EXPERIMENTAL ASSESSMENT

OF FRACTURE PERMEABILITY OF SANDSTONE

UNDER STRESS STATES

Jiraporn Buaboocha

A Thesis Submitted in Partial Fulfillment of the Requirements for the

Degree of Master of Engineering in Geotechnolgy

Suranaree University of Technology

Academic Year 2010

การทดสอบความซึมผ่านของรอยแตกในหินทรายภายใต้ความเค้น

นางสาวจิราภรณ์ บัวบูชา

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต

สาขาวิชาเทคโนโลยีธรณี

มหาวิทยาลัยเทคโนโลยีสุรนารี

ปีการศึกษา 2553

EXPERIMENTAL ASSESSMENT OF FRACTURE PERMEABILITY OF SANDSTONE UNDER STRESS STATES

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

Thesis Examining Committee

____

(Asst. Prof. Thara Lekuthai)

Chairperson

____

(Assoc. Prof. Dr. Kittitep Fuenkajorn)

Member (Thesis Advisor)

____

(Dr. Prachya Tepnarong)

Member

____

(Dr. Wut Dankittikul)

Acting Vice Rector for Academic Affairs

____

(Assoc. Prof. Dr. Vorapot Khompis)

Dean of Institute of Engineering

จิราภรณ์ บัวบูชา : การทดสอบความซึมผ่านของรอยแตกในหินทรายภายใต้ความเค้น (EXPERIMENTAL ASSESSMENT OF FRACTURE PERMEABILITY OF SANDSTONE UNDER STRESS STATES) อาจารย์ที่ปรึกษา : รองศาสตราจารย์ ดร. กิตติเทพ เฟื่องขจร, 176 หน้า

วัตถุประสงค์ของการวิจัยนี้คือ เพื่อศึกษาความซึมผ่านของรอยแตกในหินซึ่งได้รับอิทธิพลจากความดันล้อมรอบ โดยทำการทดสอบการไหลผ่านรอยแตกที่ทำขึ้นในห้องปฏิบัติการของหินทรายสี่ชนิดภายใต้แรงดัน และมีความขรุขระของผิว ความเปิดเผยอ ความดันล้อมรอบ และความเค้นตั้งฉากที่แตกต่างกัน ตัวอย่างหินทรายนั้นได้มาจากหินทรายหมวดเสาขัว ภูกระดึง พระวิหาร และภูพาน สำหรับหินทรายแต่ละชนิดนั้นได้มีการใช้ตัวอย่างสามตัวอย่างเป็นอย่างน้อยในการทดสอบแบบเฮดเปลี่ยนแปลง และใช้หกตัวอย่างในการทดสอบแบบเฮดคงที่ ผลที่ได้จากการวัดเหล่านี้ได้ถูกนำมาพัฒนาความสัมพันธ์ทางคณิตศาสตร์ระหว่างความซึมผ่านของรอยแตก ความเปิดเผยอของรอยแตก และความเค้นที่ใช้ทดสอบ ผลจากการวิจัยนี้จะเป็นประโยชน์ในการหาความซึมผ่านของมวลหินภายใต้สภาวะความเค้นในพื้นที่ ประกอบกับความหนาแน่นและการวางตัวของรอยแตก ซึ่งสามารถนำไปประยุกต์ใช้ในการหาความซึมผ่านในพื้นที่ของแหล่งน้ำมัน ชั้นหินอุ้มน้ำ ฐานรากของเขื่อน และความลาดชันของหิน

จากการทดสอบการไหลแบบเฮดคงที่ ค่าความซึมผ่านของหินทรายมีแนวโน้มที่จะลดลงในขณะที่ค่าของความดันล้อมรอบเพิ่มขึ้น ซึ่งอาจเป็นผลจากช่องว่างในหินและรอยแตกมีขนาดลดลงเนื่องจากแรงดัน ในขณะที่ทำการลดแรงดันนั้น อัตราการไหลที่วัดได้แสดงให้เห็นถึงการลดลงอย่างถาวรของค่าความซึมผ่านในหิน สมมติฐานว่าอาจเกิดการยุบตัวของช่องว่างในหินจนชิดกันอย่างถาวร ในการทดสอบการไหลแบบเฮดเปลี่ยนแปลง ความซึมผ่านของหินทรายที่ทำการทดสอบมีค่าลดลงอย่างคงตัวในขณะที่เพิ่มความเค้นตั้งฉาก โดยความซึมผ่านนั้นมีค่าอยู่ในช่วงระหว่าง 100×10^{-6} เมตรต่อวินาที และ 10000×10^{-6} เมตรต่อวินาที

สาขาวิชา เทคโนโลยีธรณี ลายมือชื่อนักศึกษา ____________________

ปีการศึกษา 2553 ลายมือชื่ออาจารย์ที่ปรึกษา ____________________

JIRAPORN BUABOOCHA : EXPERIMENTAL ASSESSMENT OF FRACTURE PERMEABILITY OF SANDSTONE UNDER STRESS STATES. THESIS ADVISOR : ASSOC. PROF. KITTITEP FUENKAJORN, Ph.D., P.E., 176 PP.

ROCK/FRACTURE/ PERMEABILITY/SANDSTONE/FLOW TEST

The objective of this research is to experimentally study the rock fracture permeability as affected by confining pressures. The effort primarily involves laboratory flow testing of tension-induced fractures in four types of sandstone under various surface roughnesses, apertures, confining pressures and normal stresses. The sandstone samples belong to Sao Khua, Phu Kradung, Phra Wihan, and Phu Phan formations. For each rock type, a minimum of 3 samples are used in falling head test, and 6 samples are used in constant head test. The measurement results can be used to develop a mathematical relationship between the fracture permeability, fracture aperture and the applied stresses. The research findings can be of useful in determining the rock mass permeability under in-situ stress conditions with different fracture intensities and orientations. Such applications include, for example, the determination of in-situ permeability of oil reservoir, aquifer, dam foundation, and rock embankments.

From constant head flow testing, the sandstone permeability tends to decreases with increasing confining pressure. This is probably due to the contraction of the pore spaces and fractures in the specimen. During unloading, the measured flow rates show a permanent reduction of the rock permeability, suggesting that a permanent closure of the pore spaces has occurred. For all sandstone types the fracture hydraulic

conductivities exponentially decrease with increasing the normal stresses in falling head flow testing. Their permeability is in the range between $100x10^{-6}$ m/s and $10000x10^{-6}$ m/s. Under normal stress alone, a permanent fracture closure is usually observed after unloading as evidenced by the permanent reduction of the fracture permeability (flow rate).

School of Geotechnology Student's Signature________________

Academic Year 2010 Advisor's Signature________________

ACKNOWLEDGMENTS

The author wishes to acknowledge the support from the Suranaree University of Technology (SUT) who has provided funding for this research.

Grateful thanks and appreciation are given to Assoc. Prof. Dr. Kittitep Fuenkajorn, thesis advisor, who lets the author work independently, but gave a critical review of this research. Many thanks are also extended to Asst. Prof. Thara Lekuthai and Dr. Prachya Tepnarong, who served on the thesis committee and commented on the manuscript.

Finally, I most gratefully acknowledge my parents and friends for all their supports throughout the period of this research.

Jiraporn Buaboocha

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

SYMBOLS AND ABBREVIATIONS

α	=	Empirical constant
β	=	Isothermal compressibility
γ	=	Fluid unit weight
Δh	=	Change in head
δ	=	Normal deformation of the fracture
μ	=	Viscosity of the fluid
ν	=	Kinematic viscosity of water
σ_c	=	Unconfined compressive strength
σ_n	=	Normal stress
A	=	Cross-sectional area
b	=	Width of the fracture
D	=	Diameter of specimen
dp/dx	=	Pressure gradient
dx	=	Length of the specimen
e_c	=	Equivalent cubic law aperture or hydraulic aperture
e_h	=	Hydraulic aperture
e_m	=	Mechanical aperture
e_{mass}	=	Equivalent mass balance aperture
g	=	Acceleration of gravity
H_1, H_2	=	Pressure head at beginning and end of test

SYMBOLS AND ABBREVIATIONS (Continued)

JCS	=	Joint Compressive Strength
JRC	=	Joint Roughness Coefficient
k	=	Coefficient of permeability
K_f	=	Fracture conductivity
k_f	=	Fracture permeability
K_j	=	Hydraulic conductivity for smooth, parallel plates
k_m	=	Matrix permeability
L	=	Length of Specimen
p_0	=	Initial pressure
P_c	=	Confining pressure
p_e	=	Exit pressure
P_i	=	Injection pressure
p_i	=	Inlet pressure
psi	=	Pound/inch^2
p_t	=	Final pressure
q	=	Fluid flow rate
R	=	Inner radius
r	=	Outer radius
r_b	=	Buret radius
t	=	Decay time
t_1, t_2	=	time at beginning and end of test
V_1, V_2	=	Volume of pore fluid at top and bottom of specimen

SYMBOLS AND ABBREVIATIONS (Continued)

w	=	Weight of specimen
PK	=	Phu Kradung sandstone
PP	=	Phu Phan sandstone
PW	=	Phra Wihan sandstone
SK	=	Sao Khua sandstone

CHAPTER I

INTRODUCTION

1.1 Rationale and Background

At present, it is difficult to predict the risk of sudden groundwater inundation and gas outbursts in complex hydro-geological environments prevailing in underground mines and tunnels. This is primarily because of the lack of proper understanding of flow through porous media containing systems of fractures. Fluid flow through rock mass is complicated by the presence of fracture systems which represent the dominant flow path. Main factors governing the fracture permeability includes fracture aperture, roughness, orientation, and magnitude of stresses normal to the fracture planes. As a result coefficient of permeability of rock mass may not be taken as a scalar from as commonly assumed, instead it should have direction and magnitude controlled by the fracture aperture and orientation and the magnitudes of in-situ stresses. Knowledge and understanding of fluid flow through rock mass containing fracture systems as affected by in-situ stresses are however rare.

1.2 Research Objectives

The objective of this research is to experimentally study the rock fracture permeability as affected by confining pressures. The effort primarily involves laboratory flow testing of rock fractures under various surface roughnesses, confining pressures and normal stresses. The measurement results are used to develop a mathematical relationship between the fracture permeability, fracture aperture and the applied stresses. The research findings can be of useful in determining the rock mass permeability under in-situ stress conditions with varying fracture intensities and orientations. Such applications include, for example, the determination of permeability of oil reservoir, aquifer, dam foundation, and rock embankments.

1.3 Research Methodology

As shown in Figure 1.1, the research methodology comprises 5 steps; including literature review, sample collection and preparation, laboratory testing, development of mathematical relations and flow equations, and discussions and conclusions.

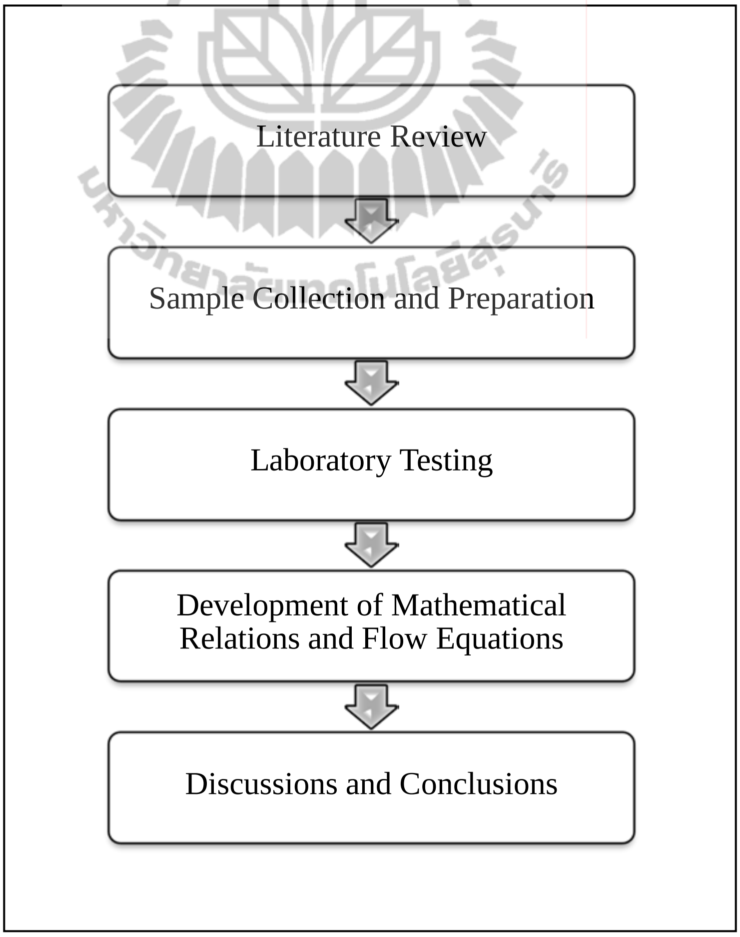


Figure 1.1 Research methodology.

1.3.1 Literature Review

Literature review is carried out to study the genesis and classification of fractures, permeability of rock mass, apertures, and stress effects on fracture void geometry. The sources of information are from text books, journals, technical reports and conference papers.

1.3.2 Sample Collection and Preparation

Sandstone samples are collected from the site. A minimum of 4 sandstone types are collected. Sample preparation is carried out in the laboratory at the Suranaree University of Technology. Samples prepared for the constant head test are 2 inches in diameter and 3 inches long. Samples for the falling head test are prepared as 6x6x10 inches rectangular blocks. The fractures are artificially made in the laboratory.

1.3.3 Laboratory Testing

The laboratory testing is divided into two groups; i.e. constant head flow test under various confining pressures, and falling head flow test under normal stresses.

(a) Constant Head Flow Test under Various Confining Pressures

Constant head are conducted. A constant diameter water pump is used to inject water pressure to one end of the specimen. The specimen is placed in triaxial cell which is used to applied constant confining pressures to the rock and fracture. The applied confining pressures vary from 500 to 3000 psi. The injected water pressure is about 20 psi which is controlled by using a regulating valve at the top of nitrogen gas tank. A high precision pipette is use to collect outflow of water at the other end of the specimen. A single fracture is induced parallel to the specimen axis.

The measured flow rates at each confining pressure are measured to calculate the fracture permeability.

(b) Falling Head Flow Test under Normal Stresses

Falling head tests are conducted by injecting water into the center hole of rectangular blocks of sandstone. A fracture is created across the block specimen either by saw-cutting or tension inducing methods. The 8 mm hole is drilled into the upper block of the sample to allow water flow through the fracture. The constant normal stresses on the fracture are varied from 50 psi to 300 psi by using dead weight loading devices. A minimum of 3 samples for each rock type are tested.

1.3.4 Development of Mathematical Relations and Flow Equations

Results from laboratory measurements in terms of rock fracture permeability and stress states are used to formulate mathematical relations. Orientations of the fractures and the applied stresses can be incorporated to the equation, and hence permeability of rock mass can be computed in any direction.

1.3.5 Conclusion and Thesis Writing

All research activities, methods, and results are documented and complied in the thesis.

1.4 Scope and Limitations

Laboratory experiments are conducted on specimens from four formations of sandstone, including Sao Khua, Phu Kradung, Phra Wihan, and Phu Phan sandstone. Testing on fractures is made under confining pressures ranging from 500 to 3000 psi (approximately up to 3000 ft depth) for constant head test and 50 to 300 psi for falling head test. All tested fractures are artificially made in the laboratory. All tests are conducted under ambient temperature. Up to 3 samples will be tested for each rock type. The minimum size of specimens is 2 inches in diameter with the maximum size of 6x6x10 inches. Water is used as flow medium. No field testing will be conducted.

1.5 Thesis Contents

Chapter I introduces the thesis by briefly describing the background of problems and significance of the study. The research objectives, methodology, scope and limitations are identified. **Chapter II** summarizes results of the literature review. **Chapter III** describes the sample collection and preparation. **Chapter IV** presents the results obtained from the laboratory testing. **Chapter V** shows the development of flow equations which can be useful in determining the rock mass permeability under in-situ stress conditions. **Chapter VI** concludes the research results, and provides recommendations for the future research studies. **Appendix A, B,** and **C** provide detailed results from constant head flow testing under confining pressures, results from falling head flow testing under normal stresses, and technical publication; respectively.

CHAPTER II

LITERATURE REVIEW

Relevant topics and previous research results will be reviewed to improve an understanding of fluid flow through porous rock and through rock fractures. These include classification of rock fractures, rock mass permeability testing and principles, fracture apertures, and the effects of applied stresses.

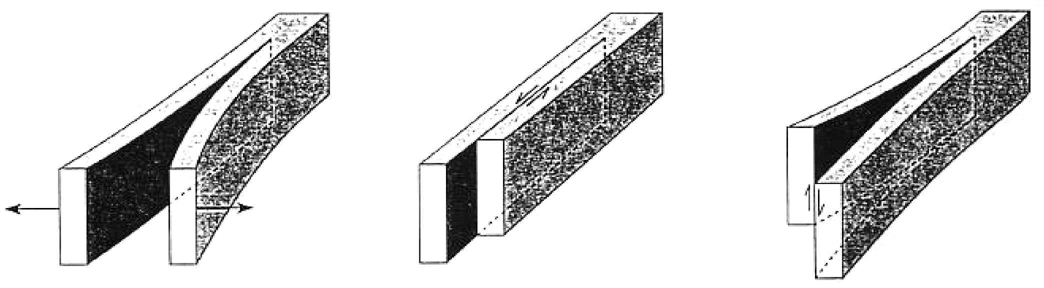
2.1 Classification of Rock Fractures

Fractures (from the Latin *fractus*, which means "broken") are surfaces along which rocks or minerals have broken; they are therefore surfaces across which the material has lost cohesion (Twiss and Moores, 1992). In general, fractures initiate and propagate when the stresses equal to the strength of rock. Several possible sources or mechanisms that are capable of producing high stresses in the earth crust can be identified. Among these are (1) lithostatic (changes in the weight of overburden either by burial or removal caused by uplift and erosion); (2) fluid pressure; (3) tectonic forces associated with the movement of lithosperic plates; (4) thermal (cooling of intrusive and extrusive rocks, and cooling caused by uplift and erosion of the crust); (5) impact by extraterrestrial objects; and (6) other geological processes such as folding, volcanic activity, and salt intrusion (National Research Council, 1996).

Fractures are distinguished by the relative motion that has occurred across the fracture surface during formation. For extension fractures or mode I fractures, that relative motion is perpendicular to the fracture walls (Figure 2.1a). For shear fractures the relative motion is parallel to the surface. For mode II shear fractures, the motion is a sliding motion perpendicular to the edge of the fracture (Figure 2.1b); for mode III shear fractures, it is a sliding motion parallel to the fracture edge (Figure 2.1c). A fracture that has components displacement both parallel and perpendicular to the fracture surface is an oblique extension fracture or mixed mode fracture (Twiss and Moores, 1992).

2.2 Permeability of Rock Mass

Indraratna and Ranjith (2001) state that Permeability is simply the ability to conduct fluids, such as water, gas or multi-phase flows (e.g. water + gas, water + gas + oil) through porous media, such as soil or rocks. The permeability of discontinuities is referred to as the fracture permeability or the intrinsic permeability, whereas intact



(a) Extension (mode I) (b) Shear (mode II) (c) Shear (mode III)

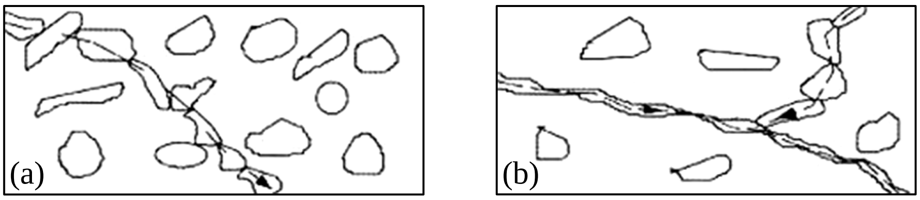
Figure 2.1 Types of fracture (Twiss and Moores, 1992).

permeability is referred to as the matrix permeability. Therefore, the combined permeability of rock mass is given by

$$k = k_f + k_m \tag{2.1}$$

where k is the combined permeability of rock mass, and k_f and k_m are the individual fracture permeability and matrix permeability, respectively.

For crystalline rocks, fluid flow through rock matrix is much less than that through fractures, because the extent of interconnected pores and the pore sizes in hard rocks are generally small. Permeability can greatly influence the mechanical behavior of rocks, thereby increasing or decreasing the stability of rock structures. As shown in Figure 2.2, fluid flow within a rock specimen can take place through either the rock matrix or interconnected discontinuities or combination of both. Under single-phase fluid flow, permeability can be divided into three main categories: (1) Matrix permeability, (2) Fracture permeability and (3) Dual permeability. Application



(a) Intact rock with voids, where flow occurs through interconnected voids.

(b) Specimen with a major discontinuity, where flow occurs through discontinuity and any interconnected voids.

Figure 2.2 Fluid flow within a rock specimen (Indraratna and Ranjith, 2001).

of fractured and matrix permeability in different locations is shown in Figure 2.3 and the calculations of permeability are as follows (Indraratna and Ranjith, 2001).

2.2.1 Permeability of Intact Rock

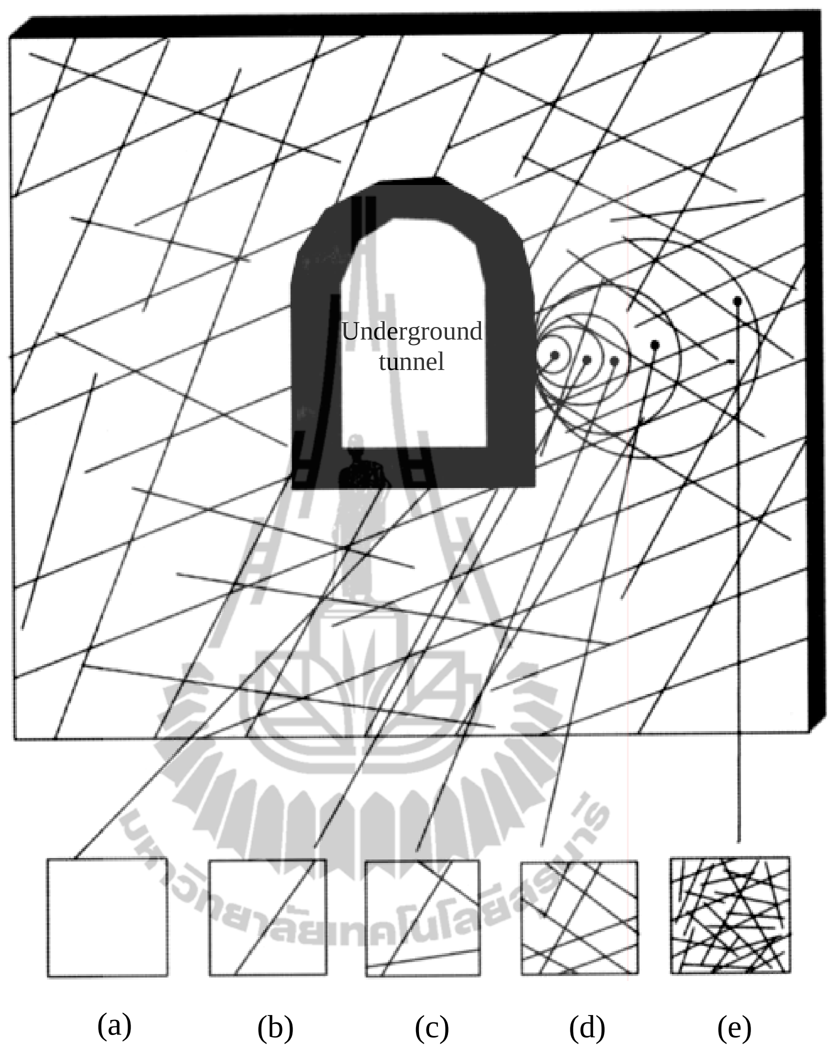
Indraratna and Ranjith (2001) state that under steady-state flow rate approach, for a cylindrical rock specimen, the coefficient of matrix/intact rock permeability (k_m) can be written using Darcy's law :

$$k_m = \frac{4q\mu}{\pi D^2 (dp/dx)} \tag{2.2}$$

where q is fluid flow rate through the specimen, dp/dx is the pressure gradient along the length (dx) of the specimen (Figure 2.4), μ is the dynamic viscosity of the fluid and D is the diameter of the specimen. Apart from the hydraulic gradient and surrounding stresses applied on the specimen, the matrix permeability depends on the properties of the matrix, characterized by the pore size (voids), shapes and the interconnectivity of voids. If the fluid traveling through the porous rock is gas, then the component of the matrix coefficient of air permeability (k_m) is estimated according to the following equation :

$$k_m = \frac{2qp_e\mu L}{(p_i^2 - p_e^2)A} \tag{2.3}$$

where q = gas flow rate, μ = dynamic viscosity of gas, L = length of the specimen, A = cross-section area of specimen, p_i = inlet pressure of gas and p_e = exit pressure of gas.



(a) Intact rock (continuum flow) – Matrix permeability.

(b) Single discontinuity – Fractured permeability.

(c) Two discontinuities – Fractured permeability.

(d) Several discontinuities – Fractured permeability.

(e) Rock mass – Matrix permeability.

Figure 2.3 Application of fracture and matrix permeability in different locations (Indraratna and Ranjith, 2001).

If the permeability measurement is based on the transient method, the following expressions are used to calculate the matrix permeability coefficient. The pressure pulse decays with time according to the expression given below :

$$p_t = p_0 e^{-\alpha t} \tag{2.4}$$

where p_t and p_0 are final and initial pressure, respectively, t is the decay time and α is an empirical constant. The matrix permeability coefficient for transient method is given by Kranz et al. (1979) :

$$k_m = \frac{\alpha \beta \mu L V_1 V_2}{A(V_1 + V_2)} \tag{2.5}$$

where β = isothermal compressibility of fluid, A = cross-sectional area, V_1 and V_2 = volume of pore fluid at the top and the bottom of the sample, respectively, L = length of the specimen and α is calculated using Eqn. 2.4 for given initial pressure, and for the time period, t.

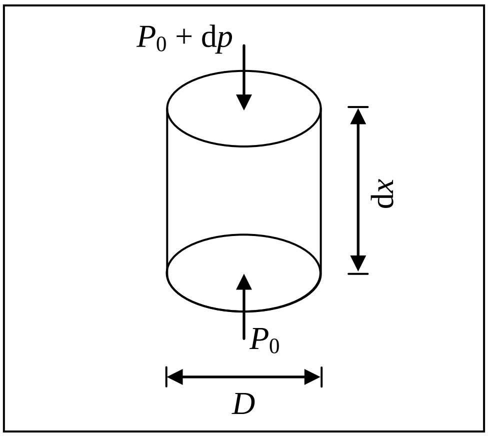


Figure 2.4 Pressure gradients along a rock specimen (Indraratna and Ranjith, 2001).

2.2.2 Permeability of Single Fracture

The main factors controlling fluid flow through a single fracture are surface roughness, variable apertures, orientation of fractures, normal and shear stress, loading and unloading behavior as shown in Figure 2.5. Out of these controlling factors, the magnitude of the joint aperture is the major parameter, which is a function of external stress, fluid pressure and geometrical properties of the fracture (Indraratna and Ranjith, 2001). Therefore, the equations for calculating the permeability will change as follow.

