loading (again, pore pressure at surface reduces to zero due to the boundary conditions), but it gradually declines to zero due to the dissipation process as the time process. It is noticeable that the magnitude of the pore pressure induced by mode 3 is much smaller compared to the pore pressure induced by mode 1 and mode 2. Even at their highest level which is right later the loading is applied, the ratio of mode 1 induce pore pressure over the mode 2 and mode 3 induced pore pressure is around 0.01%-0.02%. This is also in line with the findings from their classical pure poroelastic model (Detournay et al., 1988), which indicates that the undrained loading effect as a short-term characteristic of low permeability rock does not increase much pore pressure.

Since the peak pore pressure usually occurs at the early-time for all three loadings, we will use the smaller time intervals days after loading to illustrate the thermal osmosis and thermal filtration effect on the induced pore pressure.

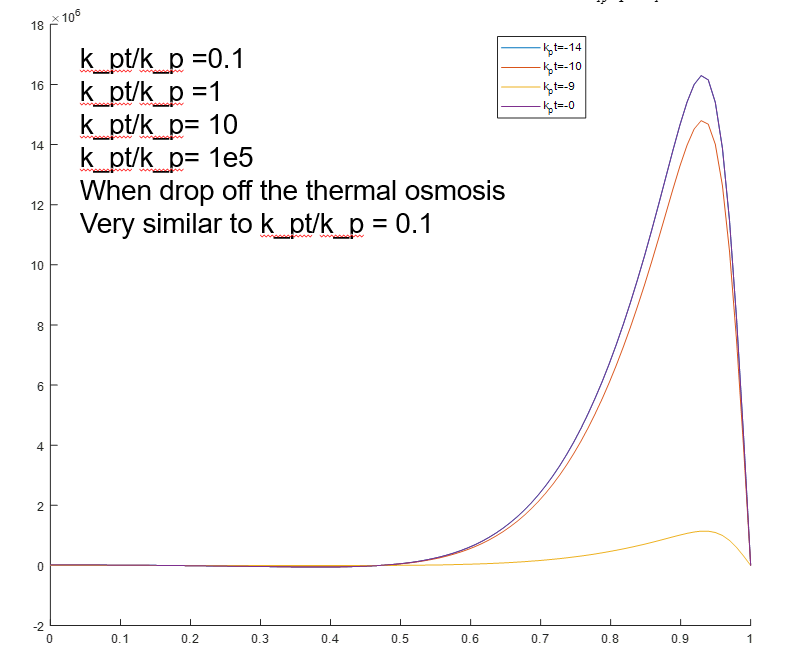


Figure 2

To investigate the impact of different ratios of k\_pt/k\_p on the pore pr, three k\_pt/k\_p (0.1, 10, 10^5) ratios are picked up to show the development of the temperature induced pore pressure. Recalling the definition of the thermal-osmosis coefficient which can be understood as the passage of a fluid that is driven by a temperature gradient but again the hydrostatic pressure (Denbigh, 1949). Taking the early time (t=60s) as example, the increased pore pressure are generated at the near surface region for all of three cases. However, the magnitude of the induced pore pressure is reduced when the thermos-osmotic coefficient is significantly larger than the hydraulic conductivity (k\_pt/k\_p=1e5). These phenomena indicate that a large thermos-osmotic coefficient can help to reduce the temperature induced pore pressure, which will fortify the effective stress in the cement and reduce the possibility of failure.