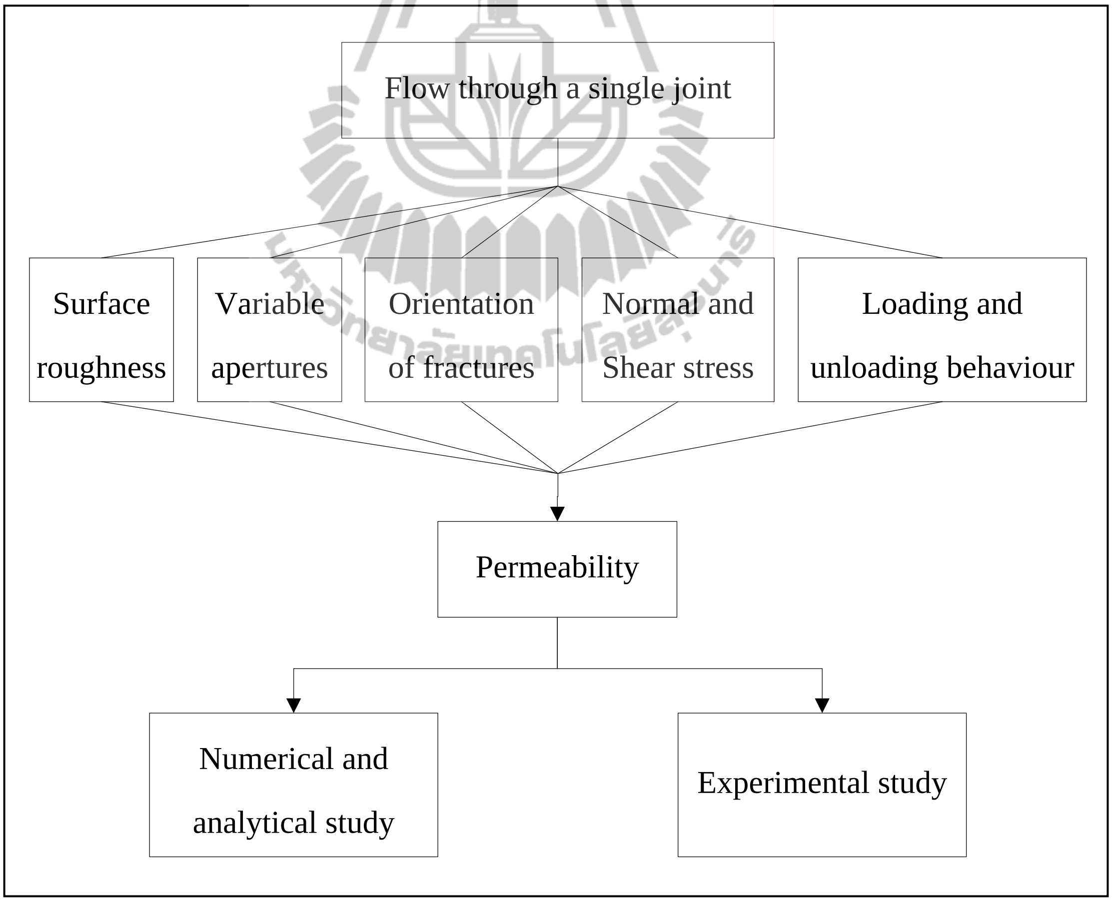


Figure 2.5 Factors controlling permeability of a single fracture (Indraratna and Ranjith, 2001).

Flow is often approximated to occur between smooth parallel plates, assuming that flow is laminar and viscous. In such a case, the conductivity of a single fracture is given by the 'cubic law' :

$$K_f = \frac{ge^3}{12vb} \tag{2.6}$$

where K_f = fracture conductivity (m/s), e = hydraulic aperture (m), g = acceleration due to gravity (m/s^2), v = kinematic viscosity, which is 1.01×10^{-6} (m^2/s) for pure water at 20°, and b is the spacing between fracture (m).

2.3 Apertures

Apart from the fluid properties and applied hydraulic head, the critical factor which controls the flow quantity is the aperture. The size and interconnectivity of fractures influence the volume and rate of flow through fractured rock.

2.3.1 Direct Measurement of Aperture

Mechanical Aperture (e_m)

Based on Joint Compressive Strength (JCS) and Joint Roughness Coefficient (JRC) values, Barton and Bakhtar (1983); Bandis et al. (1983; 1985) proposed an empirical approach to perform indirect measurements of the mechanical aperture, as discussed below :

$$e_m = \left[\frac{JRC}{5}\right]\left[\left(0.2\sigma_c / JCS\right) - 0.1\right] \tag{2.7}$$

where e_m = mechanical aperture (mm) and σ_c = unconfined compressive strength.

Based on Schmidt hammer rebound number, the following empirical relationship is used to determine the JRC.

$$\log_{10}(JCS) = 0.00088\gamma R + 1.01 \quad (2.8)$$

where γ = unit weight of rock (kN/m^3) and R = rebound number.

2.3.2 Indirect Measurement of Aperture

Equivalent Cubic Law Aperture or Hydraulic Aperture (e_c)

For laminar fluid flow through parallel joint walls, the equivalent cubic law aperture (e_c) is defined by

$$e_c = \left[\frac{12q\mu}{b(dp/dx)}\right]^{1/3} \quad (2.9)$$

Where q = steady-state flow rate, b = width of the fracture, dp/dx = pressure gradient between two ends of the specimen and μ = dynamic viscosity of fluid (Indraratna and Ranjith, 2001).

According to Tsang (1992), for radial flow, the equivalent cubic law aperture (e_c) is given by

$$e_c = \left[\frac{6\mu q}{\pi dp}\ln\left(\frac{r}{r_0}\right)\right]^{1/3} \quad (2.10)$$

Where r_0 = well radius and r = distance to the tracer collection point.

Equivalent Mass Balance Aperture (e_{mass})

For a given single fracture, having a length *l* and width *b*, if the flow rate through the fracture is *q* and the mean tracer transport time is *t*, then the mass balance equivalent aperture (e_{mass}) may be written as follows :

$$e_m = \left(\frac{qt}{lb} \right) \tag{2.11}$$

For a given well with radius r_0 and for the tracer collection point at a distance of radius *r* (Figure 2.6), Smith et al. (1987) refer to the equivalent mass balance aperture as 'volume balance aperture', given by

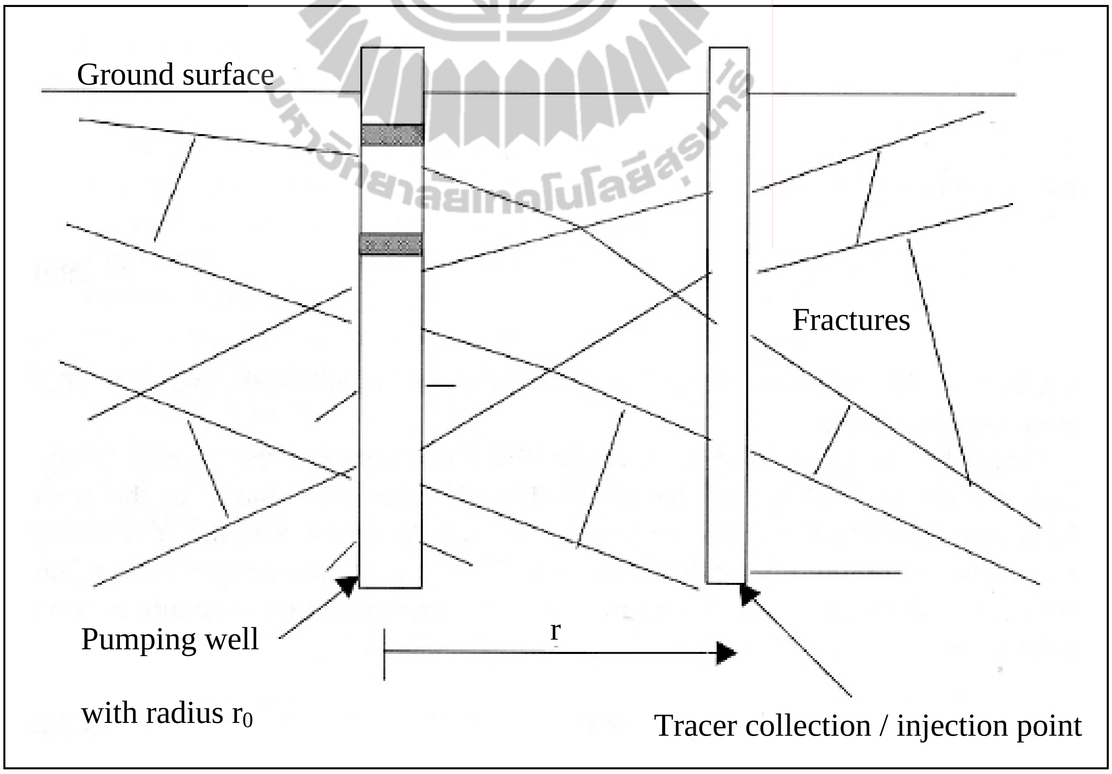


Figure 2.6 Pumping well and tracer collection point in tracer test (Indraratna and Ranjith, 2001).

$$e_{mass} = \left[\frac{qt}{\pi\left(r^2 - r_0^2\right)} \right] \tag{2.12}$$

where the symbols are the same as in Eqn. 2.11. Tsang (1992) concluded that the mass balance aperture is greater than or equal to the cubic law aperture.

2.3.3 Mechanical Aperture versus Hydraulic Aperture

The hydraulic aperture is different to the mechanical aperture of a fracture, because natural discontinuities are dissimilar to ideal parallel plates.

Based on Joint Roughness Coefficient (JRC), Barton et al. (1985) proposed following relationship between the mechanical and hydraulic apertures :

$$e_h = \frac{e_m^2}{JRC^{2.5}} \tag{2.13}$$

where e_h = hydraulic aperture and e_m = mechanical aperture.

By considering the normal deformation of the fracture, Eqn. 2.13 can be modified as follows :

$$e_h = \frac{\left(e_m - \delta\right)^2}{JRC^{2.5}} \tag{2.14}$$

where δ = normal deformation of the fracture which is given by the follow expression

$$\delta = \frac{\sigma_n}{a + b\sigma_n} \tag{2.15}$$

where σ_n = normal stress. The parameters a and b are constants which are determined using the uniaxial compression test.

2.4 Stress Effects on Fracture Void Geometry

Deformation in a fracture can arise from either a change in fluid pressure or a perturbation of the stress field in the rock. The important stress for mechanical behavior and fluid flow in fractures is the effective stress, which is generally taken to be the normal stress on the fracture minus the fluid pressure (Terzaghi, 1936).

The stress on a fracture can be decomposed into two components; one in a direction perpendicular to the surface (normal) and one in a direction parallel the surface (shear). In general, the effects of these two components are highly coupled; that is, the deformation caused by a change in one component is dependent on the magnitude of the other. Fracture surface roughness is one of the primary reasons for this coupling, as illustrated in Figure 2.7. This figure shows the distribution of voids and contacting asperities in an idealized representation of a very rough undeformed fracture. The application of shear stress to this fracture at a very low normal stress may cause one surface to ride up and over the asperities of the other, leading to large dilation. At the other extreme, at very high normal stress, the frictional forces resisting slip may exceed the strength of the rock and the asperities will be sheared off. Dilation would minimal in this case (National Research Council, 1996).

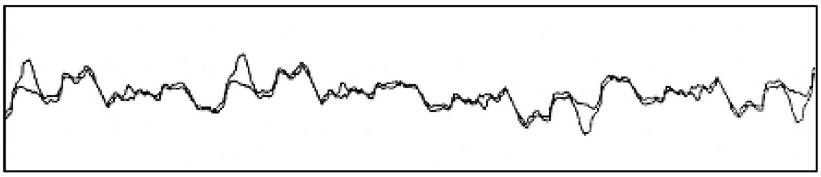


Figure 2.7 Cross section through a very rough fracture in the undeformed state showing distribution of voids and contacting asperities (National Research Council, 1996).

CHAPTER III

SAMPLE PREPARATION

3.1 Introduction

The tested sandstones are from four sources: Phu Phan, Phra Wihan, Phu Kradung and Sao Khua formations (hereafter designated as PP, PW, PK and SK sandstones). They belong to the Khorat group and widely expose in the north and northeast of Thailand. They also have significant impacts on stability of many engineering structures constructed in the regions (e.g., slope embankments, underground mines and tunnels).

3.2 Sample Preparation

A minimum of 4 sandstone types are prepared. Sample preparation is carried out in the laboratory facility at the Suranaree University of Technology.

3.2.1 Sample Preparation for Constant Head Flow Test under Various Confining Pressures

Samples for the constant head test are prepared to have cylindrical shape with a nominal dimension of 2 inches in diameter and 3 inches long both homogeneous and fractured samples. The preparation is conducted in the laboratory facility at the Suranaree University of Technology. The process includes coring, cutting and grinding (Figure 3.1 through 3.3).

The core drilling machine (model SBEL 1150) is used to drill core specimens using diamond impregnated bit with diameter of 54 mm.

Figure 3.1 Laboratory core drilling.

Figure 3.2 A core specimen of sandstone is cut to length by a cutting machine.

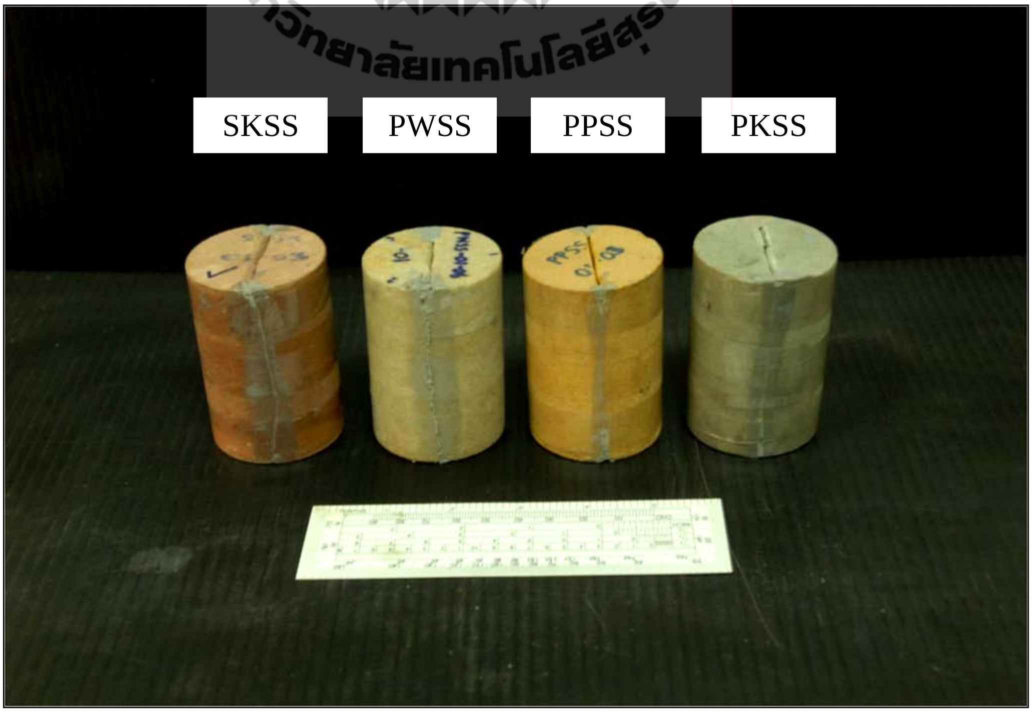


Figure 3.3 Some sandstone specimens prepared for the constant head flow test.

3.2.2 Sample Preparation for Falling Head Flow Test under Normal Stresses

Samples for the falling head test are prepared to have fractures area of about 6×6 square inches (Figure 3.4). The fractures are artificially made by applying a line load to induce a splitting tensile crack in $6\times6\times10$ in^3 prismatic blocks of SK, PW, PP and PK sandstones (Figure 3.5). The injection hole at the center of the upper block is 0.8 cm in diameter (Figure 3.6). Up to 6 samples have been prepared for each rock type. Their roughness is observed and classified by comparing with a reference profiles given by Barton (joint roughness coefficient – JRC, Barton, 1973). The properties of this sandstone rock are porous ably and permeable ability. The reservoir rock is always sandstone, too.

3.3 Mineralogical Study

The mineral compositions of the rock samples are determined by using X-ray diffraction method. Table 3.1 gives the results of the X-ray diffraction analysis. The mineral compositions determined will be used as data basis to explain the pore space of rock that affects to the hydraulic conductivity.

Table 3.1 Mineral compositions of tested sandstones obtained from X-ray diffraction.

Rocks	Density (g/cc)	Grain Size (mm)	Mineral Compositions				
			Quartz (%)	Albite (%)	Kaolinite (%)	Feldspar (%)	Mica (%)
PW	2.35	1.5 - 2.0	99.47	-	0.53	-	-
PP	2.45	1.5 - 2.0	98.40	-	-	-	1.60
PK	2.63	0.1 - 1.5	48.80	46.10	5.10	-	-
SK	2.37	0.1 - 1.0	57.00	39.50	-	2.90	0.60

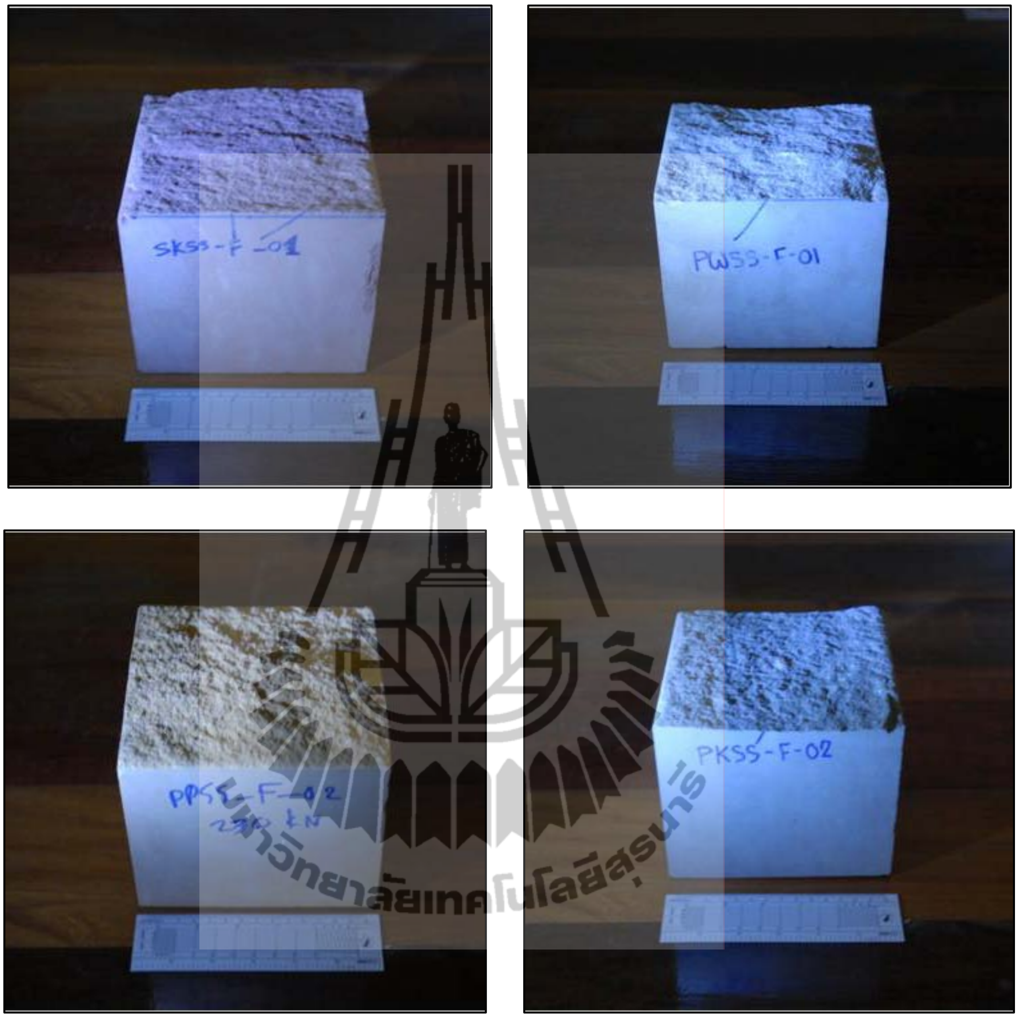


Figure 3.4 Some fracture surfaces from applying a line load to prismatic blocks.

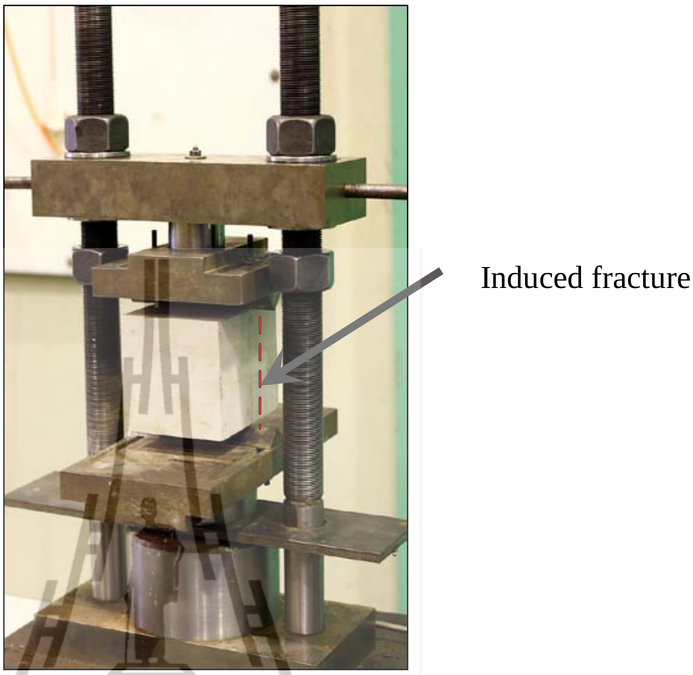


Figure 3.5 A 6×6×10 in^3 block of sandstone is line-loaded to induce tensile fracture in mid-length of the block.

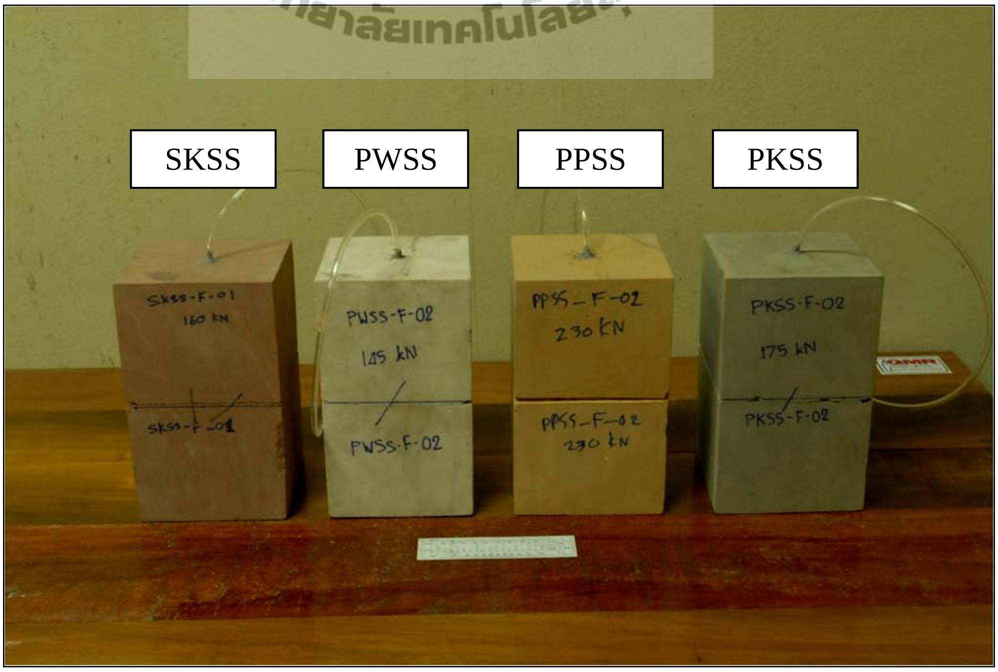


Figure 3.6 Some sandstone specimens prepared for falling head test.

CHAPTER IV

LABORATORY TESTING

4.1 Objectives

The primary objectives of the laboratory tests are to determine permeability of sandstone specimens. The laboratory testing is divided into two groups; i.e. constant head flow test under various confining pressures, and falling head flow test under normal stresses. Laboratory experiments are conducted on specimens from four formations of sandstone, including Sao Khua, Phu Kradung, Phra Wihan, and Phu Phan sandstone.

4.2 Constant Head Flow Test under Various Confining Pressures

(a) Test Method

Figure 4.1 shows the laboratory arrangement of the constant head test. A constant diameter water pump is used to inject water pressure to one end of the specimen. The specimen is placed in triaxial cell which is used to applied constant confining pressures to the rock and fracture. The applied confining pressures vary from 500 to 3000 psi. The injected water pressure is about 20 psi which is controlled by using a regulating valve at the top of nitrogen gas tank. A high precision pipette is use to collect outflow of water at the other end of the specimen. A single fracture is induced parallel to the specimen axis. The measured flow rates at each confining pressure will be measured to calculate the fracture permeability.

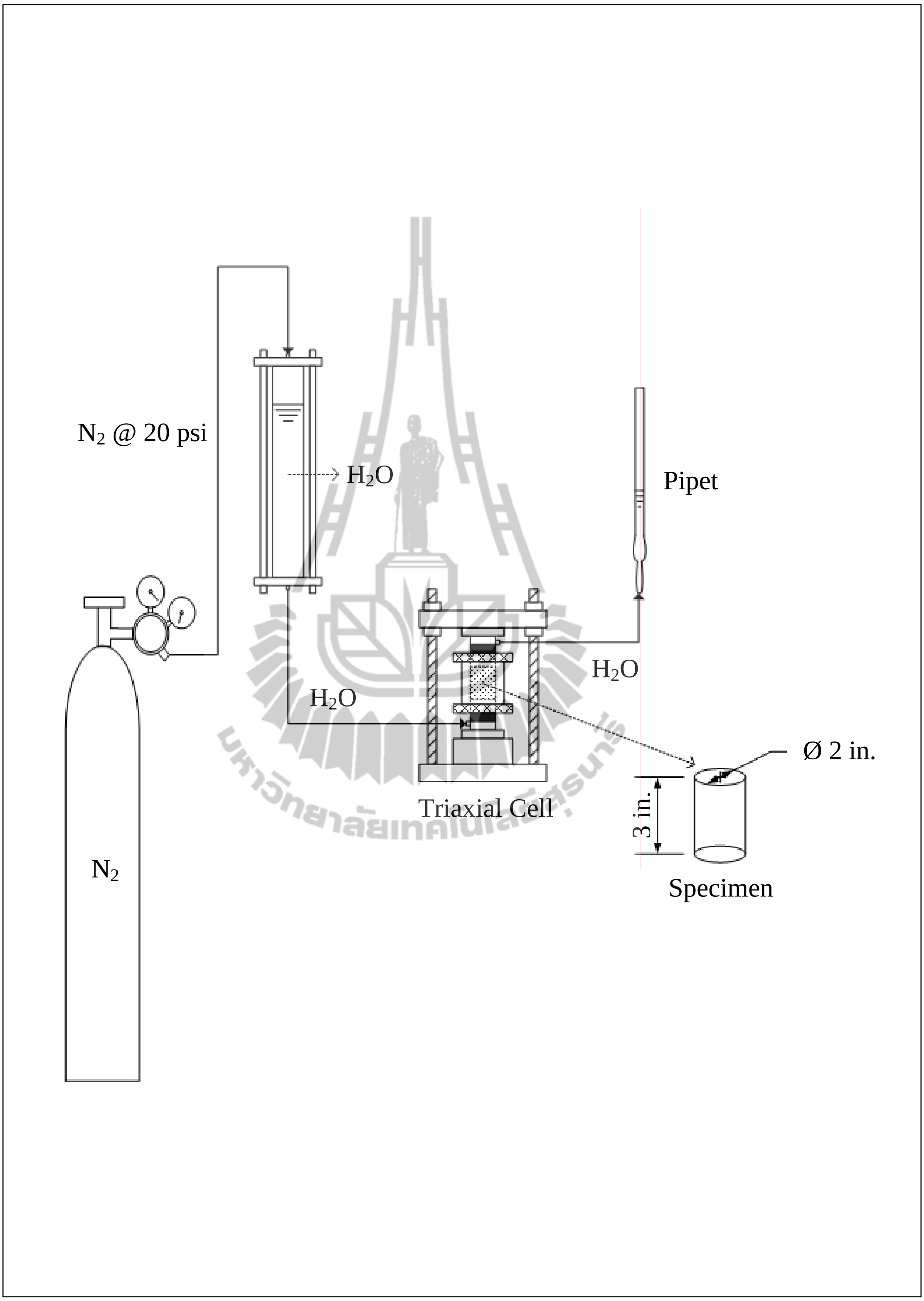


Figure 4.1 Laboratory set-up for constant head flow test under various confining pressures.

For intact specimens, the hydraulic conductivity (K) is calculated using the equation;

$$K = \frac{QL}{A\Delta h} \tag{4.1}$$

where Q is flow rate, A is cross-sectional area of flow, and Δh is change in head measured over a distance L. The intact rock permeability (k_m) can be calculated by

$$k_m = \frac{4q\mu}{\pi D^2 (dp/dx)} \tag{4.2}$$

where q is fluid flow rate through the specimen, μ is dynamic viscosity of the fluid, D is diameter of the specimen, and dp/dx is pressure gradient along the length (dx) of the specimen.

For fracture, the fracture conductivity (K_f) and fracture permeability (k) are calculated from the equations,

$$K_f = \frac{ge^3}{12\nu b} \tag{4.3}$$

$$k = \frac{e^2}{12} \tag{4.4}$$

where g is acceleration due to gravity, v is kinematic viscosity, b is spacing between fracture, and e is hydraulic aperture which received from the equation,

$$e_c = \left[\frac{12q\mu}{b(dp/dx)} \right]^{1/3} \tag{4.5}$$

where e_c is equivalent cubic law aperture or hydraulic aperture, q is steady-state flow rate, μ is dynamic viscosity of fluid, b is width of the fracture, and dp/dx is pressure gradient between two ends of the specimen.

(b) Test Result

The fracture aperture, hydraulic conductivity, permeability of PK, PP, PW and SK sandstone specimens are calculated. The results are summarized in Table 4.1 through 4.4.

The sandstone permeability tends to decreases with increasing confining pressure. This is probably due to the contraction of the pore spaces and fractures in the specimen. The flow rates measured during unloading show a permanent reduction of the rock permeability, suggesting that a permanent closure of the pore spaces has occurred. The detailed results of constant head tests are provided in Appendix A.

Table 4.1 Test parameters and results of PKSS from constant head flow testing.

Sample	P_c		e_c	K	k
	psi	MPa	($x10^{-6}$ m)	($x10^{-9}$ m/s)	($x10^{-12}$ m^2)
PKSS-01-05	500	3.45	32.81	705.42	89.75
	1000	6.89	24.22	284.44	48.95
	1500	10.34	17.24	102.40	24.78
	2000	13.79	12.98	43.61	14.04
	2500	17.24	9.68	18.20	7.83
	3000	20.68	7.71	9.48	5.01
	2500	17.24	7.25	7.59	4.37
	2000	13.79	7.11	7.21	4.22
	1500	10.34	7.86	9.67	5.14
	1000	6.89	8.29	11.38	5.73
	500	3.45	8.93	14.22	6.65
PKSS-01-07	500	3.45	22.04	205.77	40.49
	1000	6.89	15.17	67.49	19.22
	1500	10.34	10.45	21.97	9.11
	2000	13.79	8.21	10.64	5.62
	2500	17.24	6.62	5.58	3.65
	3000	20.68	5.84	3.84	2.84
	2500	17.24	5.66	3.49	2.67
	2000	13.79	5.66	3.49	2.67
	1500	10.34	6.01	4.19	3.01
	1000	6.89	6.10	4.36	3.10
	500	3.45	6.82	6.10	3.88
PKSS-03-01	500	3.45	26.98	364.22	60.68
	1000	6.89	19.34	134.12	31.18
	1500	10.34	15.54	69.60	20.14
	2000	13.79	12.18	33.53	12.37
	2500	17.24	10.47	21.29	9.14
	3000	20.68	8.96	13.35	6.69
	2500	17.24	8.86	12.87	6.54
	2000	13.79	8.82	12.71	6.48
	1500	10.34	8.96	13.35	6.70
	1000	6.89	9.27	14.78	7.17
	500	3.45	9.98	18.43	8.30

Table 4.2 Test parameters and results of PPSS from constant head flow testing.

Sample	P_c		e_c	K	k
	psi	MPa	($x10^{-6}$ m)	($x10^{-9}$ m/s)	($x10^{-12}$ m^2)
PPSS-01-01	500	3.45	18.01	99.99	27.04
	1000	6.89	10.96	22.65	10.03
	1500	10.34	6.25	4.20	3.26
	2000	13.79	5.45	2.80	2.49
	2500	17.24	5.03	2.24	2.13
	3000	20.68	4.34	1.40	1.57
	2500	17.24	4.34	1.40	1.57
	2000	13.79	4.34	1.40	1.57
	1500	10.34	4.34	1.40	1.57
	1000	6.89	4.34	1.40	1.57
	500	3.45	5.55	2.94	2.57
PPSS-01-03	500	3.45	29.02	447.18	70.18
	1000	6.89	21.23	175.23	37.57
	1500	10.34	14.81	59.53	18.29
	2000	13.79	11.11	25.10	10.29
	2500	17.24	8.64	11.78	6.21
	3000	20.68	7.27	7.04	4.41
	2500	17.24	7.38	7.35	4.53
	2000	13.79	7.62	8.11	4.84
	1500	10.34	8.24	10.25	5.66
	1000	6.89	10.73	22.96	9.65
	500	3.45	19.38	133.14	31.30
PPSS-01-09	500	3.45	51.79	3624.15	223.57
	1000	6.89	48.75	3023.47	198.14
	1500	10.34	44.53	2302.64	165.27
	2000	13.79	39.66	1626.86	131.10
	2500	17.24	36.51	1271.46	111.17
	3000	20.68	34.29	1051.20	97.99
	2500	17.24	34.29	1051.20	97.99
	2000	13.79	35.04	1121.29	102.30
	1500	10.34	35.45	1161.33	104.72
	1000	6.89	36.44	1261.45	110.66
	500	3.45	39.95	1661.90	132.99

Table 4.3 Test parameters and results of PWSS from constant head flow testing.

Sample	P_c		e_c	K	k
	psi	MPa	($x10^{-6}$ m)	($x10^{-9}$ m/s)	($x10^{-12}$ m^2)
PWSS-01-01	500	3.45	114.94	26147.34	1101
	1000	6.89	97.44	15933.53	791.36
	1500	10.34	65.42	5362.25	371.44
	2000	13.79	52.43	2485.36	229.21
	2500	17.24	38.88	1014.57	126.09
	3000	20.68	29.08	425.58	70.59
	2500	17.24	28.31	391.53	66.83
	2000	13.79	30.96	510.69	79.86
	1500	10.34	32.83	612.83	89.99
	1000	6.89	39.38	1055.43	129.41
	500	3.45	43.34	1402.7	156.57
PWSS-01-05	500	3.45	44.55	1861.24	165.46
	1000	6.89	41.59	1513.01	144.18
	1500	10.34	33.69	804.54	94.6
	2000	13.79	27.26	426.28	61.95
	2500	17.24	22.13	228.15	40.82
	3000	20.68	18.16	126.08	27.49
	2500	17.24	18.25	128.09	27.78
	2000	13.79	18.25	128.09	27.77
	1500	10.34	18.99	144.1	30.05
	1000	6.89	22.52	240.16	42.27
	500	3.45	27.81	452.3	64.45
PWSS-01-06	500	3.45	28.42	419.86	67.37
	1000	6.89	18.68	119.31	29.11
	1500	10.34	8.06	9.67	5.44
	2000	13.79	6.18	4.35	3.19
	2500	17.24	5.1	2.42	2.17
	3000	20.68	4.58	1.77	1.75
	2500	17.24	4.45	1.61	1.65
	2000	13.79	4.45	1.61	1.65
	1500	10.34	5.1	2.42	2.17
	1000	6.89	5.1	2.42	2.17
	500	3.45	5.1	2.42	2.17

Table 4.4 Test parameters and results of SKSS from constant head flow testing.

Sample	P_c		e_c	K	k
	psi	MPa	($x10^{-6}$ m)	($x10^{-9}$ m/s)	($x10^{-12}$ m^2)
SKSS-01-01	500	3.45	24.70	282.55	50.86
	1000	6.89	16.58	85.56	22.94
	1500	10.34	11.98	32.31	11.98
	2000	13.79	9.50	16.08	7.53
	2500	17.24	8.21	10.35	5.61
	3000	20.68	3.67	0.96	1.13
	2500	17.24	3.49	0.80	1.02
	2000	13.79	3.49	0.80	1.02
	1500	10.34	4.22	1.43	1.49
	1000	6.89	9.31	15.12	7.23
	500	3.45	9.65	16.87	7.77
SKSS-02-03	500	3.45	22.63	257.98	42.77
	1000	6.89	14.25	64.63	16.98
	1500	10.34	7.92	11.21	5.26
	2000	13.79	3.90	1.42	1.30
	2500	17.24	1.76	0.23	0.35
	3000	20.68	2.15	0.23	0.39
	2500	17.24	1.97	0.18	0.33
	2000	13.79	2.20	0.23	0.40
	1500	10.34	2.20	0.23	0.40
	1000	6.89	2.51	0.35	0.53
	500	3.45	5.48	3.64	2.50

4.3 Falling Head Flow Test under Normal Stresses

(a) Test Method

Falling head tests will be conducted by injecting water into the center hole of rectangular blocks of sandstone. A fracture is artificially made across the 6x6x10 in^3 prismatic block of sandstone specimen either by saw-cutting or tension inducing methods. The fracture is 6x6 in^2. The 8 mm hole is drilled into the upper block of the sample to allow water flow through the fracture. The constant normal stresses on the fracture are varied from 50 psi to 300 psi by using dead weight loading devices (Figure 4.2). A minimum of 3 samples for each rock type will be tested.

The hydraulic conductivity for smooth, parallel plates (K_j) is calculated by following equation (Zeigler, 1976) :

$$K_j = \frac{\gamma e^2}{12\mu} \tag{4.6}$$

where γ is unit weight of fluid, μ is viscosity of fluid, and e is parallel plate aperture. The equivalent parallel plate aperture for adial flow is used in this case; which can be received from using the equation (Maini, 1971),

$$e = \left[\frac{\ln(H_1 / H_2) r_b^2 \ln(r / R) 6\mu}{(t_2 - t_1)\gamma} \right]^{1/3} \tag{4.7}$$

where H_1,H_2 is excess pressure head at beginning and end of test, t_1,t_2 is time at beginning and end of test, r_b is buret radius, R is outer radius of a radial flow path, r is inner radius of a radial flow path, W is width of the fracture, and L is length of the fracture.

(b) Test Result

Table 4.5 through 4.8 give the fracture conductivity results for PW, PP, PK and SK sandstone specimens as a function of normal stresses. For all sandstone types the fracture hydraulic conductivities exponentially decrease with increasing the normal stresses. Their permeability is in the range between 100×10^{-6} m/s and 10000×10^{-6} m/s. Under normal stress alone, a permanent fracture closure is usually observed after unloading as evidenced by the permanent reduction of the fracture permeability (flow rate). The detailed results of falling head tests are provided in Appendix B.

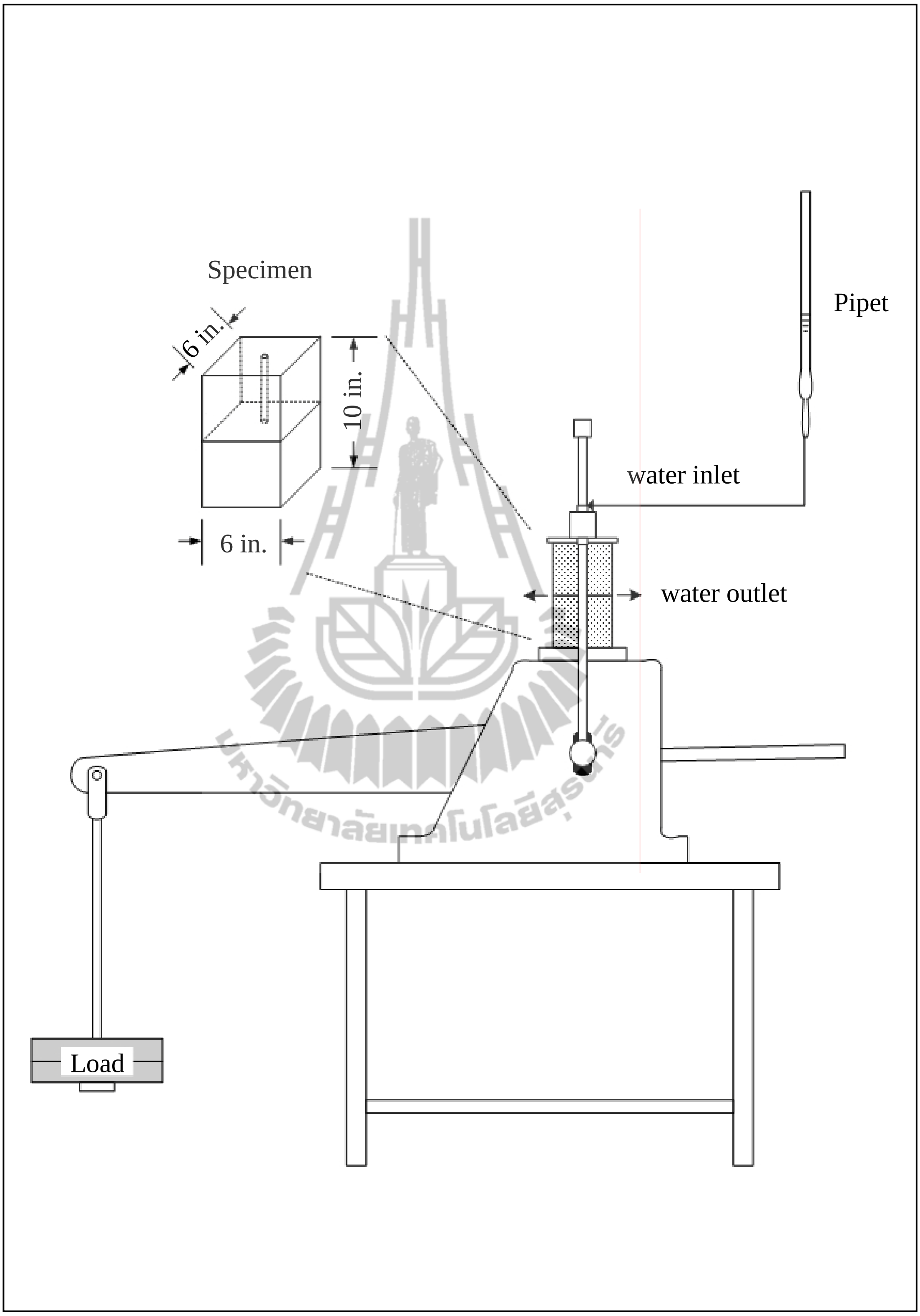


Figure 4.2 Laboratory set-up for falling head flow test under normal stresses.

Table 4.5 Test parameters and results of PKSS from falling head flow testing.

Sample	σ		e	K_j
	psi	MPa	($x10^{-18}$ m)	($x10^{-27}$ m/s)
	50	0.34	22453.89	367690.71
	100	0.69	9981.13	72686.80
	150	1.03	5061.54	26156.95
	200	1.38	1280.27	1228.76
	250	1.72	571.06	237.79
PKSS-F-01	300	2.07	288.31	60.61
	250	1.72	290.10	61.37
	200	1.38	291.91	62.13
	150	1.03	293.13	62.65
	100	0.69	295.29	63.58
	50	0.34	297.17	64.39
	50	0.34	12659.90	116901.52
	100	0.69	2905.48	6178.79
	150	1.03	951.88	667.82
	200	1.38	539.52	219.09
	250	1.72	246.75	44.39
PKSS-F-02	300	2.07	97.71	6.96
	250	1.72	96.04	6.73
	200	1.38	142.90	14.89
	150	1.03	142.90	14.89
	100	0.69	144.12	15.15
	50	0.34	144.49	15.22

Table 4.6 Test parameters and results of PPSS from falling head flow testing.

Sample	σ (psi)	σ (MPa)	e ($\times 10^{-15}$ m)	K_j ($\times 10^{-24}$ m/s)
PPSS-F-01	50	0.34	149.43	25719.66
	100	0.69	152.94	27122.70
	150	1.03	77.72	4999.99
	200	1.38	25.91	489.88
	250	1.72	17.48	223.08
	300	2.07	12.78	119.12
	250	1.72	13.27	128.93
	200	1.38	13.86	140.33
	150	1.03	15.50	175.51
	100	0.69	6.98	457.62
	50	0.34	29.07	616.22
PPSS-F-02	50	0.34	22.76	378.31
	100	0.69	13.85	140.08
	150	1.03	6.20	28.03
	200	1.38	3.30	7.97
	250	1.72	2.10	3.23
	300	2.07	1.39	1.42
	250	1.72	1.38	1.41
	200	1.38	1.33	1.31
	150	1.03	1.47	1.59
	100	0.69	1.83	2.45
	50	0.34	2.40	4.30

Table 4.7 Test parameters and results of PWSS from falling head flow testing.

Sample	σ		e	K_j
	psi	MPa	($x10^{-15}$ m)	($x10^{-24}$ m/s)
PWSS-F-01	50	0.34	9.18	61.59
	100	0.69	13.03	124.06
	150	1.03	9.64	68.01
	200	1.38	7.97	46.54
	250	1.72	6.47	30.66
	300	2.07	5.17	19.52
	250	1.72	5.21	19.79
	200	1.38	5.11	19.29
	150	1.03	5.49	22.19
	100	0.69	5.36	21.12
	50	0.34	8.14	48.37
PWSS-F-02	50	0.34	13.34	131.04
	100	0.69	9.20	62.12
	150	1.03	6.82	34.30
	200	1.38	5.77	24.46
	250	1.72	4.93	17.81
	300	2.07	4.93	17.81
	250	1.72	4.86	17.31
	200	1.38	4.52	14.94
	150	1.03	4.23	13.07
	100	0.69	4.18	12.75
	50	0.34	4.98	20.22

Table 4.8 Test parameters and results of SKSS from falling head flow testing.

Sample	σ (psi)	σ (MPa)	e ($x10^{-15}$ m)	K_j ($x10^{-24}$ m/s)
SKSS-F-01	50	0.34	71.96	4373.89
	100	0.69	26.34	506.59
	150	1.03	12.34	111.22
	200	1.38	6.15	27.56
	250	1.72	3.07	6.92
	300	2.07	1.41	1.47
	250	1.72	1.22	1.11
	200	1.38	1.14	0.96
	150	1.03	1.20	1.05
	100	0.69	1.32	1.29
	50	0.34	1.51	1.68
SKSS-F-02	50	0.34	222.55	74409.26
	100	0.69	210.61	65438.82
	150	1.03	202.55	55752.00
	200	1.38	189.79	48882.93
	250	1.72	176.74	39782.38
	300	2.07	108.12	10684.73
	250	1.72	81.26	5578.63
	200	1.38	109.80	11733.11
	150	1.03	124.08	15678.30
	100	0.69	195.54	52926.48
	50	0.34	191.85	52695.37

CHAPTER V

DEVELOPMENT OF MATHEMATICAL RELATIONS

5.1 Objective

The objective of this chapter is to develop mathematical relationships between the permeability and other parameters from two testing; i.e. constant head flow test under various confining pressures, and falling head flow test under normal stresses.

5.2 Development of Mathematical Relations

The graphical methods are used to find the formula that best fit the sets of data. All data obtained from observations and calculations are plotted in semi-log graph. By curve fitting, the best-fit curve is the power law.

5.2.1 Constant Head Flow Testing under Various Confining Pressures

Empirical equations are proposed to represent the relation between the fracture permeability and the confining pressure. They are described below. The permeability values are plotted as a function of confining pressure in Figure 5.1 through 5.11. The value of x, φ, and R^2 from each specimen are shown in Table 5.1.

$$K = x \cdot P_c^{\varphi} \qquad \text{or} \qquad \log K = \varphi \log P_c + \log x$$

where K is hydraulic conductivity, P_c is confining pressure, x and φ are constants.

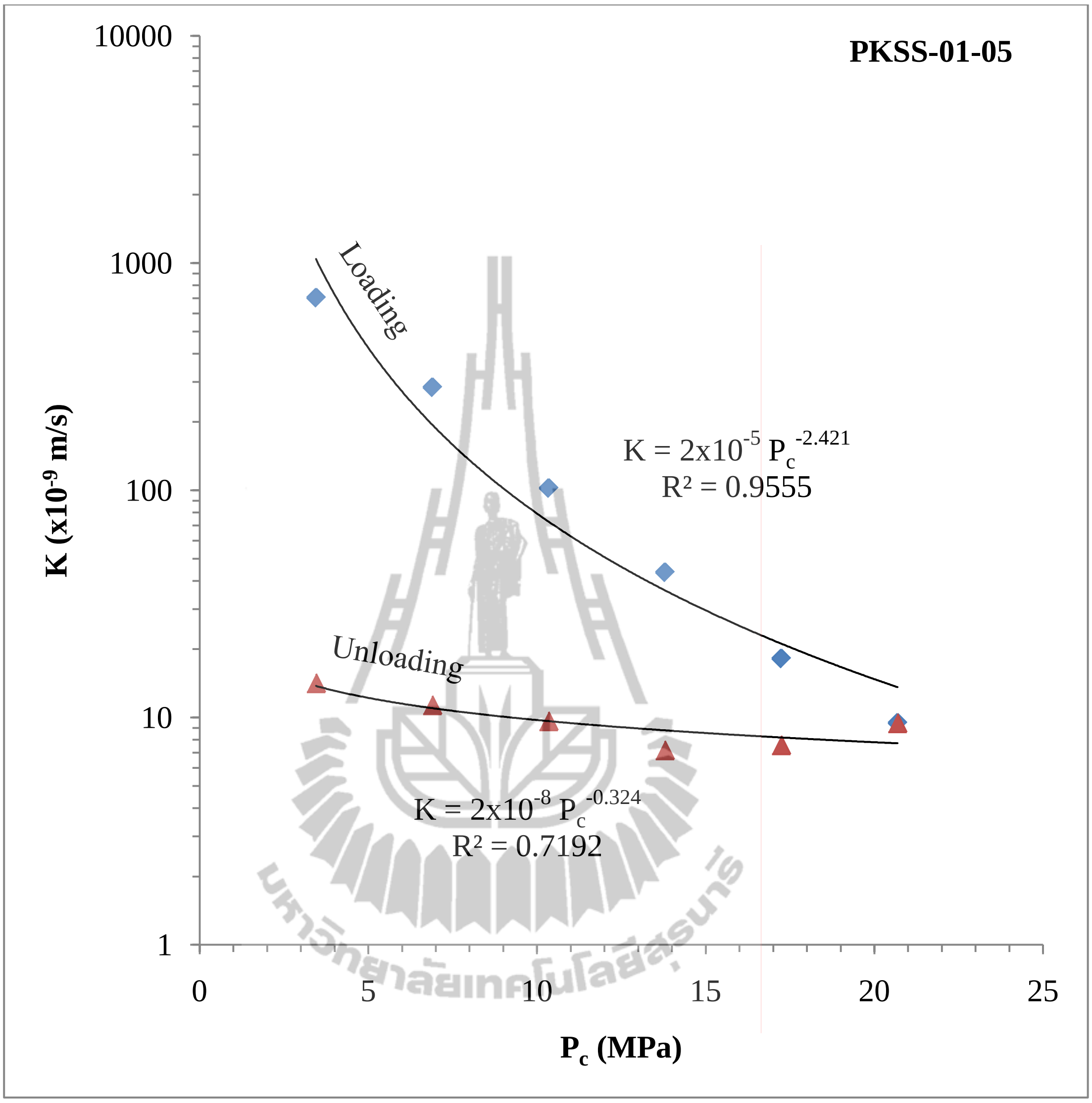


Figure 5.1 Hydraulic conductivity (K) as a function of confining pressure (P_c) for Phu Kradung sandstone specimen (PKSS-01-05) from constant head flow testing under various confining pressures.

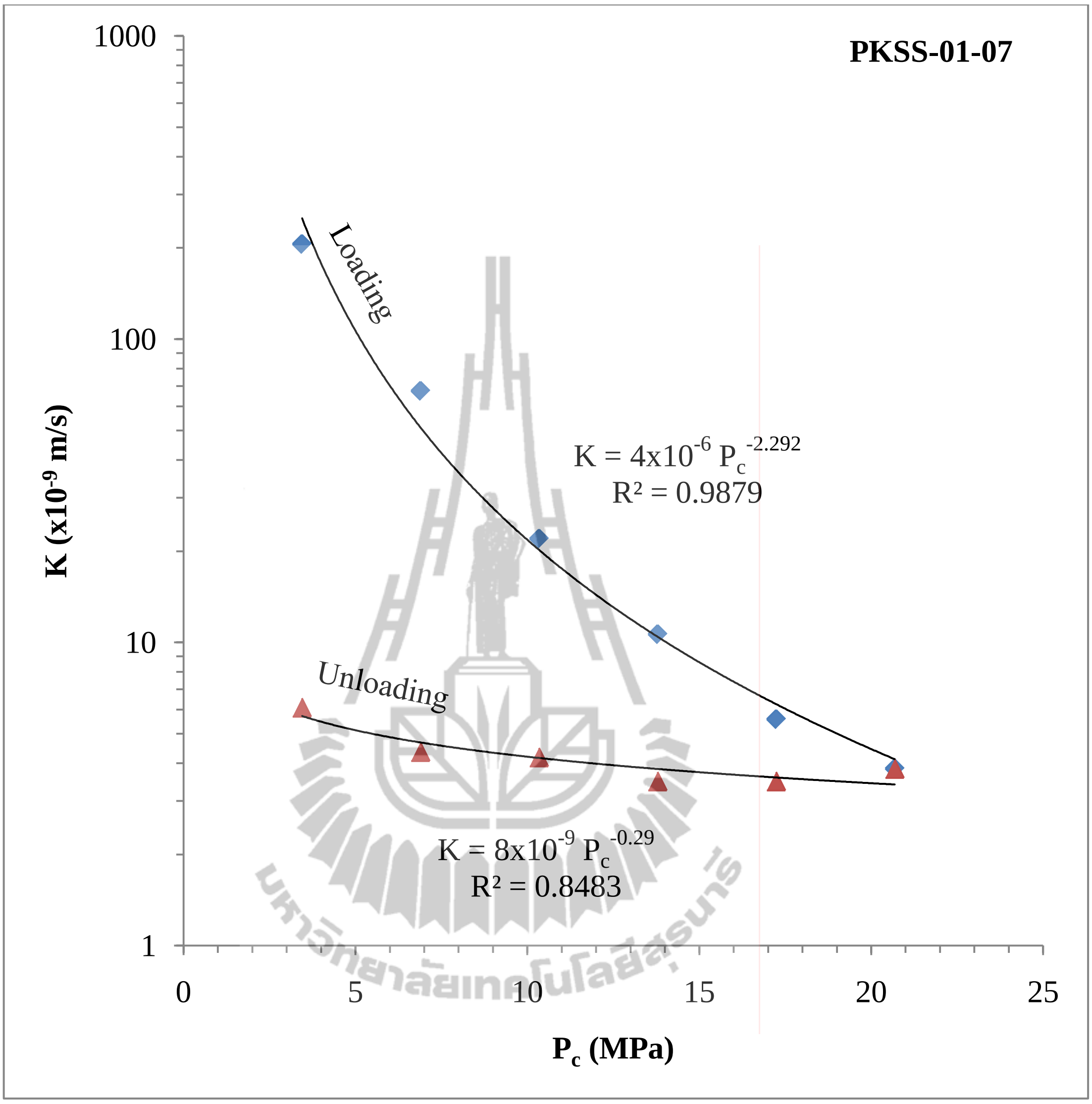


Figure 5.2 Hydraulic conductivity (K) as a function of confining pressure (P_c) for Phu Kradung sandstone specimen (PKSS-01-07) from constant head flow testing under various confining pressures.