Table 1. Notations

|  |  |  |
| --- | --- | --- |
| Symbol | Definition | Unit |
|  | Biot effective stress coefficient | --- |
|  | Drained thermoelastic effective stress coefficient | N⋅m-2⋅K-1 |
|  | Skempton pore pressure coefficient | --- |
|  | Coefficient of volumetric thermal expansion of solid | K-1 |
|  | Coefficient of volumetric thermal expansion of porosity | K-1 |
|  | Coefficient of volumetric thermal expansion of fluid | K-1 |
|  | Coefficient of volumetric thermal expansion for variation in fluid content | K-1 |
|  | Drained coefficient of volumetric thermal expansion of porous medium frame | K-1 |
|  | Specific heat of the porous medium at reference temperature | J⋅kg−1⋅K−1 |
|  | Fluid flux | m⋅s−1 |
|  | Heat flux | J⋅m−2⋅s−1 |
|  | Permeability coefficient | m2⋅Pa−1⋅s−1 |
|  | Thermal conductivity | W⋅K−1⋅m−1 |
|  | Mechano-caloric coefficient | m2⋅s−1 |
|  | Thermo-osmosis coefficient | m2⋅s−1⋅K−1 |
|  | Poisson’s ratio | --- |
|  | Drained bulk modulus | N⋅m-2 |
|  | Shear modulus | N⋅m-2 |

3.2 Temperature profile

The thermal filtration effect on the evolution of temperature is herein studied in this section. Firstly, the temperature evolution under the temperate loading mode is show in figure 3. As the time proceeds, temperature is increasing monotonically from surface towards the inner core of the plug and finally arrives the equilibrium at larger time.



Figure 3

Three different ratios of thermal conductivity over the thermal filtration coefficients are selected to show their impact on the temperature profile that is changed by the pore pressure gradient. As shown in figure 4, among the three selected ratios, the maximum temperature difference induced by the pore pressure gradient is within 1 degree Kalvin. Furthermore, the thermal conductivity is signicantly larger than the thermal filtration coefficient (k\_pt/k\_p=1e8), the induced temperature difference neglectable under the current model settings and input.

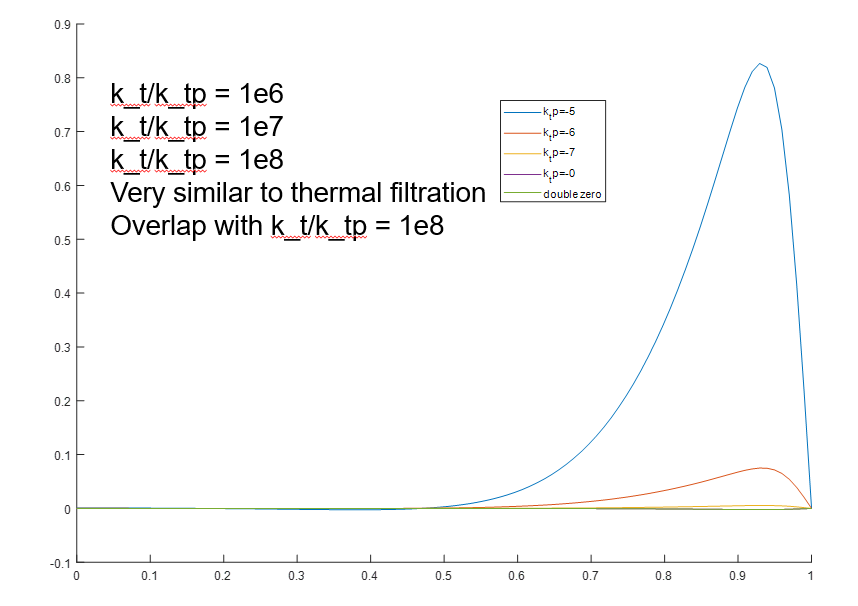
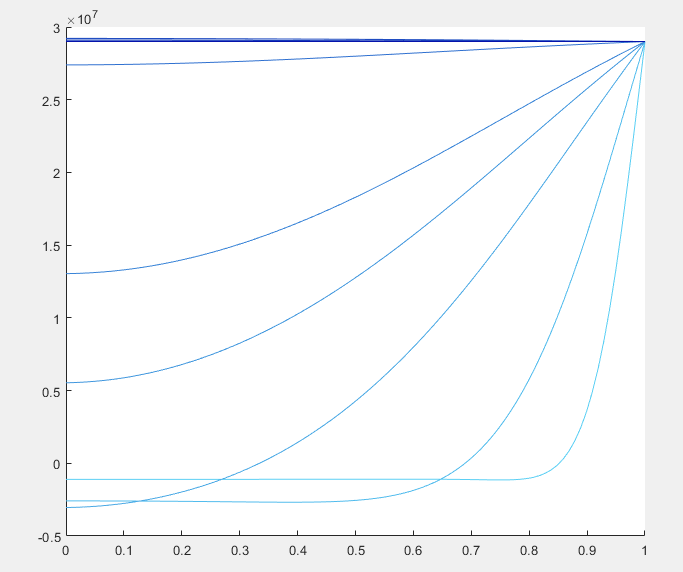