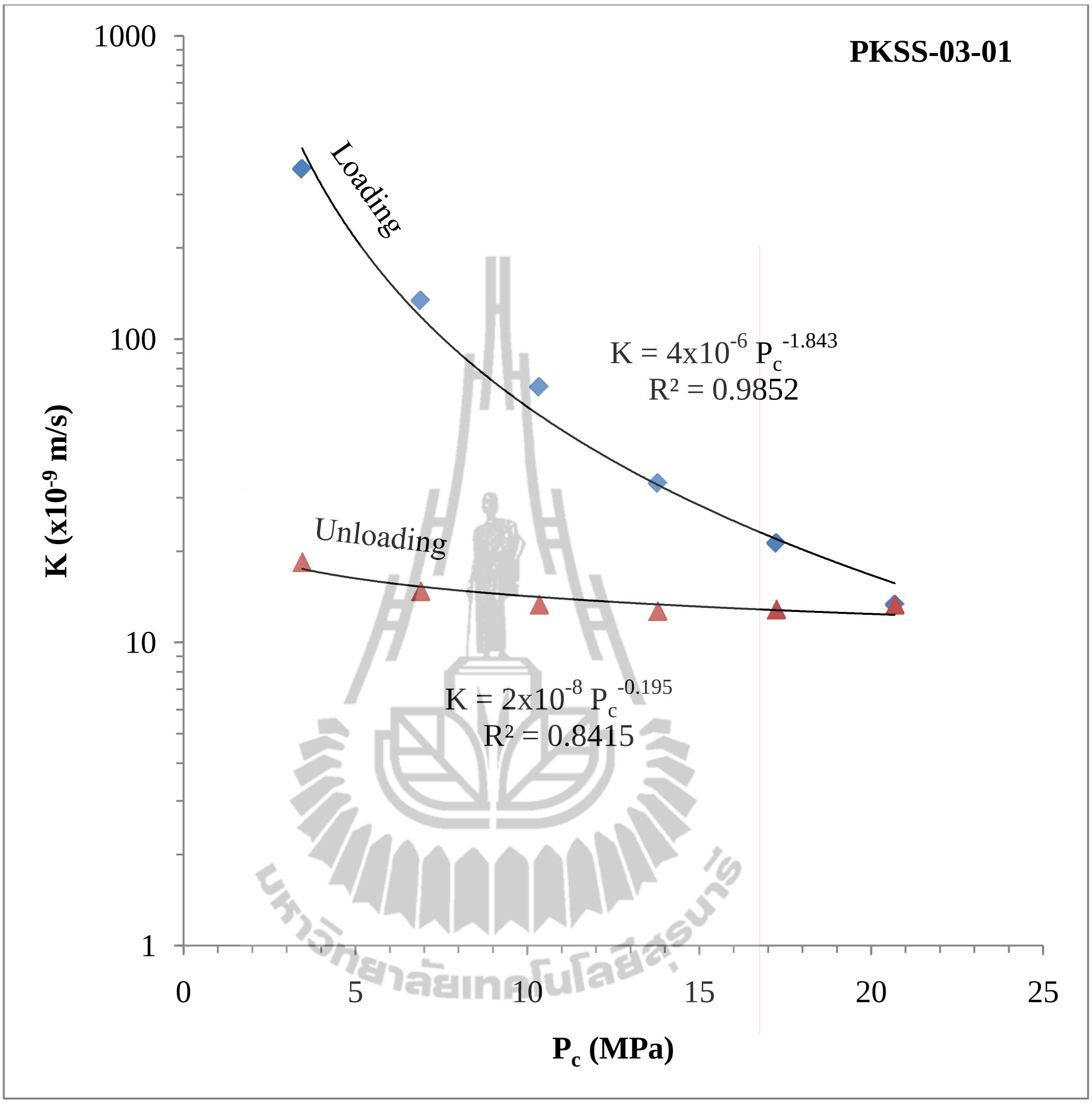


Figure 5.3 Hydraulic conductivity (K) as a function of confining pressure (P_c) for Phu Kradung sandstone specimen (PKSS-03-01) from constant head flow testing under various confining pressures.

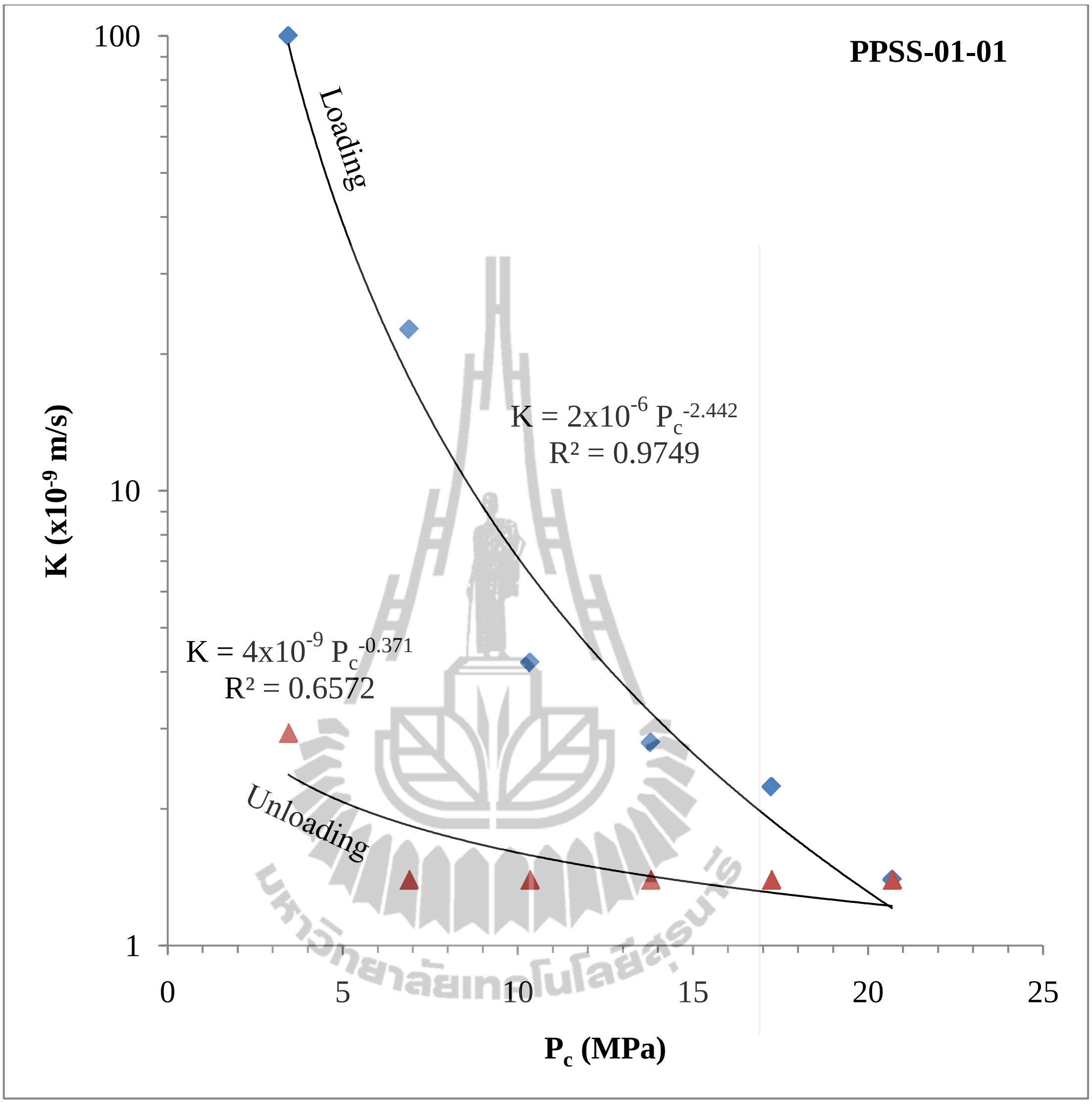


Figure 5.4 Hydraulic conductivity (K) as a function of confining pressure (P_c) for Phu Phan sandstone specimen (PPSS-01-01) from constant head flow testing under various confining pressures.

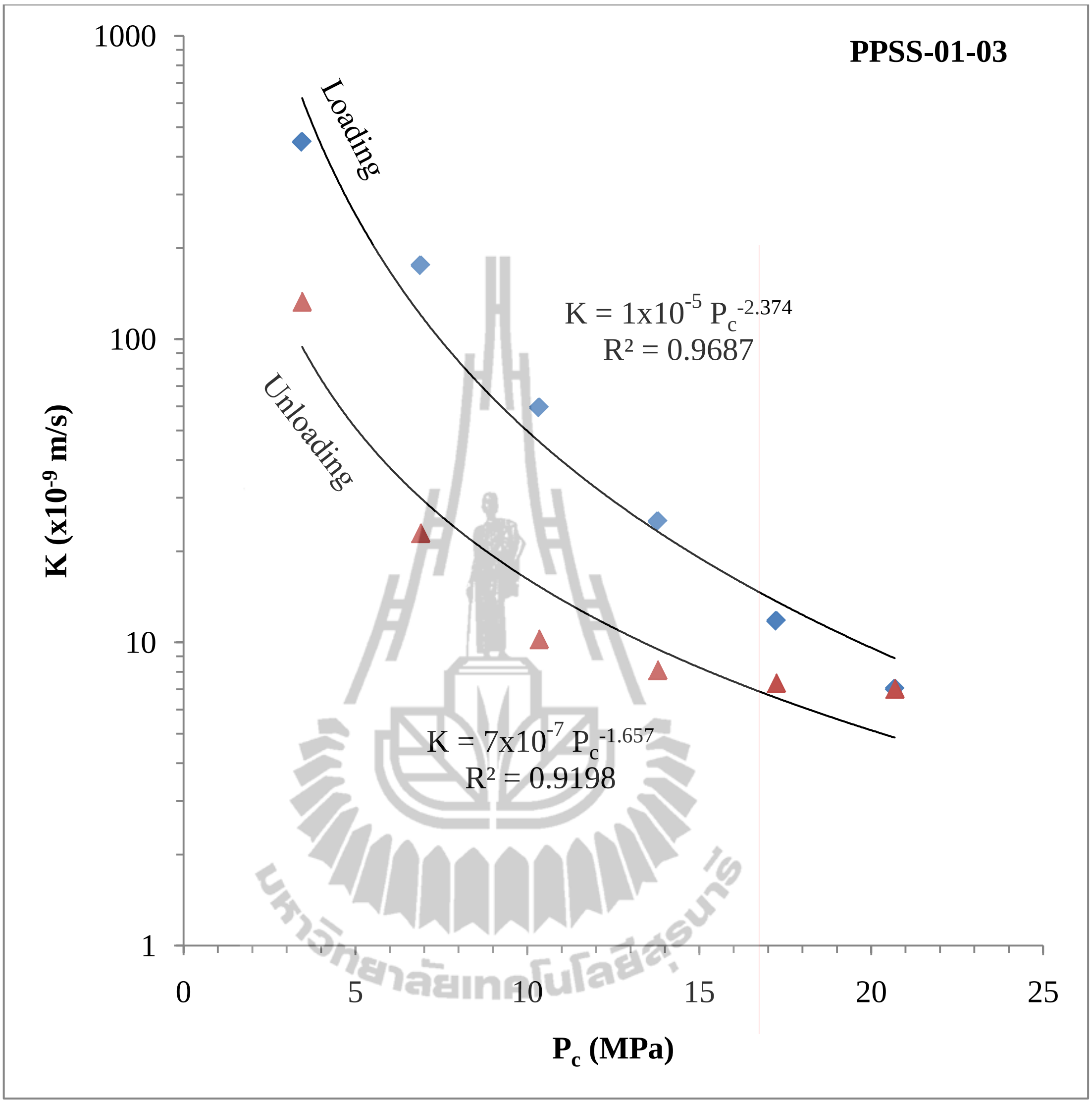


Figure 5.5 Hydraulic conductivity (K) as a function of confining pressure (P_c) for Phu Phan sandstone specimen (PPSS-01-03) from constant head flow testing under various confining pressures.

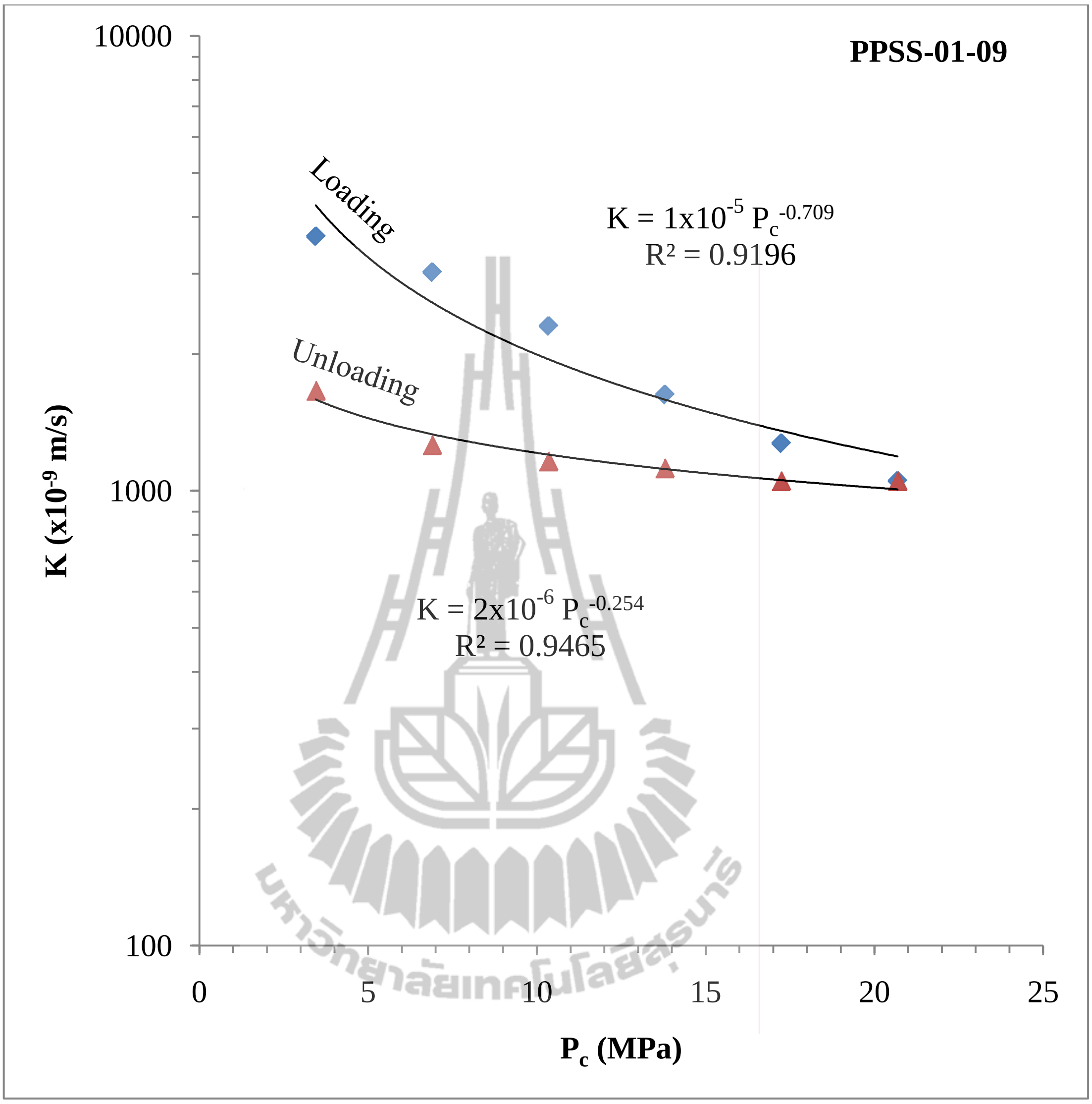


Figure 5.6 Hydraulic conductivity (K) as a function of confining pressure (P_c) for Phu Phan sandstone specimen (PPSS-01-09) from constant head flow testing under various confining pressures.

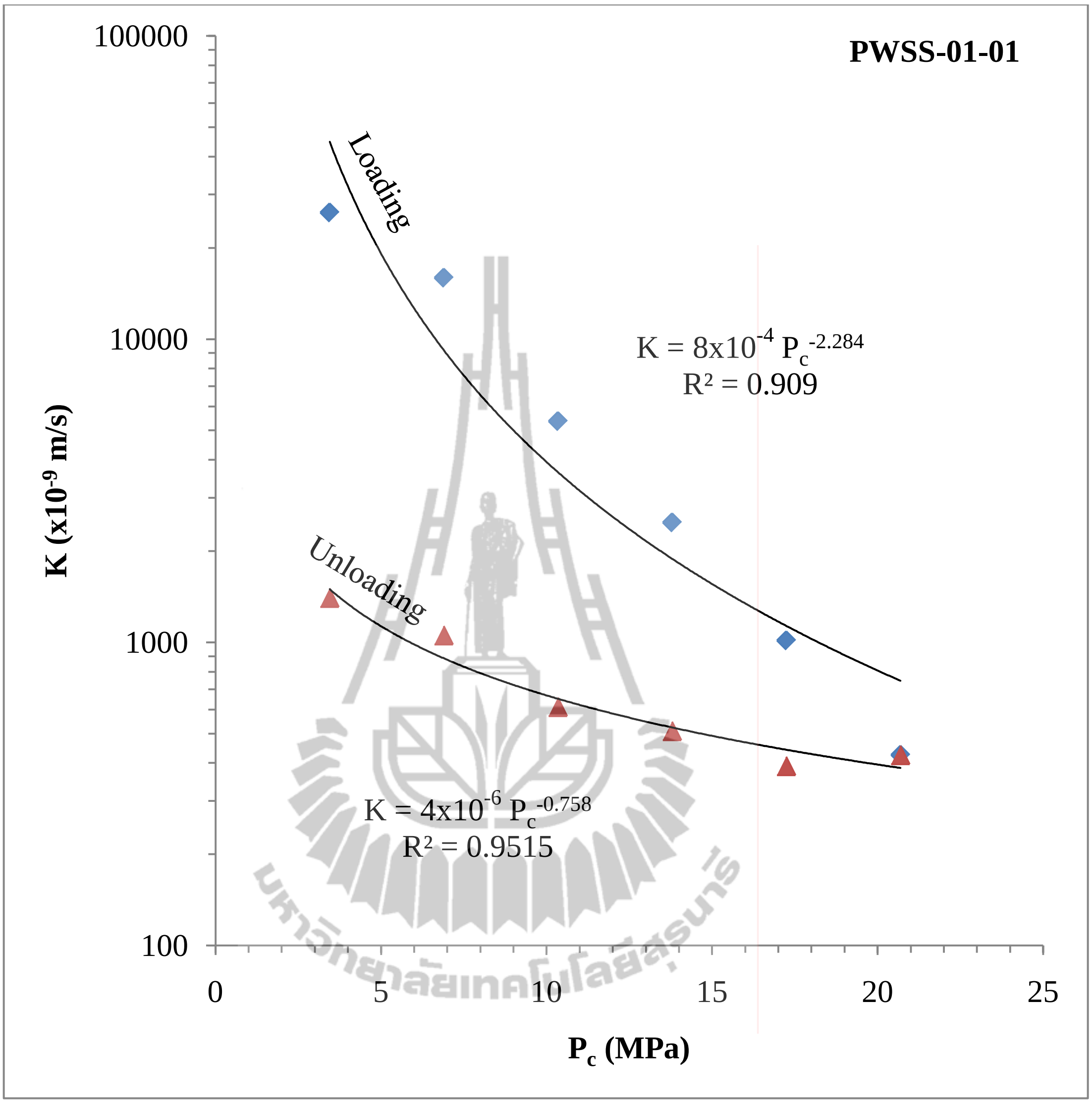


Figure 5.7 Hydraulic conductivity (K) as a function of confining pressure (P_c) for Phra Wihan sandstone specimen (PWSS-01-01) from constant head flow testing under various confining pressures.

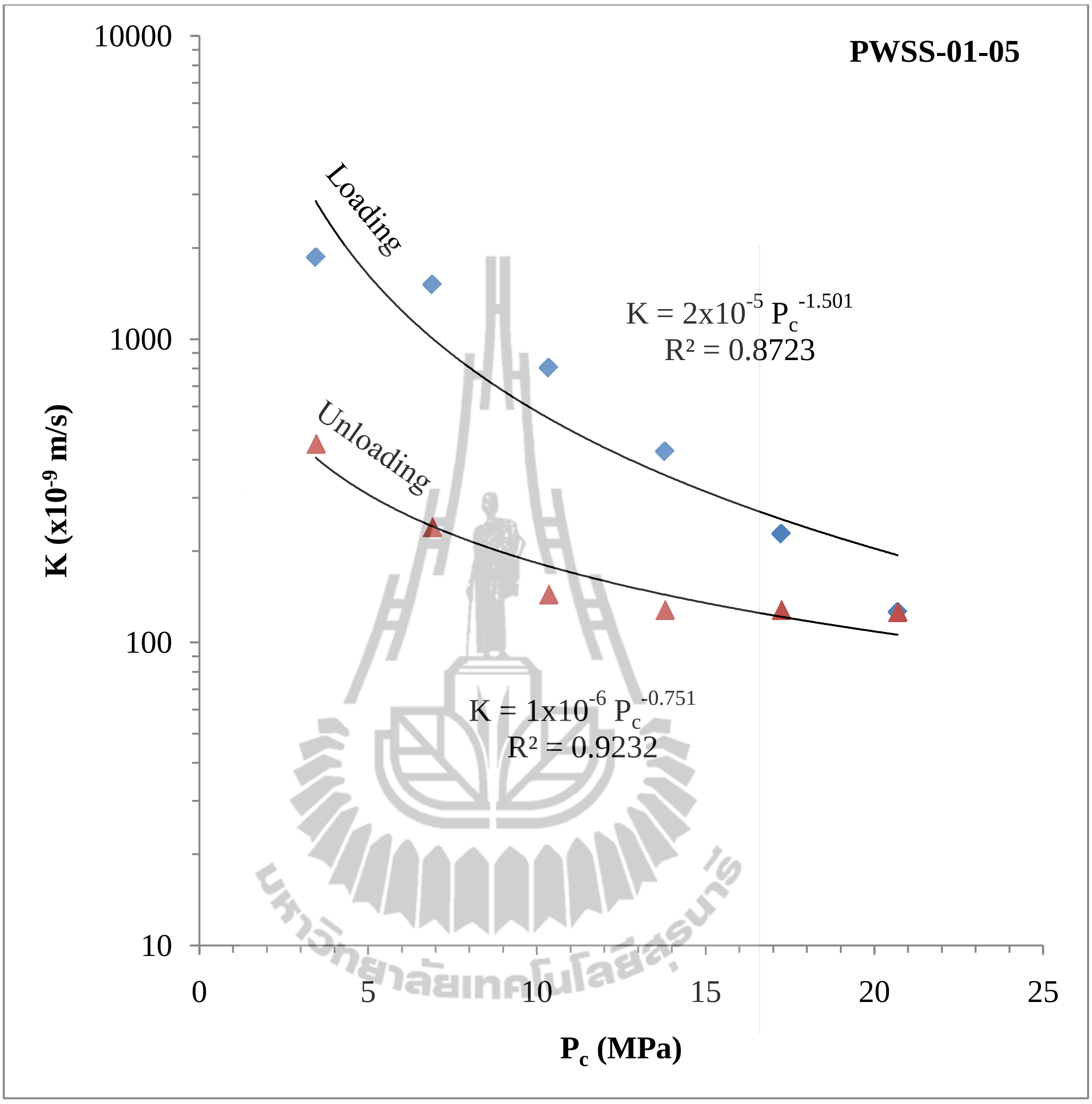


Figure 5.8 Hydraulic conductivity (K) as a function of confining pressure (P_c) for Phra Wihan sandstone specimen (PWSS-01-05) from constant head flow testing under various confining pressures.