Figure 4



Pore pressure induced effective stress



Thermal induced effective stress

Effective radial stress induced by thermal loading

Total effective stress



3.3 Effective Stress

Many literatures have shown that the increase pore pressure will reduce of effective stress which can increase the possibility of the failure (citations). Thus, it is important to obtain the effective stress under each loading mode and then superposition them to obtain the total effective stress of the system. As shown in figure 5 where the total effective radial stress is plotted, after the cement is placed under the boundary conditions that setup previously, the induced pore pressure will reduce the radial effective stress near the surface region and as the induced pore pressure is increased and diffused towards the inner core, the effective stress will be further reduced and the tensile region will be created inside the core. At the later stage, the induced pore pressure will be dissipated, the radial total effective stress returns to compressive again. This demonstration of the whole process of PTEOF model with given input indicates that cementing under the high temperature and high pressure conditions will lower the effective stress and even induced the tensile effective stress response to the induced high pore pressure diffusing inward. The phenomenon will increase the possibility of failure of the cement under HTHP conditions and thus will cause more severe sequences. It is worth to mention that the system behaviors discussed above are depending on the different values of input parameters and the mutual interaction and group effect among them. These features will be investigated and discussed in the next sections.

4. Fully parametric studies

As mentioned in the previous section, the system behaviors of the PTEOF are controlled by input of several parameters. If some of these parameters are taking different values, the results can be much different. To firstly grasp a full figure of how each parameter will influence the system behavior in the PTEOF model, a heat map is thus created. This heat map is generated based on the constitutive equations that discussed in the previous section and it consists ten different parameters. The algorithm behind this heat map, which is shown in figure, is changing only one parameter each time while the rest of them are maintained as the same. Thus, 10 different parameters will requires 310 times of calculations. In the heat map, each number in the small block is representing the percentage of the cases of tensile radial effective stress associate with the corresponding parameter and the side color bar indicates the scale of the probability. A general trend can be found from this heat map that a higher values of  and lower value of and cause increase the probability of tensile radial effective stress generation. However, the mutual interactions of different parameters and their group effect can not be analyzed based on the algorithm that is used in this heat map.

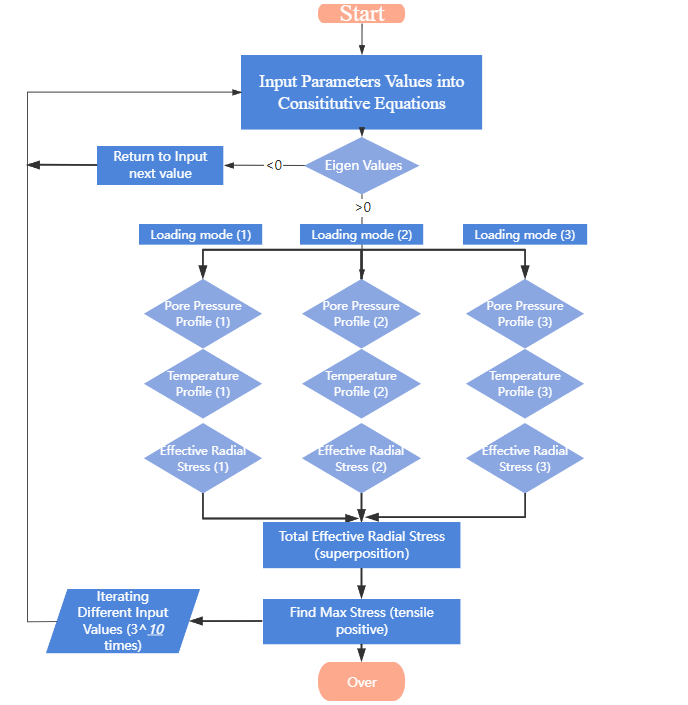
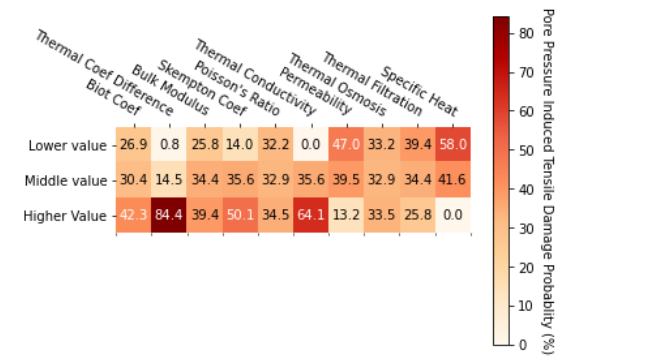


Figure. The Algorithm behind the heat map



To solve the just mentioned above problem, scaling is a very powerful tool. It is usually used to reducing complex physical problem to a simpler version prior to obtaining a quantitative answer and can grasp the effects of various physical phenomena at the same time (citations). We indeed can follow the typical procedures to conduct the scaling analysis to investigate the mutual interaction and group effect of the PTOEF model. However, the new dimensionless numbers that is resulting from the scaling analysis is often in a very complicated expressions and lacking of direct meaning at the physical level, which can be very ambiguous to many cementing practitioner. Thus, inspired by the spirit of the methodology of scaling analysis, we here adapted to manually compose several new dimensionless numbers with clearer physical meaning and then reconstruct a new heat map that can account for the mutual interactions and group effects among these different parameters.

Thus, two new dimensionless numbers are hereby proposed as follows:



Concluding from the first heat map, there are four important parameters  will contribute to the tensile stress. Thus, the first dimensionless number is composed as shown in Eq. 25 (in the numerator is added to balance/eliminate the unit). From the new heat map, it is clearly showing that when the new dimensionless numberis taking the higher value, the probability of the induced tensile case is 100%. However, whenis taking middle value and lower value, there is no induced tensile case at all. This indicates that when these four important parameters are grouping together, their influence over the system is absolutely dominate. This is also evidenced by that the probability distributions of the rest parameters are all around 33%, which are all most all evenly distributed. It is also showing that when this powerfuldimensionless number is dominating the system, the influence of all other parameters are very trivial.

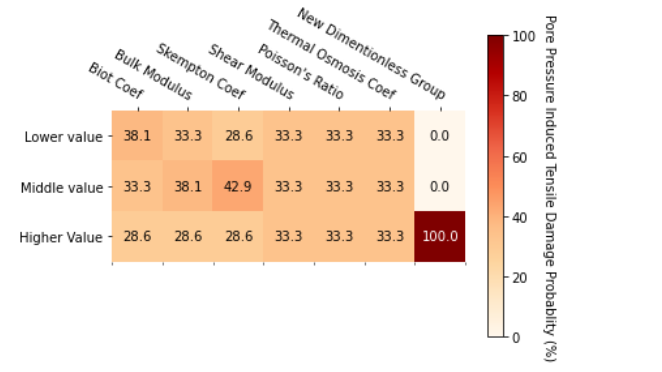


Figure 6. Heat map of the different parameters contributing to the tensile effective radial stress. The number in each block shows the percentage of the cases of tensile effective radial stress that associates with the corresponding parameters (the value of lower/middle/higher input is shown in the table 2 in appendix).

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