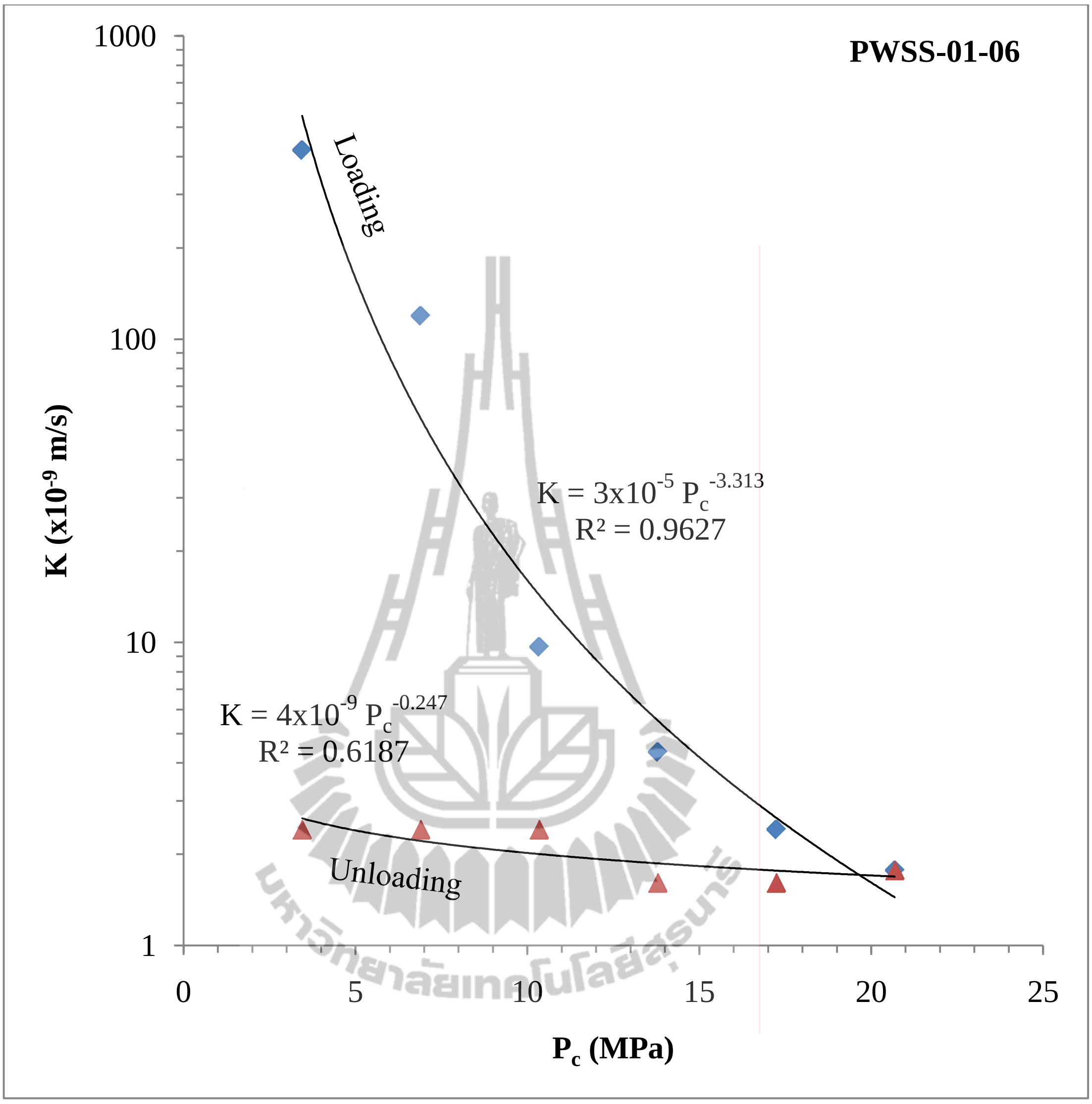


Figure 5.9 Hydraulic conductivity (K) as a function of confining pressure (P_c) for Phra Wihan sandstone specimen (PWSS-01-06) from constant head flow testing under various confining pressures.

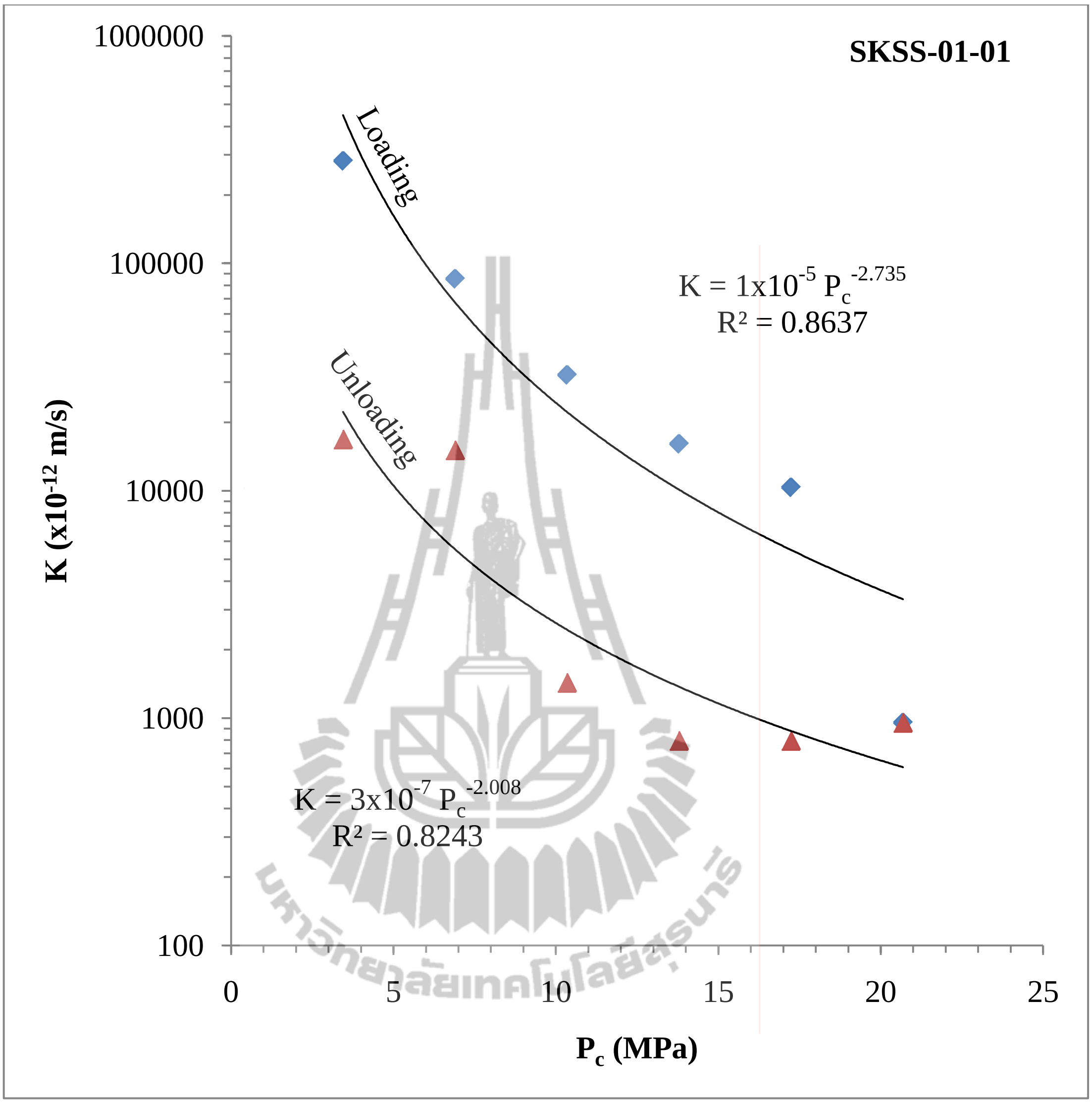


Figure 5.10 Hydraulic conductivity (K) as a function of confining pressure (P_c) for Sao Khua sandstone specimen (SKSS-01-01) from constant head flow testing under various confining pressures.

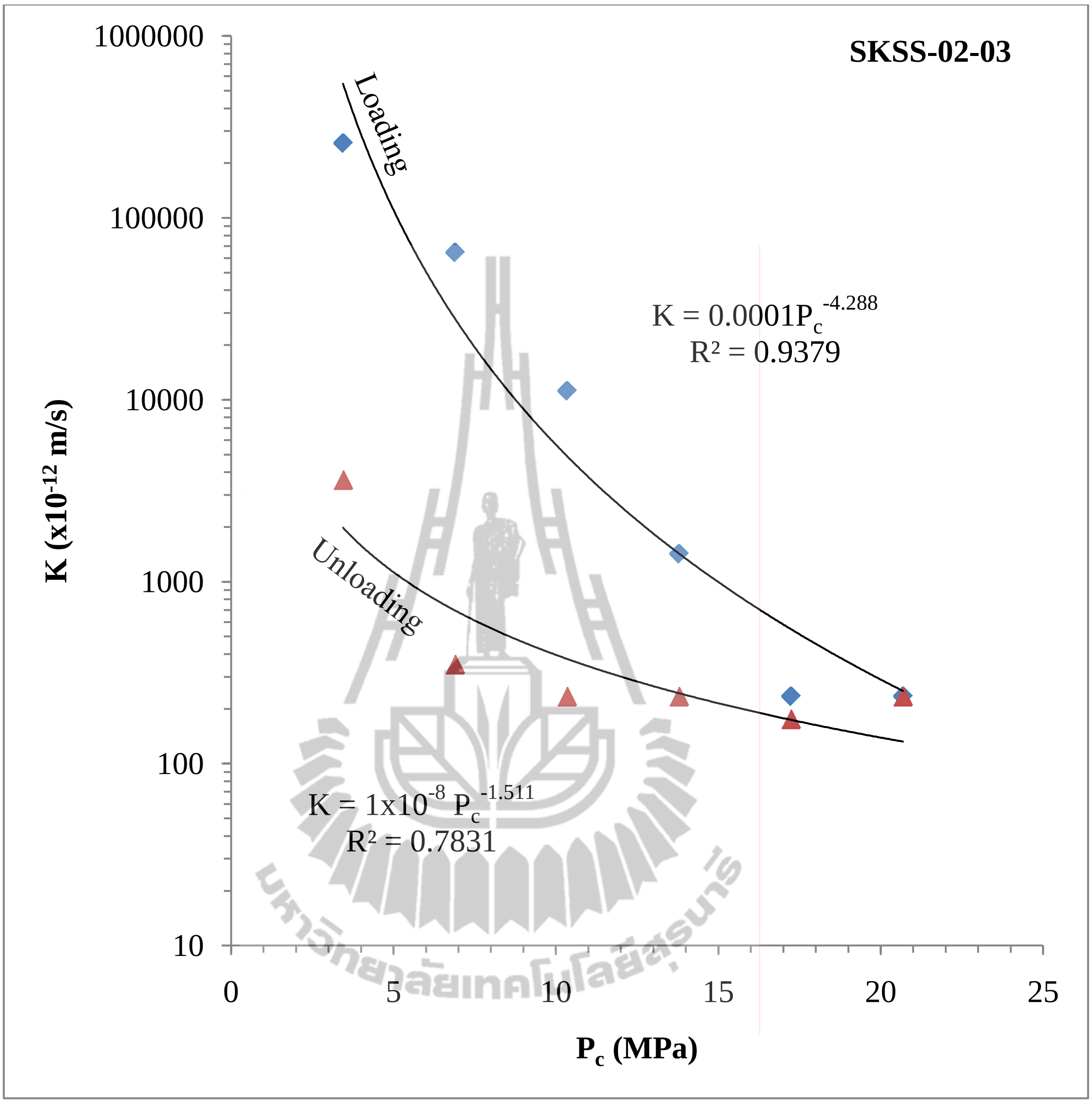


Figure 5.11 Hydraulic conductivity (K) as a function of confining pressure (P_c) for Sao Khua sandstone specimen (SKSS-02-03) from constant head flow testing under various confining pressures.

Table 5.1 Value of x, φ, and R^2 from each sample specimen tested by constant head flow testing under various confining pressures.

Sample	Loading			Unloading		
	x **($x10^{-6}$)**	***φ***	**R^2**	***x*** **($x10^{-9}$)**	***φ***	**R^2**
PKSS-01-05	20	-2.421	0.9555	20	-3.24	0.7192
PKSS-01-07	4	-2.292	0.9879	8	-0.29	0.8483
PKSS-03-01	4	-1.843	0.9852	20	-0.195	0.8415
PPSS-01-01	2	-2.442	0.9749	4	-0.371	0.6572
PPSS-01-03	10	-2.374	0.9687	700	-1.657	0.9198
PPSS-01-09	10	-0.709	0.9196	2000	-0.254	0.9465
PWSS-01-01	800	-2.285	0.9092	4000	-0.758	0.9518
PWSS-01-05	20	-1.501	0.8726	1000	-0.751	0.9231
PWSS-01-06	30	-3.313	0.9627	4	-0.247	0.6191
SKSS-01-01	10	-2.735	0.8637	300	-2.008	0.8243
SKSS-02-03	100	-4.288	0.9379	10	-1.511	0.7831

5.2.2 Falling Head Flow Testing under Normal Stresses

Empirical equations are proposed to represent the relation between the fracture permeability and the applied normal stress. They are described below. The permeability values are plotted as a function of applied pressure in Figure 5.12 through 5.19. The value of A, λ, and R^2 from each specimen are shown in Table 5.2.

$$K_j = A\sigma^{\lambda} \quad \text{or} \quad \log K_j = \lambda \log \sigma + \log A$$

where K_j is fracture conductivity, σ is normal stress, A and λ are constants.

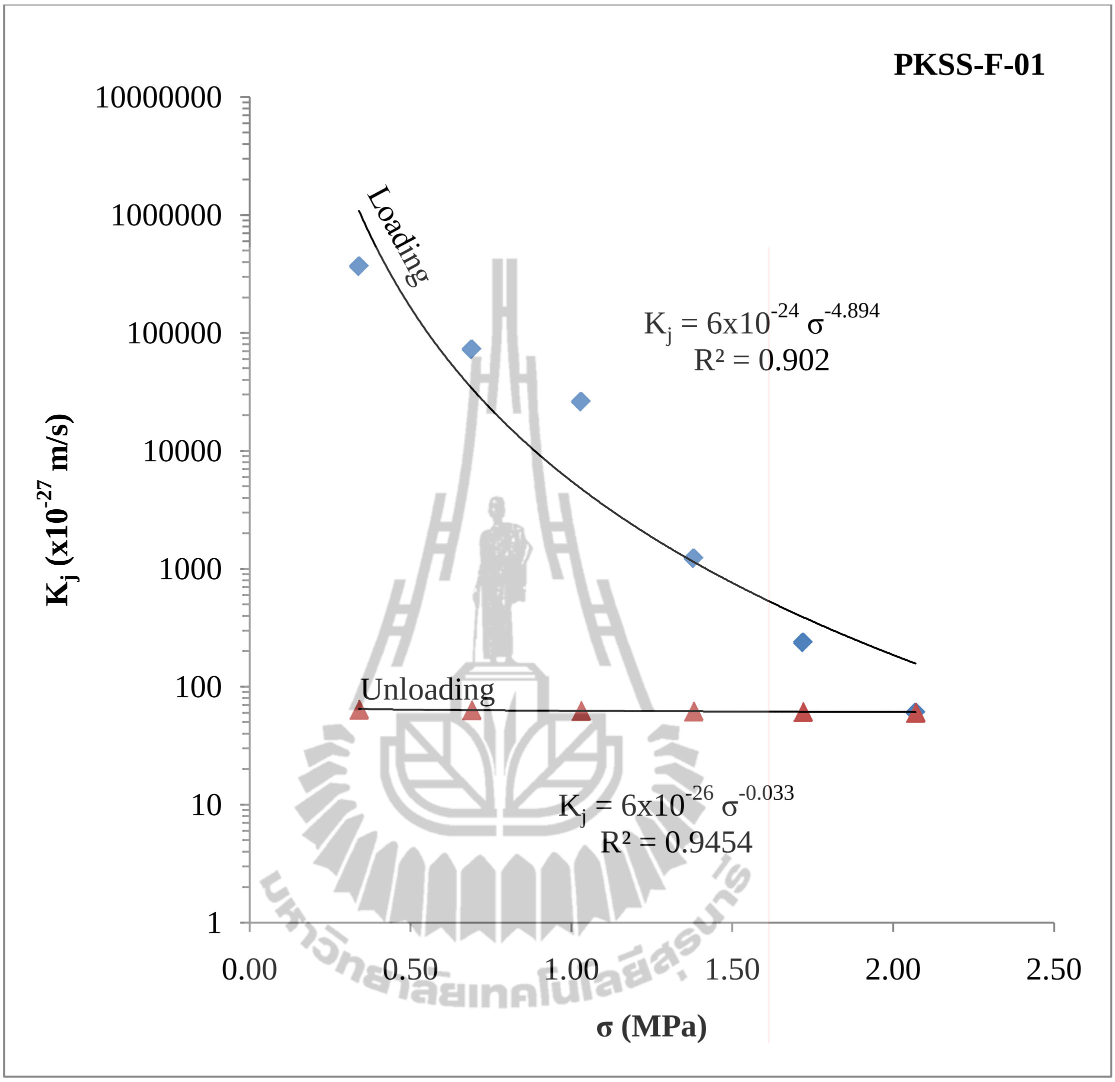


Figure 5.12 Fracture conductivity (K_j) as a function of normal stress (σ) from falling head flow testing under various normal stresses for fractures in Phu Kradung sandstone specimen (PKSS-F-01).

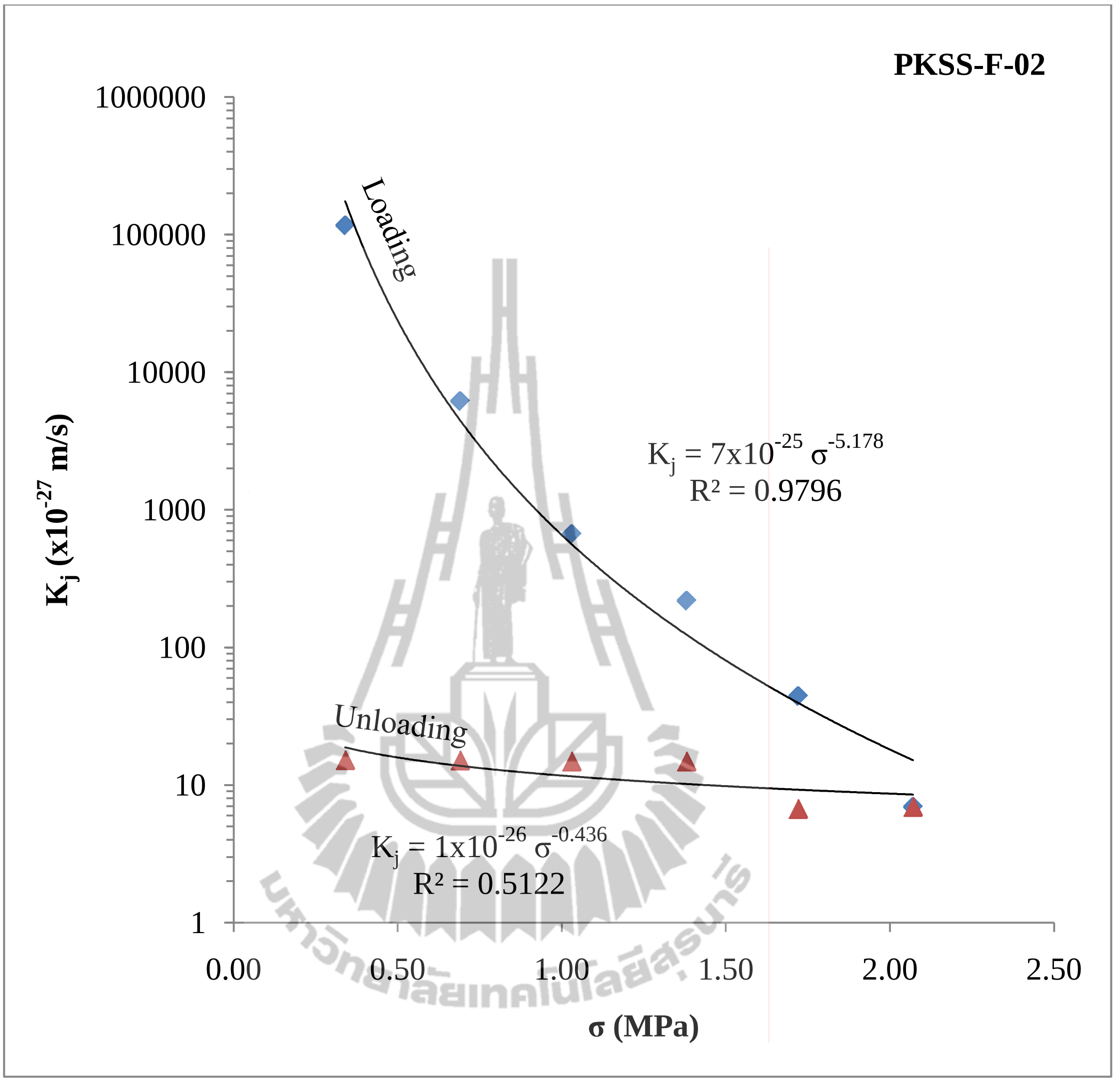


Figure 5.13 Fracture conductivity (K_j) as a function of normal stress (σ) from falling head flow testing under various normal stresses for fractures in Phu Kradung sandstone specimen (PKSS-F-02).

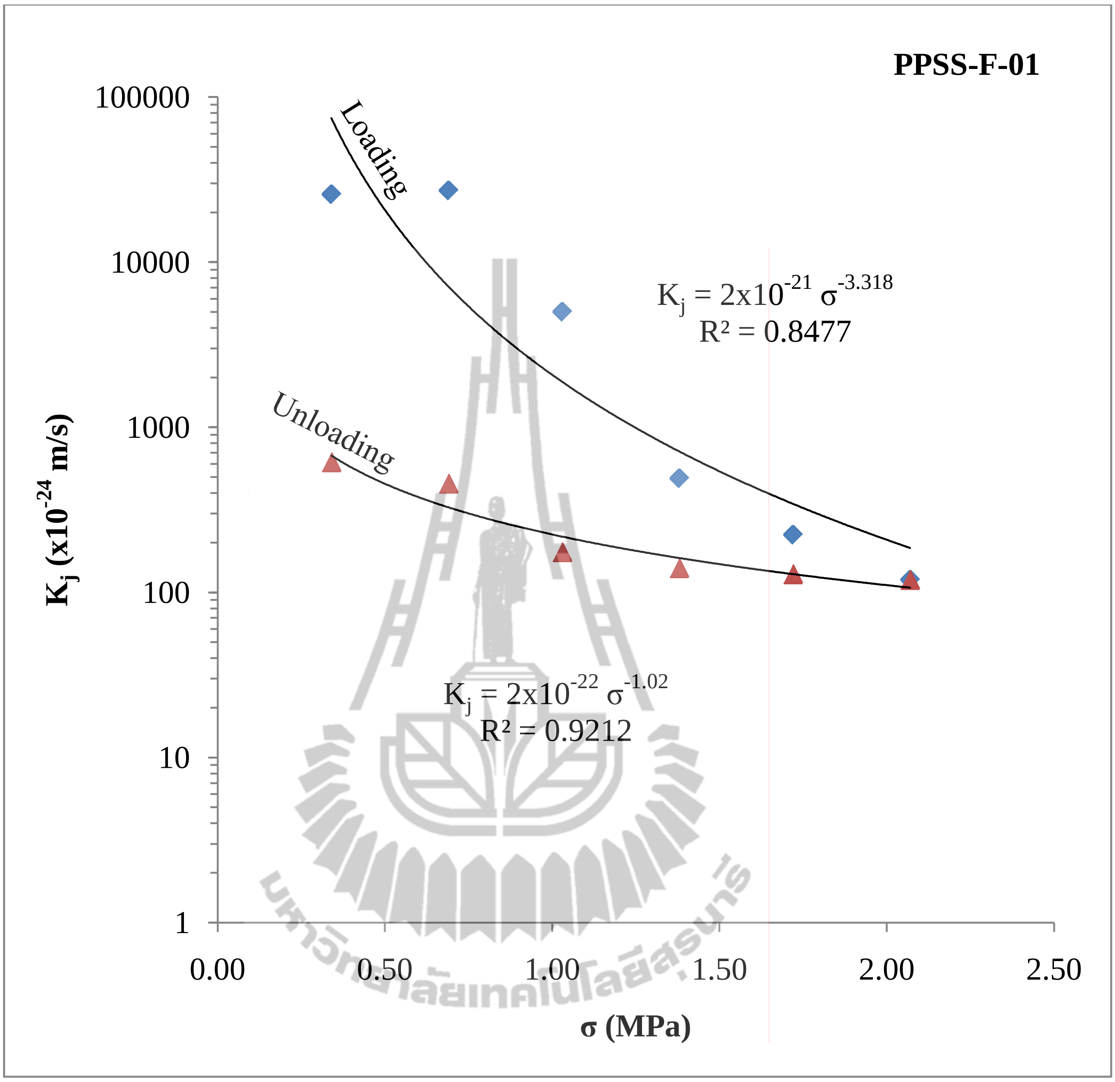


Figure 5.14 Fracture conductivity (K_j) as a function of normal stress (σ) from falling head flow testing under various normal stresses for fractures in Phu Phan sandstone specimen (PPSS-F-01).

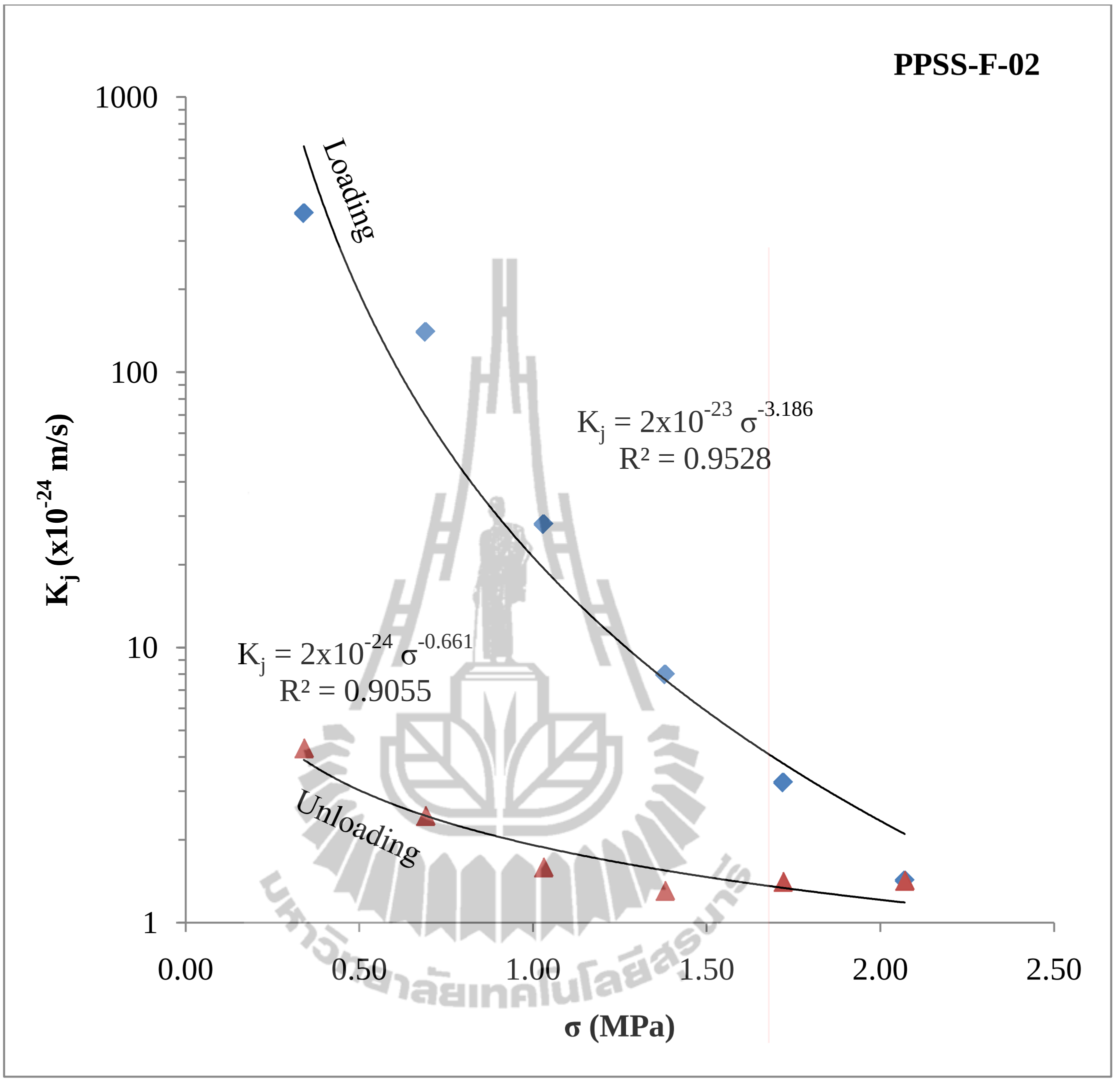


Figure 5.15 Fracture conductivity (K_j) as a function of normal stress (σ) from falling head flow testing under various normal stresses for fractures in Phu Phan sandstone specimen (PPSS-F-02).

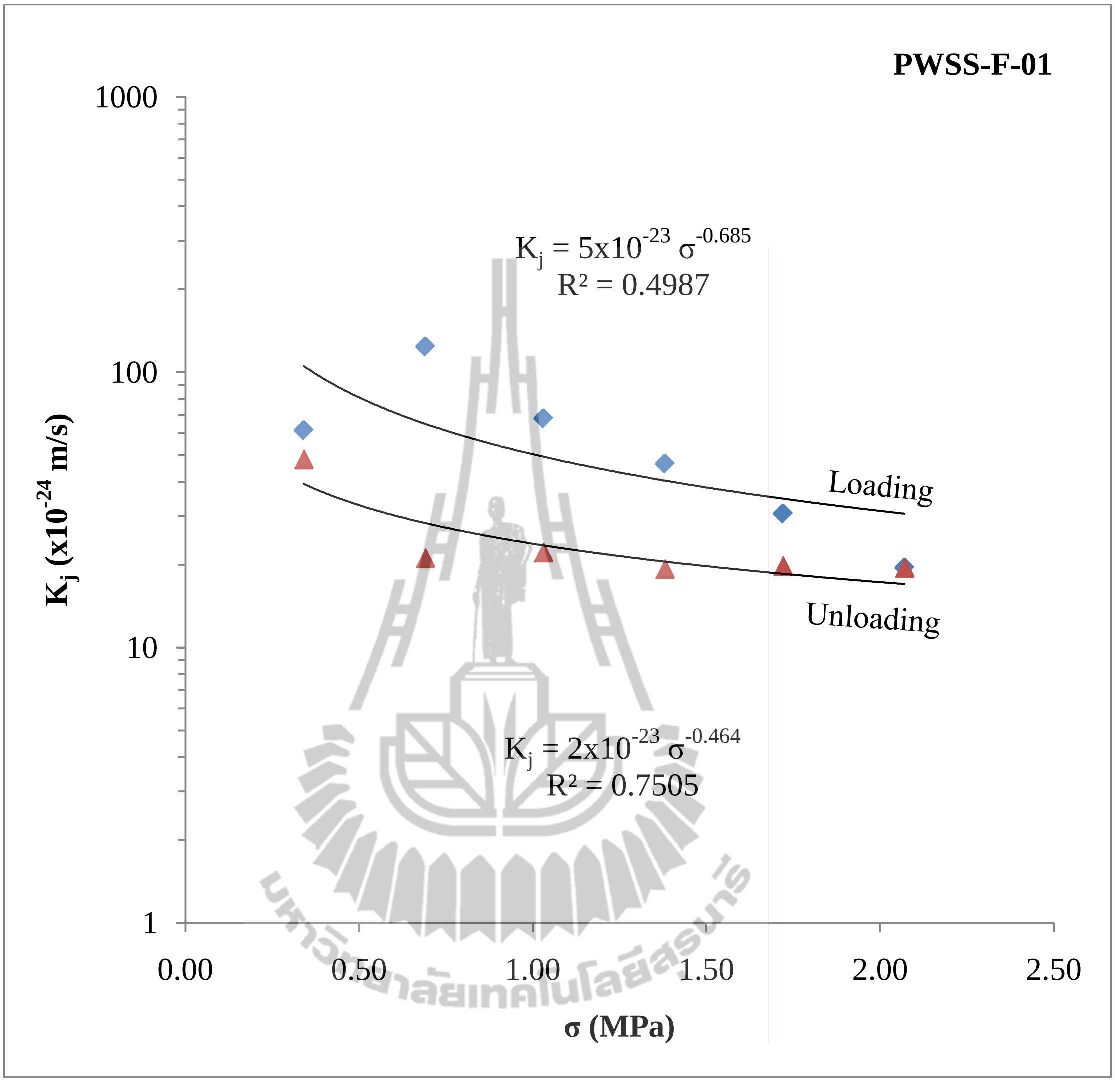


Figure 5.16 Fracture conductivity (K_j) as a function of normal stress (σ) from falling head flow testing under various normal stresses for fractures in Phra Wihan sandstone specimen (PWSS-F-01).

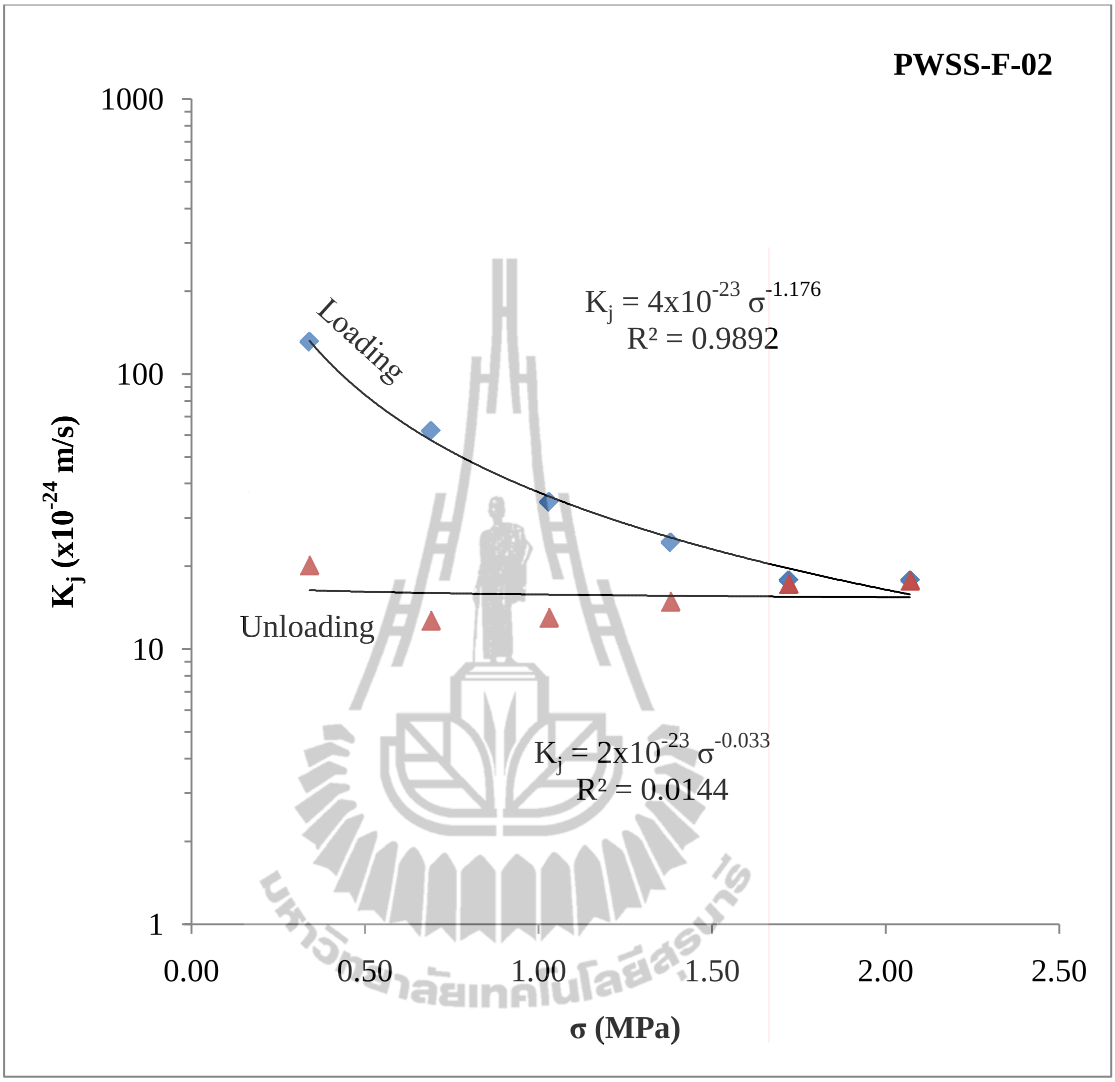


Figure 5.17 Fracture conductivity (K_j) as a function of normal stress (σ) from falling head flow testing under various normal stresses for fractures in Phra Wihan sandstone specimen (PWSS-F-02).

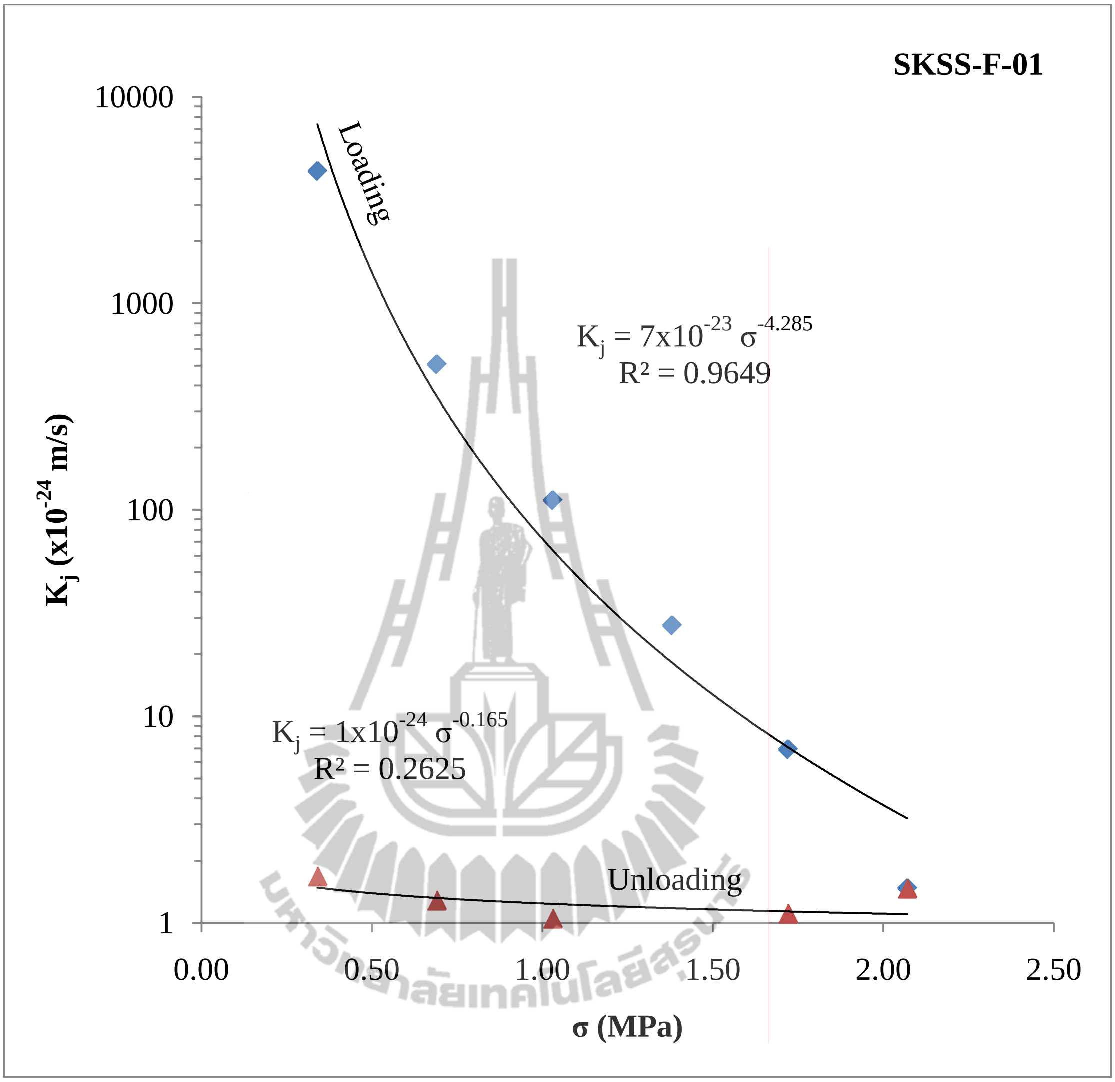


Figure 5.18 Fracture conductivity (K_j) as a function of normal stress (σ) from falling head flow testing under various normal stresses for fractures in Sao Khua sandstone specimen (SKSS-F-01).

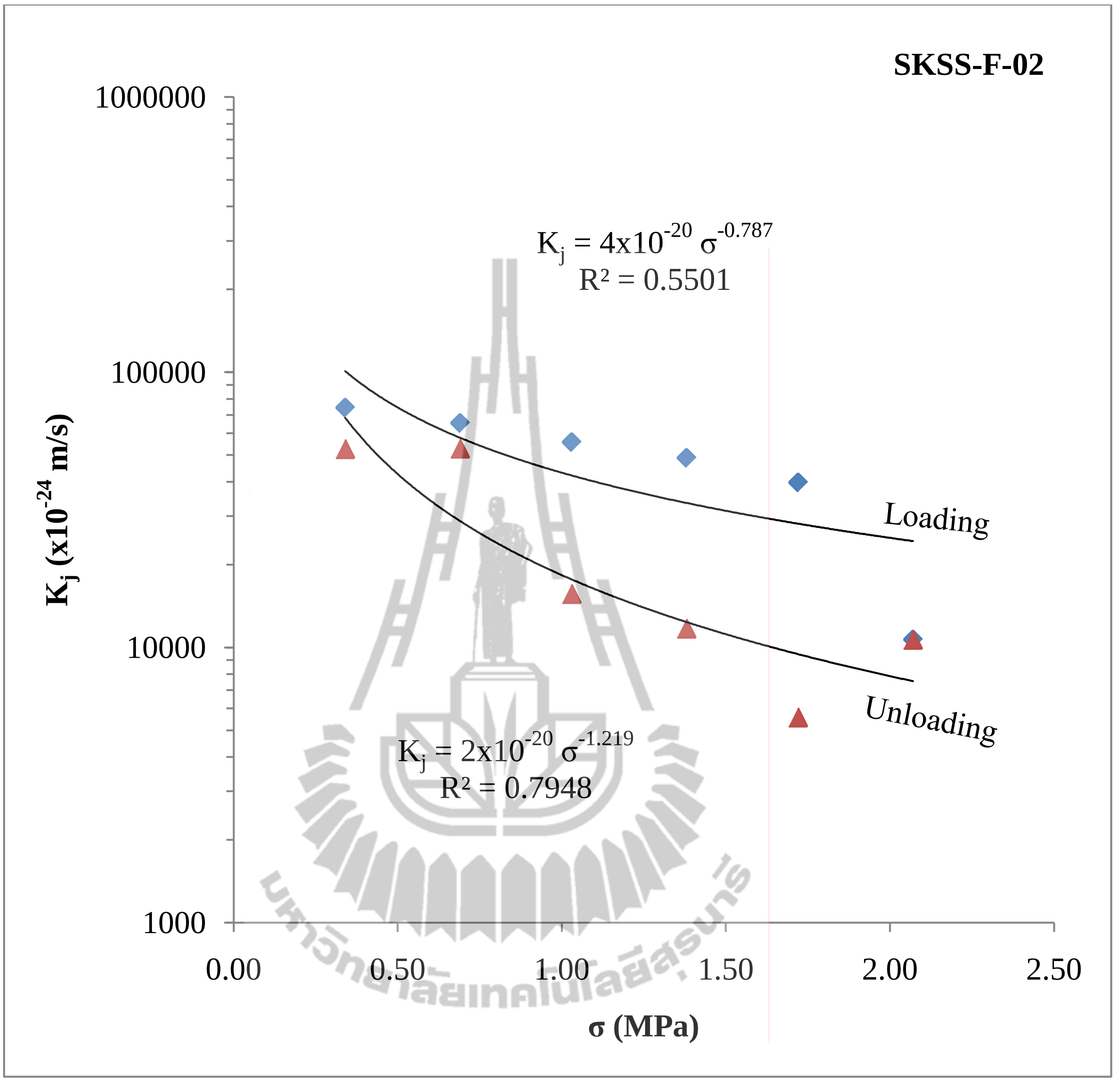


Figure 5.19 Fracture conductivity (K_j) as a function of normal stress (σ) from falling head flow testing under various normal stresses for fractures in Sao Khua sandstone specimen (SKSS-F-02).

Table 5.2 Value of A, λ, and R^2 from each sample specimen tested by falling head flow testing under normal stresses.

Sample	Loading			Unloading		
	A **(x10^{-24})**	***λ***	**R^2**	***A*** **(x10^{-24})**	***λ***	**R^2**
PKSS-F-01	6	-4.894	0.9020	0.06	-0.033	0.9454
PKSS-F-02	0.7	-5.178	0.9786	0.01	-0.436	0.5122
PPSS-F-01	2000	-3.318	0.8477	200	-1.020	0.9212
PPSS-F-02	20	-3.186	0.9528	2	-0.661	0.9055
PWSS-F-01	50	-0.685	0.4987	20	-0.464	0.7505
PWSS-F-02	40	-1.176	0.9892	20	-0.033	0.0144
SKSS-F-01	70	-4.285	0.9649	1	-0.165	0.2625
SKSS-F-02	40000	-0.787	0.5501	20000	-1.219	0.7948

CHAPTER VI

DISCUSSIONS AND CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

6.1 Discussions and Conclusions

(a) Constant Head Flow Test

The hydraulic conductivity for sandstone specimens, under confining pressures between 500 psi and 3000 psi, decreases as the confining pressures increase from 500 psi to 3000 psi. The flow rates measured during unloading show a permanent reduction of the rock permeability, suggesting that a permanent closure of the pore spaces has occurred.

(b) Falling Head Flow Test

Falling head flow test have been performed to determine the fracture permeability of tension-induced fractures in Sao Khua, Phu Kradung, Phra Wihan, and Phu Phan sandstone specimens under normal stresses. The changes of apertures, water flow rates, and applied stress has been monitored and used to calculate the changes of the fracture permeability as a function of normal stress. For all sandstone types the fracture hydraulic conductivities exponentially decrease with increasing the normal stresses. Their permeability is in the range between 100×10^{-6} m/s and 10000×10^{-6} m/s. A permanent fracture closure is usually observed after unloading as evidenced by the permanent reduction of the fracture permeability (flow rate).

6.2 Recommendations for Future Studies

More testing is required to develop mathematical relationships between the fracture hydraulic conductivity (or hydraulic apertures) with the applied normal stresses for the peak and the residual regions. Such relations would be useful in predicting the fracture permeability in rock mass around underground excavations or in the slope embankments where displacement of fractures usually occur.

REFFERENCES

Bandis, S. C., Lumsden, A. C., and Barton, N. R. (1983). Fundamentals of Rock Joint Deformation. **International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts**, 20(6), 249-268.

Bandis, S. C., Barton, N. R., and Christianson, M. (1985). Application of a New Numerical Model of Joint Behavior to Rock Mechanics Problems. Paper presented at the **Proceeding of the International Symposium on Fundamentals of Rock Joints**, Björkliden, Sweden.

Barton, N., Bandis, S., and Bakhtar, K. (1985). Strength, Deformation and Conductivity Coupling of Rock Joints. **International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts**, 22(3), 121-140.

Barton, N. R., and Bakhtar, K. (1983). **Rock Joint Description and Modeling for Hydrothermomechanical Design of Nuclear Waste Repositories**. Ottawa, Ontario, Canada: CANMET Mining Research Laboratories.

Indraratna, B., and Ranjith, P. (2001). **Hydromechanical Aspects and Unsaturated Flow in Jointed Rock**. Lisse: A.A. Balkema.

National Research Council (1996). **Rock Fractures and Fluid Flow: Contemporary Understanding and Applications**. Washington, D.C.: National Academies Press.

Smith, L. C., Mase, C. W., and Schwartz, F. W. (1987). Estimation of Fracture Using Hydraulic and Tracer Tests. Paper presented at the **28th U.S. Symposium on Rock Mechanics**.

Terzaghi, K. (1936). The Shearing Resistence of Saturated Soils. Paper presented at the **Proceedings of the International Conference on Foundation Engineering**, Graduate School of Engineering, Havard University, Cambridge, USA.

Tsang, Y. W. (1992). Usage of "Equivalent Apertures" For Rock Fractures as Derived from Hydraulic and Tracer Tests. **Water Resources Research**, 28(5), 1451-1455.

Twiss, R. J., and Moores, E. M. (1992). **Structural Geology**. New York: W. H. Freeman.

APPENDIX A

RESULT FROM CONSTANT HEAD FLOW TEST

UNDER VARIOUS CONFINING PRESSURES

Table A.1 Test parameters and results of PKSS-01-05.

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	(m^3/s)	(m)	(m/s)	(m^2)
500 Load	3.45	10	0.07	0						
	3.45	10	0.07	10	13.00	1.30E-05	1.30E-06	3.33E-05	7.40E-07	9.27E-11
	3.45	10	0.07	20	13.50	1.35E-05	1.35E-06	3.38E-05	7.68E-07	9.50E-11
	3.45	10	0.07	30	12.30	1.23E-05	1.23E-06	3.27E-05	7.00E-07	8.93E-11
	3.45	10	0.07	40	11.20	1.12E-05	1.12E-06	3.17E-05	6.37E-07	8.39E-11
	3.45	10	0.07	50	12.00	1.20E-05	1.20E-06	3.25E-05	6.83E-07	8.79E-11
							Average	**3.28E-05**	**7.05E-07**	**8.98E-11**
							SD	**7.90E-07**	**5.07E-08**	**4.31E-12**
1000 Load	6.89	10	0.07	0						
	6.89	10	0.07	10	5.50	5.50E-06	5.50E-07	2.50E-05	3.13E-07	5.22E-11
	6.89	10	0.07	20	6.00	6.00E-06	6.00E-07	2.58E-05	3.41E-07	5.53E-11
	6.89	10	0.07	30	5.50	5.50E-06	5.50E-07	2.50E-05	3.13E-07	5.22E-11
	6.89	10	0.07	40	5.00	5.00E-06	5.00E-07	2.43E-05	2.84E-07	4.90E-11
	6.89	10	0.07	50	4.70	4.70E-06	4.70E-07	2.38E-05	2.67E-07	4.70E-11
	6.89	10	0.07	60	4.80	4.80E-06	4.80E-07	2.39E-05	2.73E-07	4.77E-11
	6.89	10	0.07	70	4.50	4.50E-06	4.50E-07	2.34E-05	2.56E-07	4.57E-11
	6.89	10	0.07	80	4.60	4.60E-06	4.60E-07	2.36E-05	2.62E-07	4.64E-11
	6.89	10	0.07	90	4.40	4.40E-06	4.40E-07	2.32E-05	2.50E-07	4.50E-11
							Average	**2.42E-05**	**2.84E-07**	**4.90E-11**
							SD	**8.69E-07**	**3.12E-08**	**3.54E-12**

Table A.1 Test parameters and results of PKSS-01-05 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	(m^3/s)	(m)	(m/s)	(m^2)
1500 Load	10.34	10	0.07	0						
	10.34	10	0.07	20	4.10	4.10E-06	2.05E-07	1.80E-05	1.17E-07	2.70E-11
	10.34	10	0.07	40	3.70	3.70E-06	1.85E-07	1.74E-05	1.05E-07	2.53E-11
	10.34	10	0.07	60	3.60	3.60E-06	1.80E-07	1.73E-05	1.02E-07	2.48E-11
	10.34	10	0.07	80	3.20	3.20E-06	1.60E-07	1.66E-05	9.10E-08	2.29E-11
	10.34	10	0.07	100	3.40	3.40E-06	1.70E-07	1.69E-05	9.67E-08	2.39E-11
							Average	**1.72E-05**	**1.02E-07**	**2.48E-11**
							SD	**5.37E-07**	**9.65E-09**	**1.55E-12**
2000 Load	13.79	10	0.07	0						
	13.79	10	0.07	30	2.40	2.40E-06	8.00E-08	1.32E-05	4.55E-08	1.44E-11
	13.79	10	0.07	60	2.30	2.30E-06	7.67E-08	1.30E-05	4.36E-08	1.40E-11
	13.79	10	0.07	90	2.30	2.30E-06	7.67E-08	1.30E-05	4.36E-08	1.40E-11
	13.79	10	0.07	120	2.20	2.20E-06	7.33E-08	1.28E-05	4.17E-08	1.36E-11
	13.79	10	0.07	150	2.30	2.30E-06	7.67E-08	1.30E-05	4.36E-08	1.40E-11
							Average	**1.30E-05**	**4.36E-08**	**1.40E-11**
							SD	**1.33E-07**	**1.34E-09**	**2.88E-13**

Table A.1 Test parameters and results of PKSS-01-05 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	(m^3/s)	(m)	(m/s)	(m^2)
2500 Load	17.24	10	0.07	0						
	17.24	10	0.07	60	2.30	2.30E-06	3.83E-08	1.03E-05	2.18E-08	8.84E-12
	17.24	10	0.07	120	2.10	2.10E-06	3.50E-08	9.99E-06	1.99E-08	8.32E-12
	17.24	10	0.07	180	1.90	1.90E-06	3.17E-08	9.67E-06	1.80E-08	7.79E-12
	17.24	10	0.07	240	1.70	1.70E-06	2.83E-08	9.31E-06	1.61E-08	7.23E-12
	17.24	10	0.07	300	1.60	1.60E-06	2.67E-08	9.13E-06	1.52E-08	6.94E-12
							Average	**9.68E-06**	**1.82E-08**	**7.83E-12**
							SD	**4.81E-07**	**2.72E-09**	**7.78E-13**
3000 Load	20.68	10	0.07	0						
	20.68	10	0.07	60	1.00	1.00E-06	1.67E-08	7.80E-06	9.48E-09	5.08E-12
	20.68	10	0.07	120	0.70	7.00E-07	1.17E-08	6.93E-06	6.64E-09	4.00E-12
	20.68	10	0.07	180	0.80	8.00E-07	1.33E-08	7.25E-06	7.59E-09	4.37E-12
	20.68	10	0.07	240	0.80	8.00E-07	1.33E-08	7.25E-06	7.59E-09	4.37E-12
	20.68	10	0.07	300	1.70	1.70E-06	2.83E-08	9.31E-06	1.61E-08	7.23E-12
							Average	**7.71E-06**	**9.48E-09**	**5.01E-12**
							SD	**9.52E-07**	**3.85E-09**	**1.30E-12**

Table A.1 Test parameters and results of PKSS-01-05 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**(m^3/s)**	**(m)**	**(m/s)**	**(m^2)**
2500 Unload	17.24	10	0.07	0						
	17.24	10	0.07	60	0.80	8.00E-07	1.33E-08	7.25E-06	7.59E-09	4.37E-12
	17.24	10	0.07	120	0.80	8.00E-07	1.33E-08	7.25E-06	7.59E-09	4.37E-12
	17.24	10	0.07	180	0.80	8.00E-07	1.33E-08	7.25E-06	7.59E-09	4.37E-12
	17.24	10	0.07	240	0.80	8.00E-07	1.33E-08	7.25E-06	7.59E-09	4.37E-12
	17.24	10	0.07	300	0.80	8.00E-07	1.33E-08	7.25E-06	7.59E-09	4.37E-12
							Average	**7.25E-06**	**7.59E-09**	**4.37E-12**
							SD	**5.68E-21**	**1.78E-23**	**6.87E-27**
2000 Unload	13.79	10	0.07	0						
	13.79	10	0.07	60	0.80	8.00E-07	1.33E-08	7.25E-06	7.59E-09	4.37E-12
	13.79	10	0.07	120	0.60	6.00E-07	1.00E-08	6.58E-06	5.69E-09	3.61E-12
	13.79	10	0.07	180	0.80	8.00E-07	1.33E-08	7.25E-06	7.59E-09	4.37E-12
	13.79	10	0.07	240	0.80	8.00E-07	1.33E-08	7.25E-06	7.59E-09	4.37E-12
	13.79	10	0.07	300	0.80	8.00E-07	1.33E-08	7.25E-06	7.59E-09	4.37E-12
							Average	**7.11E-06**	**7.21E-09**	**4.22E-12**
							SD	**2.96E-07**	**8.48E-10**	**3.41E-13**

Table A.1 Test parameters and results of PKSS-01-05 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**(m^3/s)**	**(m)**	**(m/s)**	**(m^2)**
1500 Unload	10.34	10	0.07	0						
	10.34	10	0.07	60	1.00	1.00E-06	1.67E-08	7.80E-06	9.48E-09	5.08E-12
	10.34	10	0.07	120	1.00	1.00E-06	1.67E-08	7.80E-06	9.48E-09	5.08E-12
	10.34	10	0.07	180	1.00	1.00E-06	1.67E-08	7.80E-06	9.48E-09	5.08E-12
	10.34	10	0.07	240	1.00	1.00E-06	1.67E-08	7.80E-06	9.48E-09	5.08E-12
	10.34	10	0.07	300	1.10	1.10E-06	1.83E-08	8.06E-06	1.04E-08	5.41E-12
							Average	**7.86E-06**	**9.67E-09**	**5.14E-12**
							SD	**1.13E-07**	**4.24E-10**	**1.49E-13**
1000 Unload	6.89	10	0.07	0						
	6.89	10	0.07	60	1.20	1.20E-06	2.00E-08	8.29E-06	1.14E-08	5.73E-12
	6.89	10	0.07	120	1.20	1.20E-06	2.00E-08	8.29E-06	1.14E-08	5.73E-12
	6.89	10	0.07	180	1.20	1.20E-06	2.00E-08	8.29E-06	1.14E-08	5.73E-12
	6.89	10	0.07	240	1.20	1.20E-06	2.00E-08	8.29E-06	1.14E-08	5.73E-12
	6.89	10	0.07	300	1.20	1.20E-06	2.00E-08	8.29E-06	1.14E-08	5.73E-12
							Average	**8.29E-06**	**1.14E-08**	**5.73E-12**
							SD	**1.58E-20**	**6.53E-23**	**2.21E-26**

Table A.1 Test parameters and results of PKSS-01-05 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**(m^3/s)**	**(m)**	**(m/s)**	**(m^2)**
500 Unload	3.45	10	0.07	0						
	3.45	10	0.07	60	1.50	1.50E-06	2.50E-08	8.93E-06	1.42E-08	6.65E-12
	3.45	10	0.07	120	1.50	1.50E-06	2.50E-08	8.93E-06	1.42E-08	6.65E-12
	3.45	10	0.07	180	1.50	1.50E-06	2.50E-08	8.93E-06	1.42E-08	6.65E-12
	3.45	10	0.07	240	1.50	1.50E-06	2.50E-08	8.93E-06	1.42E-08	6.65E-12
	3.45	10	0.07	300	1.50	1.50E-06	2.50E-08	8.93E-06	1.42E-08	6.65E-12
							Average	**8.93E-06**	**1.42E-08**	**6.65E-12**
							SD	**0.00E+00**	**0.00E+00**	**9.03E-28**

Table A.2 Test parameters and results of PKSS-01-07.

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**m^3/s**	**(m)**	**(m/s)**	**(m^2)**
500 Load	3.45	15	0.10	0						
	3.45	15	0.10	30	12.80	1.28E-05	4.27E-07	2.27E-05	2.23E-07	4.28E-11
	3.45	15	0.10	60	11.70	1.17E-05	3.90E-07	2.20E-05	2.04E-07	4.03E-11
	3.45	15	0.10	90	11.10	1.11E-05	3.70E-07	2.16E-05	1.94E-07	3.89E-11
	3.45	15	0.10	120	11.40	1.14E-05	3.80E-07	2.18E-05	1.99E-07	3.96E-11
	3.45	15	0.10	150	12.00	1.20E-05	4.00E-07	2.22E-05	2.09E-07	4.10E-11
							Average	**2.20E-05**	**2.06E-07**	**4.05E-11**
							SD	**4.02E-07**	**1.14E-08**	**1.48E-12**
1000 Load	6.89	15	0.10	0						
	6.89	15	0.10	60	9.00	9.00E-06	1.50E-07	1.60E-05	7.85E-08	2.13E-11
	6.89	15	0.10	120	8.20	8.20E-06	1.37E-07	1.55E-05	7.15E-08	2.00E-11
	6.89	15	0.10	180	8.30	8.30E-06	1.38E-07	1.56E-05	7.24E-08	2.02E-11
	6.89	15	0.10	240	7.20	7.20E-06	1.20E-07	1.48E-05	6.28E-08	1.84E-11
	6.89	15	0.10	300	6.00	6.00E-06	1.00E-07	1.40E-05	5.23E-08	1.63E-11
							Average	**1.52E-05**	**6.75E-08**	**1.92E-11**
							SD	**7.88E-07**	**1.02E-08**	**1.96E-12**

Table A.2 Test parameters and results of PKSS-01-07 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
1500 Load	10.34	15	0.10	0						
	10.34	15	0.10	60	2.80	2.80E-06	4.67E-08	1.08E-05	2.44E-08	9.78E-12
	10.34	15	0.10	120	2.70	2.70E-06	4.50E-08	1.07E-05	2.35E-08	9.54E-12
	10.34	15	0.10	180	2.50	2.50E-06	4.17E-08	1.04E-05	2.18E-08	9.07E-12
	10.34	15	0.10	240	2.40	2.40E-06	4.00E-08	1.03E-05	2.09E-08	8.82E-12
	10.34	15	0.10	300	2.20	2.20E-06	3.67E-08	1.00E-05	1.92E-08	8.33E-12
							Average	**1.04E-05**	**2.20E-08**	**9.11E-12**
							SD	**3.32E-07**	**2.08E-09**	**5.77E-13**
2000 Load	13.79	15	0.10	0						
	13.79	15	0.10	60	1.40	1.40E-06	2.33E-08	8.60E-06	1.22E-08	6.16E-12
	13.79	15	0.10	120	1.20	1.20E-06	2.00E-08	8.17E-06	1.05E-08	5.56E-12
	13.79	15	0.10	180	1.20	1.20E-06	2.00E-08	8.17E-06	1.05E-08	5.56E-12
	13.79	15	0.10	240	1.10	1.10E-06	1.83E-08	7.93E-06	9.59E-09	5.24E-12
	13.79	15	0.10	300	1.20	1.20E-06	2.00E-08	8.17E-06	1.05E-08	5.56E-12
							Average	**8.21E-06**	**1.06E-08**	**5.62E-12**
							SD	**2.41E-07**	**9.55E-10**	**3.33E-13**

Table A.2 Test parameters and results of PKSS-01-07 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
2500 Load	17.24	15	0.10	0						
	17.24	15	0.10	60	0.70	7.00E-07	1.17E-08	6.82E-06	6.10E-09	3.88E-12
	17.24	15	0.10	120	0.70	7.00E-07	1.17E-08	6.82E-06	6.10E-09	3.88E-12
	17.24	15	0.10	180	0.60	6.00E-07	1.00E-08	6.48E-06	5.23E-09	3.50E-12
	17.24	15	0.10	240	0.60	6.00E-07	1.00E-08	6.48E-06	5.23E-09	3.50E-12
	17.24	15	0.10	300	0.60	6.00E-07	1.00E-08	6.48E-06	5.23E-09	3.50E-12
							Average	**6.62E-06**	**5.58E-09**	**3.65E-12**
							SD	**1.87E-07**	**4.78E-10**	**2.08E-13**
3000 Load	20.68	15	0.10	0						
	20.68	15	0.10	60	0.50	5.00E-07	8.33E-09	6.10E-06	4.36E-09	3.10E-12
	20.68	15	0.10	120	0.50	5.00E-07	8.33E-09	6.10E-06	4.36E-09	3.10E-12
	20.68	15	0.10	180	0.40	4.00E-07	6.67E-09	5.66E-06	3.49E-09	2.67E-12
	20.68	15	0.10	240	0.40	4.00E-07	6.67E-09	5.66E-06	3.49E-09	2.67E-12
	20.68	15	0.10	300	0.40	4.00E-07	6.67E-09	5.66E-06	3.49E-09	2.67E-12
							Average	**5.84E-06**	**3.84E-09**	**2.84E-12**
							SD	**2.39E-07**	**4.78E-10**	**2.35E-13**

Table A.2 Test parameters and results of PKSS-01-07 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**m^3/s**	**(m)**	**(m/s)**	**(m^2)**
2500 Unload	17.24	15	0.10	0						
	17.24	15	0.10	60	0.40	4.00E-07	6.67E-09	5.66E-06	3.49E-09	2.67E-12
	17.24	15	0.10	120	0.40	4.00E-07	6.67E-09	5.66E-06	3.49E-09	2.67E-12
	17.24	15	0.10	180	0.40	4.00E-07	6.67E-09	5.66E-06	3.49E-09	2.67E-12
	17.24	15	0.10	240	0.40	4.00E-07	6.67E-09	5.66E-06	3.49E-09	2.67E-12
	17.24	15	0.10	300	0.40	4.00E-07	6.67E-09	5.66E-06	3.49E-09	2.67E-12
							Average	**5.66E-06**	**3.49E-09**	**2.67E-12**
							SD	**1.82E-20**	**3.38E-23**	**1.73E-26**
2000 Unload	13.79	15	0.10	0						
	13.79	15	0.10	60	0.40	4.00E-07	6.67E-09	5.66E-06	3.49E-09	2.67E-12
	13.79	15	0.10	120	0.40	4.00E-07	6.67E-09	5.66E-06	3.49E-09	2.67E-12
	13.79	15	0.10	180	0.40	4.00E-07	6.67E-09	5.66E-06	3.49E-09	2.67E-12
	13.79	15	0.10	240	0.40	4.00E-07	6.67E-09	5.66E-06	3.49E-09	2.67E-12
	13.79	15	0.10	300	0.40	4.00E-07	6.67E-09	5.66E-06	3.49E-09	2.67E-12
							Average	**5.66E-06**	**3.49E-09**	**2.67E-12**
							SD	**1.82E-20**	**3.38E-23**	**1.73E-26**

Table A.2 Test parameters and results of PKSS-01-07 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
1500 Unload	10.34	15	0.10	0						
	10.34	15	0.10	60	0.50	5.00E-07	8.33E-09	6.10E-06	4.36E-09	3.10E-12
	10.34	15	0.10	120	0.50	5.00E-07	8.33E-09	6.10E-06	4.36E-09	3.10E-12
	10.34	15	0.10	180	0.50	5.00E-07	8.33E-09	6.10E-06	4.36E-09	3.10E-12
	10.34	15	0.10	240	0.40	4.00E-07	6.67E-09	5.66E-06	3.49E-09	2.67E-12
	10.34	15	0.10	300	0.50	5.00E-07	8.33E-09	6.10E-06	4.36E-09	3.10E-12
							Average	**6.01E-06**	**4.19E-09**	**3.01E-12**
							SD	**1.96E-07**	**3.90E-10**	**1.92E-13**
1000 Unload	6.89	15	0.10	0						
	6.89	15	0.10	60	0.50	5.00E-07	8.33E-09	6.10E-06	4.36E-09	3.10E-12
	6.89	15	0.10	120	0.50	5.00E-07	8.33E-09	6.10E-06	4.36E-09	3.10E-12
	6.89	15	0.10	180	0.50	5.00E-07	8.33E-09	6.10E-06	4.36E-09	3.10E-12
	6.89	15	0.10	240	0.50	5.00E-07	8.33E-09	6.10E-06	4.36E-09	3.10E-12
	6.89	15	0.10	300	0.50	5.00E-07	8.33E-09	6.10E-06	4.36E-09	3.10E-12
							Average	**6.10E-06**	**4.36E-09**	**3.10E-12**
							SD	**0.00E+00**	**0.00E+00**	**0.00E+00**

Table A.2 Test parameters and results of PKSS-01-07 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
500 Unload	3.45	15	0.10	0						
	3.45	15	0.10	60	0.70	7.00E-07	1.17E-08	6.82E-06	6.10E-09	3.88E-12
	3.45	15	0.10	120	0.70	7.00E-07	1.17E-08	6.82E-06	6.10E-09	3.88E-12
	3.45	15	0.10	180	0.70	7.00E-07	1.17E-08	6.82E-06	6.10E-09	3.88E-12
	3.45	15	0.10	240	0.70	7.00E-07	1.17E-08	6.82E-06	6.10E-09	3.88E-12
	3.45	15	0.10	300	0.70	7.00E-07	1.17E-08	6.82E-06	6.10E-09	3.88E-12
							Average	**6.82E-06**	**6.10E-09**	**3.88E-12**
							SD	**2.00E-20**	**5.35E-23**	**2.26E-26**

Table A.3 Test parameters and results of PKSS-03-01.

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
500 Load	3.45	10	0.07	0						
	3.45	10	0.07	30	25.00	2.50E-05	8.33E-07	2.78E-05	3.97E-07	6.43E-11
	3.45	10	0.07	60	24.00	2.40E-05	8.00E-07	2.74E-05	3.81E-07	6.26E-11
	3.45	10	0.07	90	22.50	2.25E-05	7.50E-07	2.68E-05	3.58E-07	6.00E-11
	3.45	10	0.07	120	21.50	2.15E-05	7.17E-07	2.64E-05	3.42E-07	5.82E-11
	3.45	10	0.07	150	21.60	2.16E-05	7.20E-07	2.65E-05	3.43E-07	5.83E-11
							Average	**2.70E-05**	**3.64E-07**	**6.07E-11**
							SD	**5.99E-07**	**2.44E-08**	**2.70E-12**
1000 Load	6.89	10	0.07	0						
	6.89	10	0.07	30	8.70	8.70E-06	2.90E-07	1.95E-05	1.38E-07	3.18E-11
	6.89	10	0.07	60	8.30	8.30E-06	2.77E-07	1.92E-05	1.32E-07	3.08E-11
	6.89	10	0.07	90	8.00	8.00E-06	2.67E-07	1.90E-05	1.27E-07	3.01E-11
	6.89	10	0.07	120	8.00	8.00E-06	2.67E-07	1.90E-05	1.27E-07	3.01E-11
	6.89	10	0.07	150	9.20	9.20E-06	3.07E-07	1.99E-05	1.46E-07	3.30E-11
							Average	**1.93E-05**	**1.34E-07**	**3.12E-11**
							SD	**3.88E-07**	**8.15E-09**	**1.26E-12**

Table A.3 Test parameters and results of PKSS-03-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
1500 Load	10.34	10	0.07	0						
	10.34	10	0.07	30	4.50	4.50E-06	1.50E-07	1.57E-05	7.15E-08	2.05E-11
	10.34	10	0.07	60	4.50	4.50E-06	1.50E-07	1.57E-05	7.15E-08	2.05E-11
	10.34	10	0.07	90	4.50	4.50E-06	1.50E-07	1.57E-05	7.15E-08	2.05E-11
	10.34	10	0.07	120	4.20	4.20E-06	1.40E-07	1.53E-05	6.67E-08	1.96E-11
	10.34	10	0.07	150	4.20	4.20E-06	1.40E-07	1.53E-05	6.67E-08	1.96E-11
							Average	**1.55E-05**	**6.96E-08**	**2.01E-11**
							SD	**1.95E-07**	**2.61E-09**	**5.05E-13**
2000 Load	13.79	10	0.07	0						
	13.79	10	0.07	60	4.50	4.50E-06	7.50E-08	1.25E-05	3.58E-08	1.29E-11
	13.79	10	0.07	120	4.50	4.50E-06	7.50E-08	1.25E-05	3.58E-08	1.29E-11
	13.79	10	0.07	180	4.00	4.00E-06	6.67E-08	1.20E-05	3.18E-08	1.19E-11
	13.79	10	0.07	240	4.20	4.20E-06	7.00E-08	1.22E-05	3.34E-08	1.23E-11
	13.79	10	0.07	300	3.90	3.90E-06	6.50E-08	1.19E-05	3.10E-08	1.17E-11
							Average	**1.22E-05**	**3.35E-08**	**1.24E-11**
							SD	**2.67E-07**	**2.20E-09**	**5.43E-13**

Table A.3 Test parameters and results of PKSS-03-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
2500 Load	17.24	10	0.07	0						
	17.24	10	0.07	60	2.80	2.80E-06	4.67E-08	1.06E-05	2.22E-08	9.41E-12
	17.24	10	0.07	120	2.60	2.60E-06	4.33E-08	1.04E-05	2.07E-08	8.96E-12
	17.24	10	0.07	180	2.60	2.60E-06	4.33E-08	1.04E-05	2.07E-08	8.96E-12
	17.24	10	0.07	240	2.70	2.70E-06	4.50E-08	1.05E-05	2.15E-08	9.19E-12
	17.24	10	0.07	300	2.70	2.70E-06	4.50E-08	1.05E-05	2.15E-08	9.19E-12
							Average	**1.05E-05**	**2.13E-08**	**9.14E-12**
							SD	**1.09E-07**	**6.65E-10**	**1.90E-13**
3000 Load	20.68	10	0.07	0						
	20.68	10	0.07	60	1.70	1.70E-06	2.83E-08	9.00E-06	1.35E-08	6.75E-12
	20.68	10	0.07	120	1.90	1.90E-06	3.17E-08	9.34E-06	1.51E-08	7.27E-12
	20.68	10	0.07	180	1.60	1.60E-06	2.67E-08	8.82E-06	1.27E-08	6.48E-12
	20.68	10	0.07	240	1.60	1.60E-06	2.67E-08	8.82E-06	1.27E-08	6.48E-12
	20.68	10	0.07	300	1.60	1.60E-06	2.67E-08	8.82E-06	1.27E-08	6.48E-12
							Average	**8.96E-06**	**1.33E-08**	**6.69E-12**
							SD	**2.26E-07**	**1.04E-09**	**3.42E-13**

Table A.3 Test parameters and results of PKSS-03-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
2500 Unload	17.24	10	0.07	0						
	17.24	10	0.07	60	1.70	1.70E-06	2.83E-08	9.00E-06	1.35E-08	6.75E-12
	17.24	10	0.07	120	1.60	1.60E-06	2.67E-08	8.82E-06	1.27E-08	6.48E-12
	17.24	10	0.07	180	1.60	1.60E-06	2.67E-08	8.82E-06	1.27E-08	6.48E-12
	17.24	10	0.07	240	1.60	1.60E-06	2.67E-08	8.82E-06	1.27E-08	6.48E-12
	17.24	10	0.07	300	1.60	1.60E-06	2.67E-08	8.82E-06	1.27E-08	6.48E-12
							Average	**8.86E-06**	**1.29E-08**	**6.54E-12**
							SD	**8.05E-08**	**3.55E-10**	**1.20E-13**
2000 Unload	13.79	10	0.07	0						
	13.79	10	0.07	60	1.60	1.60E-06	2.67E-08	8.82E-06	1.27E-08	6.48E-12
	13.79	10	0.07	120	1.60	1.60E-06	2.67E-08	8.82E-06	1.27E-08	6.48E-12
	13.79	10	0.07	180	1.60	1.60E-06	2.67E-08	8.82E-06	1.27E-08	6.48E-12
	13.79	10	0.07	240	1.60	1.60E-06	2.67E-08	8.82E-06	1.27E-08	6.48E-12
	13.79	10	0.07	300	1.60	1.60E-06	2.67E-08	8.82E-06	1.27E-08	6.48E-12
							Average	**8.82E-06**	**1.27E-08**	**6.48E-12**
							SD	**0.00E+00**	**1.85E-24**	**0.00E+00**

Table A.3 Test parameters and results of PKSS-03-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
1500 Unload	10.34	10	0.07	0						
	10.34	10	0.07	60	1.70	1.70E-06	2.83E-08	9.00E-06	1.35E-08	6.75E-12
	10.34	10	0.07	120	1.60	1.60E-06	2.67E-08	8.82E-06	1.27E-08	6.48E-12
	10.34	10	0.07	180	1.70	1.70E-06	2.83E-08	9.00E-06	1.35E-08	6.75E-12
	10.34	10	0.07	240	1.70	1.70E-06	2.83E-08	9.00E-06	1.35E-08	6.75E-12
	10.34	10	0.07	300	1.70	1.70E-06	2.83E-08	9.00E-06	1.35E-08	6.75E-12
							Average	**8.96E-06**	**1.33E-08**	**6.70E-12**
							SD	**8.05E-08**	**3.55E-10**	**1.20E-13**
1000 Unload	6.89	10	0.07	0						
	6.89	10	0.07	60	1.80	1.80E-06	3.00E-08	9.17E-06	1.43E-08	7.01E-12
	6.89	10	0.07	120	1.90	1.90E-06	3.17E-08	9.34E-06	1.51E-08	7.27E-12
	6.89	10	0.07	180	1.70	1.70E-06	2.83E-08	9.00E-06	1.35E-08	6.75E-12
	6.89	10	0.07	240	1.90	1.90E-06	3.17E-08	9.34E-06	1.51E-08	7.27E-12
	6.89	10	0.07	300	2.00	2.00E-06	3.33E-08	9.50E-06	1.59E-08	7.52E-12
							Average	**9.27E-06**	**1.48E-08**	**7.17E-12**
							SD	**1.91E-07**	**9.06E-10**	**2.94E-13**

Table A.3 Test parameters and results of PKSS-03-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
500 Unload	3.45	10	0.07	0						
	3.45	10	0.07	60	2.50	2.50E-06	4.17E-08	1.02E-05	1.99E-08	8.73E-12
	3.45	10	0.07	120	2.20	2.20E-06	3.67E-08	9.81E-06	1.75E-08	8.02E-12
	3.45	10	0.07	180	2.30	2.30E-06	3.83E-08	9.95E-06	1.83E-08	8.26E-12
	3.45	10	0.07	240	2.30	2.30E-06	3.83E-08	9.95E-06	1.83E-08	8.26E-12
	3.45	10	0.07	300	2.30	2.30E-06	3.83E-08	9.95E-06	1.83E-08	8.26E-12
Average								**9.98E-06**	**1.84E-08**	**8.30E-12**
SD								**1.55E-07**	**8.70E-10**	**2.60E-13**

Table A.4 Test parameters and results of PPSS-01-01.

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**m^3/s**	**(m)**	**(m/s)**	**(m^2)**
500 Load	3.45	15	0.10	0						
	3.45	15	0.10	60	15.50	1.55E-05	2.58E-07	1.85E-05	1.08E-07	2.85E-11
	3.45	15	0.10	120	14.50	1.45E-05	2.42E-07	1.81E-05	1.01E-07	2.73E-11
	3.45	15	0.10	180	14.50	1.45E-05	2.42E-07	1.81E-05	1.01E-07	2.73E-11
	3.45	15	0.10	240	14.00	1.40E-05	2.33E-07	1.79E-05	9.79E-08	2.67E-11
	3.45	15	0.10	300	13.00	1.30E-05	2.17E-07	1.75E-05	9.09E-08	2.54E-11
							Average	**1.80E-05**	**1.00E-07**	**2.70E-11**
							SD	**3.83E-07**	**6.35E-09**	**1.15E-12**
1000 Load	6.89	15	0.10	0						
	6.89	15	0.10	60	3.70	3.70E-06	6.17E-08	1.15E-05	2.59E-08	1.10E-11
	6.89	15	0.10	120	3.30	3.30E-06	5.50E-08	1.10E-05	2.31E-08	1.02E-11
	6.89	15	0.10	180	2.50	2.50E-06	4.17E-08	1.01E-05	1.75E-08	8.46E-12
	6.89	15	0.10	240	3.40	3.40E-06	5.67E-08	1.12E-05	2.38E-08	1.04E-11
	6.89	15	0.10	300	3.30	3.30E-06	5.50E-08	1.10E-05	2.31E-08	1.02E-11
							Average	**1.10E-05**	**2.27E-08**	**1.00E-11**
							SD	**5.27E-07**	**3.11E-09**	**9.42E-13**

Table A.4 Test parameters and results of PPSS-01-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
1500 Load	10.34	15	0.10	0						
	10.34	15	0.10	60	0.70	7.00E-07	1.17E-08	6.59E-06	4.89E-09	3.62E-12
	10.34	15	0.10	120	0.60	6.00E-07	1.00E-08	6.26E-06	4.20E-09	3.27E-12
	10.34	15	0.10	180	0.60	6.00E-07	1.00E-08	6.26E-06	4.20E-09	3.27E-12
	10.34	15	0.10	240	0.60	6.00E-07	1.00E-08	6.26E-06	4.20E-09	3.27E-12
	10.34	15	0.10	300	0.50	5.00E-07	8.33E-09	5.89E-06	3.50E-09	2.89E-12
							Average	**6.25E-06**	**4.20E-09**	**3.26E-12**
							SD	**2.47E-07**	**4.94E-10**	**2.57E-13**
2000 Load	13.79	15	0.10	0						
	13.79	15	0.10	60	0.50	5.00E-07	8.33E-09	5.89E-06	3.50E-09	2.89E-12
	13.79	15	0.10	120	0.40	4.00E-07	6.67E-09	5.47E-06	2.80E-09	2.49E-12
	13.79	15	0.10	180	0.40	4.00E-07	6.67E-09	5.47E-06	2.80E-09	2.49E-12
	13.79	15	0.10	240	0.30	3.00E-07	5.00E-09	4.97E-06	2.10E-09	2.06E-12
	13.79	15	0.10	300	0.40	4.00E-07	6.67E-09	5.47E-06	2.80E-09	2.49E-12
							Average	**5.45E-06**	**2.80E-09**	**2.49E-12**
							SD	**3.27E-07**	**4.94E-10**	**2.95E-13**

Table A.4 Test parameters and results of PPSS-01-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
2500 Load	17.24	15	0.10	0						
	17.24	15	0.10	60	0.30	3.00E-07	5.00E-09	4.97E-06	2.10E-09	2.06E-12
	17.24	15	0.10	120	0.50	5.00E-07	8.33E-09	5.89E-06	3.50E-09	2.89E-12
	17.24	15	0.10	180	0.30	3.00E-07	5.00E-09	4.97E-06	2.10E-09	2.06E-12
	17.24	15	0.10	240	0.30	3.00E-07	5.00E-09	4.97E-06	2.10E-09	2.06E-12
	17.24	15	0.10	300	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
							Average	**5.03E-06**	**2.24E-09**	**2.13E-12**
							SD	**5.54E-07**	**7.66E-10**	**4.77E-13**
3000 Load	20.68	15	0.10	0						
	20.68	15	0.10	60	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	20.68	15	0.10	120	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	20.68	15	0.10	180	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	20.68	15	0.10	240	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	20.68	15	0.10	300	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
							Average	**4.34E-06**	**1.40E-09**	**1.57E-12**
							SD	**2.97E-20**	**2.88E-23**	**2.15E-26**

Table A.4 Test parameters and results of PPSS-01-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
2500 Unload	17.24	15	0.10	0						
	17.24	15	0.10	60	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	17.24	15	0.10	120	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	17.24	15	0.10	180	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	17.24	15	0.10	240	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	17.24	15	0.10	300	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
							Average	**4.34E-06**	**1.40E-09**	**1.57E-12**
							SD	**2.97E-20**	**2.88E-23**	**2.15E-26**
2000 Unload	13.79	15	0.10	0						
	13.79	15	0.10	60	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	13.79	15	0.10	120	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	13.79	15	0.10	180	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	13.79	15	0.10	240	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	13.79	15	0.10	300	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
							Average	**4.34E-06**	**1.40E-09**	**1.57E-12**
							SD	**2.97E-20**	**2.88E-23**	**2.15E-26**

Table A.4 Test parameters and results of PPSS-01-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**m^3/s**	**(m)**	**(m/s)**	**(m^2)**
1500 Unload	10.34	15	0.10	0						
	10.34	15	0.10	60	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	10.34	15	0.10	120	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	10.34	15	0.10	180	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	10.34	15	0.10	240	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	10.34	15	0.10	300	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
							Average	**4.34E-06**	**1.40E-09**	**1.57E-12**
							SD	**2.97E-20**	**2.88E-23**	**2.15E-26**
1000 Unload	6.89	15	0.10	0						
	6.89	15	0.10	60	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	6.89	15	0.10	120	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	6.89	15	0.10	180	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	6.89	15	0.10	240	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
	6.89	15	0.10	300	0.20	2.00E-07	3.33E-09	4.34E-06	1.40E-09	1.57E-12
							Average	**4.34E-06**	**1.40E-09**	**1.57E-12**
							SD	**2.97E-20**	**2.88E-23**	**2.15E-26**

Table A.4 Test parameters and results of PPSS-01-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
500 Unload	3.45	15	0.10	0						
	3.45	15	0.10	60	0.40	4.00E-07	6.67E-09	5.47E-06	2.80E-09	2.49E-12
	3.45	15	0.10	120	0.50	5.00E-07	8.33E-09	5.89E-06	3.50E-09	2.89E-12
	3.45	15	0.10	180	0.40	4.00E-07	6.67E-09	5.47E-06	2.80E-09	2.49E-12
	3.45	15	0.10	240	0.40	4.00E-07	6.67E-09	5.47E-06	2.80E-09	2.49E-12
	3.45	15	0.10	300	0.40	4.00E-07	6.67E-09	5.47E-06	2.80E-09	2.49E-12
							Average	**5.55E-06**	**2.94E-09**	**2.57E-12**
							SD	**1.89E-07**	**3.13E-10**	**1.79E-13**

Table A.5 Test parameters and results of PPSS-01-03.

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	(m^3/s)	(m)	(m/s)	(m^2)
500 Load	3.45	10	0.07	0						
	3.45	10	0.07	30	29.50	2.95E-05	9.83E-07	2.91E-05	4.51E-07	7.06E-11
	3.45	10	0.07	60	30.50	3.05E-05	1.02E-06	2.94E-05	4.67E-07	7.22E-11
	3.45	10	0.07	90	30.40	3.04E-05	1.01E-06	2.94E-05	4.65E-07	7.21E-11
	3.45	10	0.07	120	27.70	2.77E-05	9.23E-07	2.85E-05	4.24E-07	6.77E-11
	3.45	10	0.07	150	28.00	2.80E-05	9.33E-07	2.86E-05	4.29E-07	6.82E-11
							Average	**2.90E-05**	**4.47E-07**	**7.02E-11**
							SD	**4.36E-07**	**2.01E-08**	**2.11E-12**
1000 Load	6.89	10	0.07	0						
	6.89	10	0.07	60	25.00	2.50E-05	4.17E-07	2.19E-05	1.91E-07	3.98E-11
	6.89	10	0.07	120	23.00	2.30E-05	3.83E-07	2.13E-05	1.76E-07	3.77E-11
	6.89	10	0.07	180	23.00	2.30E-05	3.83E-07	2.13E-05	1.76E-07	3.77E-11
	6.89	10	0.07	240	22.00	2.20E-05	3.67E-07	2.10E-05	1.68E-07	3.66E-11
	6.89	10	0.07	300	21.50	2.15E-05	3.58E-07	2.08E-05	1.65E-07	3.60E-11
							Average	**2.12E-05**	**1.75E-07**	**3.76E-11**
							SD	**4.10E-07**	**1.03E-08**	**1.46E-12**

Table A.5 Test parameters and results of PPSS-01-03 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	(m^3/s)	(m)	(m/s)	(m^2)
1500 Load	10.34	10	0.07	0						
	10.34	10	0.07	60	8.40	8.40E-06	1.40E-07	1.52E-05	6.43E-08	1.93E-11
	10.34	10	0.07	120	8.40	8.40E-06	1.40E-07	1.52E-05	6.43E-08	1.93E-11
	10.34	10	0.07	180	7.80	7.80E-06	1.30E-07	1.48E-05	5.97E-08	1.83E-11
	10.34	10	0.07	240	7.40	7.40E-06	1.23E-07	1.46E-05	5.66E-08	1.77E-11
	10.34	10	0.07	300	6.90	6.90E-06	1.15E-07	1.42E-05	5.28E-08	1.69E-11
							Average	**1.48E-05**	**5.95E-08**	**1.83E-11**
							SD	**4.16E-07**	**4.97E-09**	**1.02E-12**
2000 Load	13.79	10	0.07	0						
	13.79	10	0.07	60	3.50	3.50E-06	5.83E-08	1.14E-05	2.68E-08	1.07E-11
	13.79	10	0.07	120	3.40	3.40E-06	5.67E-08	1.12E-05	2.60E-08	1.05E-11
	13.79	10	0.07	180	3.30	3.30E-06	5.50E-08	1.11E-05	2.53E-08	1.03E-11
	13.79	10	0.07	240	3.10	3.10E-06	5.17E-08	1.09E-05	2.37E-08	9.91E-12
	13.79	10	0.07	300	3.10	3.10E-06	5.17E-08	1.09E-05	2.37E-08	9.91E-12
							Average	**1.11E-05**	**2.51E-08**	**1.03E-11**
							SD	**2.02E-07**	**1.37E-09**	**3.74E-13**

Table A.5 Test parameters and results of PPSS-01-03 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	(m^3/s)	(m)	(m/s)	(m^2)
2500 Load	17.24	10	0.07	0						
	17.24	10	0.07	60	1.60	1.60E-06	2.67E-08	8.75E-06	1.22E-08	6.38E-12
	17.24	10	0.07	120	1.50	1.50E-06	2.50E-08	8.56E-06	1.15E-08	6.11E-12
	17.24	10	0.07	180	1.50	1.50E-06	2.50E-08	8.56E-06	1.15E-08	6.11E-12
	17.24	10	0.07	240	1.60	1.60E-06	2.67E-08	8.75E-06	1.22E-08	6.38E-12
	17.24	10	0.07	300	1.50	1.50E-06	2.50E-08	8.56E-06	1.15E-08	6.11E-12
							Average	**8.64E-06**	**1.18E-08**	**6.21E-12**
							SD	**1.02E-07**	**4.19E-10**	**1.47E-13**
3000 Load	20.68	10	0.07	0						
	20.68	10	0.07	60	1.00	1.00E-06	1.67E-08	7.48E-06	7.65E-09	4.66E-12
	20.68	10	0.07	120	0.90	9.00E-07	1.50E-08	7.22E-06	6.89E-09	4.34E-12
	20.68	10	0.07	180	1.00	1.00E-06	1.67E-08	7.48E-06	7.65E-09	4.66E-12
	20.68	10	0.07	240	0.80	8.00E-07	1.33E-08	6.94E-06	6.12E-09	4.02E-12
	20.68	10	0.07	300	0.90	9.00E-07	1.50E-08	7.22E-06	6.89E-09	4.34E-12
							Average	**7.27E-06**	**7.04E-09**	**4.41E-12**
							SD	**2.23E-07**	**6.40E-10**	**2.69E-13**

Table A.5 Test parameters and results of PPSS-01-03 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**(m^3/s)**	**(m)**	**(m/s)**	**(m^2)**
2500 Unload	17.24	10	0.07	0						
	17.24	10	0.07	60	1.00	1.00E-06	1.67E-08	7.48E-06	7.65E-09	4.66E-12
	17.24	10	0.07	120	1.00	1.00E-06	1.67E-08	7.48E-06	7.65E-09	4.66E-12
	17.24	10	0.07	180	0.90	9.00E-07	1.50E-08	7.22E-06	6.89E-09	4.34E-12
	17.24	10	0.07	240	0.90	9.00E-07	1.50E-08	7.22E-06	6.89E-09	4.34E-12
	17.24	10	0.07	300	1.00	1.00E-06	1.67E-08	7.48E-06	7.65E-09	4.66E-12
							Average	**7.38E-06**	**7.35E-09**	**4.53E-12**
							SD	**1.41E-07**	**4.19E-10**	**1.73E-13**
2000 Unload	13.79	10	0.07	0						
	13.79	10	0.07	60	1.10	1.10E-06	1.83E-08	7.72E-06	8.42E-09	4.97E-12
	13.79	10	0.07	120	1.10	1.10E-06	1.83E-08	7.72E-06	8.42E-09	4.97E-12
	13.79	10	0.07	180	1.10	1.10E-06	1.83E-08	7.72E-06	8.42E-09	4.97E-12
	13.79	10	0.07	240	1.10	1.10E-06	1.83E-08	7.72E-06	8.42E-09	4.97E-12
	13.79	10	0.07	300	0.90	9.00E-07	1.50E-08	7.22E-06	6.89E-09	4.34E-12
							Average	**7.62E-06**	**8.11E-09**	**4.84E-12**
							SD	**2.23E-07**	**6.84E-10**	**2.78E-13**

Table A.5 Test parameters and results of PPSS-01-03 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**(m^3/s)**	**(m)**	**(m/s)**	**(m^2)**
1500 Unload	10.34	10	0.07	0						
	10.34	10	0.07	60	1.40	1.40E-06	2.33E-08	8.37E-06	1.07E-08	5.83E-12
	10.34	10	0.07	120	1.30	1.30E-06	2.17E-08	8.16E-06	9.95E-09	5.55E-12
	10.34	10	0.07	180	1.40	1.40E-06	2.33E-08	8.37E-06	1.07E-08	5.83E-12
	10.34	10	0.07	240	1.30	1.30E-06	2.17E-08	8.16E-06	9.95E-09	5.55E-12
	10.34	10	0.07	300	1.30	1.30E-06	2.17E-08	8.16E-06	9.95E-09	5.55E-12
							Average	**8.24E-06**	**1.03E-08**	**5.66E-12**
							SD	**1.12E-07**	**4.19E-10**	**1.54E-13**
1000 Unload	6.89	10	0.07	0						
	6.89	10	0.07	60	4.00	4.00E-06	6.67E-08	1.19E-05	3.06E-08	1.17E-11
	6.89	10	0.07	120	3.00	3.00E-06	5.00E-08	1.08E-05	2.30E-08	9.69E-12
	6.89	10	0.07	180	3.00	3.00E-06	5.00E-08	1.08E-05	2.30E-08	9.69E-12
	6.89	10	0.07	240	2.00	2.00E-06	3.33E-08	9.42E-06	1.53E-08	7.40E-12
	6.89	10	0.07	300	3.00	3.00E-06	5.00E-08	1.08E-05	2.30E-08	9.69E-12
							Average	**1.07E-05**	**2.30E-08**	**9.65E-12**
							SD	**8.69E-07**	**5.41E-09**	**1.54E-12**

Table A.5 Test parameters and results of PPSS-01-03 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	(m^3/s)	(m)	(m/s)	(m^2)
500 Unload	3.45	10	0.07	0						
	3.45	10	0.07	60	18.00	1.80E-05	3.00E-07	1.96E-05	1.38E-07	3.20E-11
	3.45	10	0.07	120	17.00	1.70E-05	2.83E-07	1.92E-05	1.30E-07	3.08E-11
	3.45	10	0.07	180	17.50	1.75E-05	2.92E-07	1.94E-05	1.34E-07	3.14E-11
	3.45	10	0.07	240	17.00	1.70E-05	2.83E-07	1.92E-05	1.30E-07	3.08E-11
	3.45	10	0.07	300	17.50	1.75E-05	2.92E-07	1.94E-05	1.34E-07	3.14E-11
							Average	**1.94E-05**	**1.33E-07**	**3.13E-11**
							SD	**1.55E-07**	**3.20E-09**	**5.01E-13**

Table A.6 Test parameters and results of PPSS-01-09.

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**m^3/s**	**(m)**	**(m/s)**	**(m^2)**
500 Load	3.45	7	0.05	0						
	3.45	7	0.05	10	39.00	3.90E-05	3.90E-06	5.31E-05	3.90E-06	2.35E-10
	3.45	7	0.05	20	34.00	3.40E-05	3.40E-06	5.07E-05	3.40E-06	2.14E-10
	3.45	7	0.05	30	37.00	3.70E-05	3.70E-06	5.22E-05	3.70E-06	2.27E-10
	3.45	7	0.05	40	34.00	3.40E-05	3.40E-06	5.07E-05	3.40E-06	2.14E-10
	3.45	7	0.05	50	37.00	3.70E-05	3.70E-06	5.22E-05	3.70E-06	2.27E-10
							Average	**5.18E-05**	**3.62E-06**	**2.24E-10**
							SD	**1.03E-06**	**2.17E-07**	**8.93E-12**
1000 Load	6.89	7	0.05	0						
	6.89	7	0.05	10	32.00	3.20E-05	3.20E-06	4.97E-05	3.20E-06	2.06E-10
	6.89	7	0.05	20	32.00	3.20E-05	3.20E-06	4.97E-05	3.20E-06	2.06E-10
	6.89	7	0.05	30	29.00	2.90E-05	2.90E-06	4.81E-05	2.90E-06	1.93E-10
	6.89	7	0.05	40	29.00	2.90E-05	2.90E-06	4.81E-05	2.90E-06	1.93E-10
	6.89	7	0.05	50	29.00	2.90E-05	2.90E-06	4.81E-05	2.90E-06	1.93E-10
							Average	**4.88E-05**	**3.02E-06**	**1.98E-10**
							SD	**8.79E-07**	**1.65E-07**	**7.17E-12**

Table A.6 Test parameters and results of PPSS-01-09 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
1500 Load	10.34	7	0.05	0						
	10.34	7	0.05	10	24.00	2.40E-05	2.40E-06	4.52E-05	2.40E-06	1.70E-10
	10.34	7	0.05	20	23.00	2.30E-05	2.30E-06	4.45E-05	2.30E-06	1.65E-10
	10.34	7	0.05	30	23.00	2.30E-05	2.30E-06	4.45E-05	2.30E-06	1.65E-10
	10.34	7	0.05	40	23.00	2.30E-05	2.30E-06	4.45E-05	2.30E-06	1.65E-10
	10.34	7	0.05	50	22.00	2.20E-05	2.20E-06	4.39E-05	2.20E-06	1.60E-10
							Average	**4.45E-05**	**2.30E-06**	**1.65E-10**
							SD	**4.57E-07**	**7.08E-08**	**3.39E-12**
2000 Load	13.79	7	0.05	0						
	13.79	7	0.05	20	33.00	3.30E-05	1.65E-06	3.99E-05	1.65E-06	1.32E-10
	13.79	7	0.05	40	31.00	3.10E-05	1.55E-06	3.90E-05	1.55E-06	1.27E-10
	13.79	7	0.05	60	32.00	3.20E-05	1.60E-06	3.95E-05	1.60E-06	1.30E-10
	13.79	7	0.05	80	34.00	3.40E-05	1.70E-06	4.03E-05	1.70E-06	1.35E-10
							Average	**3.97E-05**	**1.63E-06**	**1.31E-10**
							SD	**5.25E-07**	**6.46E-08**	**3.47E-12**

Table A.6 Test parameters and results of PPSS-01-09 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
2500 Load	17.24	7	0.05	0						
	17.24	7	0.05	20	28.00	2.80E-05	1.40E-06	3.77E-05	1.40E-06	1.19E-10
	17.24	7	0.05	40	26.00	2.60E-05	1.30E-06	3.68E-05	1.30E-06	1.13E-10
	17.24	7	0.05	60	26.00	2.60E-05	1.30E-06	3.68E-05	1.30E-06	1.13E-10
	17.24	7	0.05	80	22.00	2.20E-05	1.10E-06	3.48E-05	1.10E-06	1.01E-10
	17.24	7	0.05	100	25.00	2.50E-05	1.25E-06	3.63E-05	1.25E-06	1.10E-10
							Average	**3.65E-05**	**1.27E-06**	**1.11E-10**
							SD	**1.07E-06**	**1.10E-07**	**6.45E-12**
3000 Load	20.68	7	0.05	0						
	20.68	7	0.05	20	21.00	2.10E-05	1.05E-06	3.43E-05	1.05E-06	9.80E-11
	20.68	7	0.05	40	21.00	2.10E-05	1.05E-06	3.43E-05	1.05E-06	9.80E-11
	20.68	7	0.05	60	21.00	2.10E-05	1.05E-06	3.43E-05	1.05E-06	9.80E-11
	20.68	7	0.05	80	21.00	2.10E-05	1.05E-06	3.43E-05	1.05E-06	9.80E-11
	20.68	7	0.05	100	21.00	2.10E-05	1.05E-06	3.43E-05	1.05E-06	9.80E-11
							Average	**3.43E-05**	**1.05E-06**	**9.80E-11**
							SD	**0.00E+00**	**0.00E+00**	**0.00E+00**

Table A.6 Test parameters and results of PPSS-01-09 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
2500 Unload	17.24	7	0.05	0						
	17.24	7	0.05	20	21.00	2.10E-05	1.05E-06	3.43E-05	1.05E-06	9.80E-11
	17.24	7	0.05	40	21.00	2.10E-05	1.05E-06	3.43E-05	1.05E-06	9.80E-11
	17.24	7	0.05	60	21.00	2.10E-05	1.05E-06	3.43E-05	1.05E-06	9.80E-11
	17.24	7	0.05	80	21.00	2.10E-05	1.05E-06	3.43E-05	1.05E-06	9.80E-11
	17.24	7	0.05	100	21.00	2.10E-05	1.05E-06	3.43E-05	1.05E-06	9.80E-11
							Average	**3.43E-05**	**1.05E-06**	**9.80E-11**
							SD	**0.00E+00**	**0.00E+00**	**0.00E+00**
2000 Unload	13.79	7	0.05	0						
	13.79	7	0.05	20	23.00	2.30E-05	1.15E-06	3.53E-05	1.15E-06	1.04E-10
	13.79	7	0.05	40	23.00	2.30E-05	1.15E-06	3.53E-05	1.15E-06	1.04E-10
	13.79	7	0.05	60	22.00	2.20E-05	1.10E-06	3.48E-05	1.10E-06	1.01E-10
	13.79	7	0.05	80	22.00	2.20E-05	1.10E-06	3.48E-05	1.10E-06	1.01E-10
	13.79	7	0.05	100	22.00	2.20E-05	1.10E-06	3.48E-05	1.10E-06	1.01E-10
							Average	**3.50E-05**	**1.12E-06**	**1.02E-10**
							SD	**2.85E-07**	**2.74E-08**	**1.67E-12**

Table A.6 Test parameters and results of PPSS-01-09 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**m^3/s**	**(m)**	**(m/s)**	**(m^2)**
1500 Unload	10.34	7	0.05	0						
	10.34	7	0.05	20	24.00	2.40E-05	1.20E-06	3.59E-05	1.20E-06	1.07E-10
	10.34	7	0.05	40	23.00	2.30E-05	1.15E-06	3.53E-05	1.15E-06	1.04E-10
	10.34	7	0.05	60	23.00	2.30E-05	1.15E-06	3.53E-05	1.15E-06	1.04E-10
	10.34	7	0.05	80	23.00	2.30E-05	1.15E-06	3.53E-05	1.15E-06	1.04E-10
	10.34	7	0.05	100	23.00	2.30E-05	1.15E-06	3.53E-05	1.15E-06	1.04E-10
							Average	**3.54E-05**	**1.16E-06**	**1.05E-10**
							SD	**2.26E-07**	**2.24E-08**	**1.34E-12**
1000 Unload	6.89	7	0.05	0						
	6.89	7	0.05	20	26.00	2.60E-05	1.30E-06	3.68E-05	1.30E-06	1.13E-10
	6.89	7	0.05	40	25.00	2.50E-05	1.25E-06	3.63E-05	1.25E-06	1.10E-10
	6.89	7	0.05	60	25.00	2.50E-05	1.25E-06	3.63E-05	1.25E-06	1.10E-10
	6.89	7	0.05	80	25.00	2.50E-05	1.25E-06	3.63E-05	1.25E-06	1.10E-10
	6.89	7	0.05	100	25.00	2.50E-05	1.25E-06	3.63E-05	1.25E-06	1.10E-10
							Average	**3.64E-05**	**1.26E-06**	**1.11E-10**
							SD	**2.14E-07**	**2.24E-08**	**1.30E-12**

Table A.6 Test parameters and results of PPSS-01-09 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**m^3/s**	**(m)**	**(m/s)**	**(m^2)**
500 Unload	3.45	7	0.05	0						
	3.45	7	0.05	20	33.00	3.30E-05	1.65E-06	3.99E-05	1.65E-06	1.32E-10
	3.45	7	0.05	40	34.00	3.40E-05	1.70E-06	4.03E-05	1.70E-06	1.35E-10
	3.45	7	0.05	60	33.00	3.30E-05	1.65E-06	3.99E-05	1.65E-06	1.32E-10
	3.45	7	0.05	80	33.00	3.30E-05	1.65E-06	3.99E-05	1.65E-06	1.32E-10
	3.45	7	0.05	100	33.00	3.30E-05	1.65E-06	3.99E-05	1.65E-06	1.32E-10
							Average	**3.99E-05**	**1.66E-06**	**1.33E-10**
							SD	**1.78E-07**	**2.24E-08**	**1.19E-12**

Table A.7 Test parameters and results of PWSS-01-01.

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**m^3/s**	**(m)**	**(m/s)**	**(m^2)**
500 Load	3.45	6	0.04	0						
	3.45	6	0.04	10	26.00	2.60E-05	2.60E-06	1.16E-04	2.66E-05	1.11E-09
	3.45	6	0.04	20	26.00	2.60E-05	2.60E-06	1.16E-04	2.66E-05	1.11E-09
	3.45	6	0.04	30	24.00	2.40E-05	2.40E-06	1.13E-04	2.45E-05	1.05E-09
	3.45	6	0.04	40	26.00	2.60E-05	2.60E-06	1.16E-04	2.66E-05	1.11E-09
	3.45	6	0.04	50	26.00	2.60E-05	2.60E-06	1.16E-04	2.66E-05	1.11E-09
							Average	**1.15E-04**	**2.61E-05**	**1.10E-09**
							SD	**1.36E-06**	**9.14E-07**	**2.59E-11**
1000 Load	6.89	6	0.04	0						
	6.89	6	0.04	10	15.00	1.50E-05	1.50E-06	9.62E-05	1.53E-05	7.71E-10
	6.89	6	0.04	20	15.00	1.50E-05	1.50E-06	9.62E-05	1.53E-05	7.71E-10
	6.89	6	0.04	30	16.00	1.60E-05	1.60E-06	9.83E-05	1.63E-05	8.05E-10
	6.89	6	0.04	40	16.00	1.60E-05	1.60E-06	9.83E-05	1.63E-05	8.05E-10
	6.89	6	0.04	50	16.00	1.60E-05	1.60E-06	9.83E-05	1.63E-05	8.05E-10
							Average	**9.74E-05**	**1.59E-05**	**7.91E-10**
							SD	**1.15E-06**	**5.59E-07**	**1.86E-11**

Table A.7 Test parameters and results of PWSS-01-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**m^3/s**	**(m)**	**(m/s)**	**(m^2)**
1500 Load	10.34	6	0.04	0						
	10.34	6	0.04	20	14.50	1.45E-05	7.25E-07	7.55E-05	7.41E-06	4.75E-10
	10.34	6	0.04	40	12.50	1.25E-05	6.25E-07	7.18E-05	6.38E-06	4.30E-10
	10.34	6	0.04	60	11.50	1.15E-05	5.75E-07	6.99E-05	5.87E-06	4.07E-10
	10.34	6	0.04	80	12.00	1.20E-05	6.00E-07	7.09E-05	6.13E-06	4.19E-10
	10.34	6	0.04	100	2.00	2.00E-06	1.00E-07	3.90E-05	1.02E-06	1.27E-10
							Average	**6.54E-05**	**5.36E-06**	**3.71E-10**
							SD	**1.49E-05**	**2.50E-06**	**1.39E-10**
2000 Load	13.79	6	0.04	0						
	13.79	6	0.04	30	8.00	8.00E-06	2.67E-07	5.41E-05	2.72E-06	2.44E-10
	13.79	6	0.04	60	7.50	7.50E-06	2.50E-07	5.29E-05	2.55E-06	2.34E-10
	13.79	6	0.04	90	7.00	7.00E-06	2.33E-07	5.17E-05	2.38E-06	2.23E-10
	13.79	6	0.04	120	6.50	6.50E-06	2.17E-07	5.05E-05	2.21E-06	2.12E-10
	13.79	6	0.04	150	7.50	7.50E-06	2.50E-07	5.29E-05	2.55E-06	2.34E-10
							Average	**5.24E-05**	**2.49E-06**	**2.29E-10**
							SD	**1.38E-06**	**1.94E-07**	**1.20E-11**

Table A.7 Test parameters and results of PWSS-01-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**m^3/s**	**(m)**	**(m/s)**	**(m^2)**
2500 Load	17.24	6	0.04	0						
	17.24	6	0.04	60	6.80	6.80E-06	1.13E-07	4.07E-05	1.16E-06	1.38E-10
	17.24	6	0.04	120	6.30	6.30E-06	1.05E-07	3.96E-05	1.07E-06	1.31E-10
	17.24	6	0.04	180	5.90	5.90E-06	9.83E-08	3.88E-05	1.00E-06	1.25E-10
	17.24	6	0.04	240	5.50	5.50E-06	9.17E-08	3.79E-05	9.36E-07	1.20E-10
	17.24	6	0.04	300	5.30	5.30E-06	8.83E-08	3.74E-05	9.02E-07	1.17E-10
							Average	**3.89E-05**	**1.01E-06**	**1.26E-10**
							SD	**1.31E-06**	**1.03E-07**	**8.53E-12**
3000 Load	20.68	6	0.04	0						
	20.68	6	0.04	60	2.90	2.90E-06	4.83E-08	3.06E-05	4.94E-07	7.81E-11
	20.68	6	0.04	120	2.80	2.80E-06	4.67E-08	3.03E-05	4.77E-07	7.63E-11
	20.68	6	0.04	180	2.50	2.50E-06	4.17E-08	2.91E-05	4.26E-07	7.07E-11
	20.68	6	0.04	240	2.20	2.20E-06	3.67E-08	2.79E-05	3.75E-07	6.49E-11
	20.68	6	0.04	300	2.10	2.10E-06	3.50E-08	2.75E-05	3.57E-07	6.30E-11
							Average	**2.91E-05**	**4.26E-07**	**7.06E-11**
							SD	**1.38E-06**	**6.02E-08**	**6.68E-12**

Table A.7 Test parameters and results of PWSS-01-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**m^3/s**	**(m)**	**(m/s)**	**(m^2)**
2500 Unload	17.24	6	0.04	0						
	17.24	6	0.04	60	2.50	2.50E-06	4.17E-08	2.91E-05	4.26E-07	7.07E-11
	17.24	6	0.04	120	2.40	2.40E-06	4.00E-08	2.87E-05	4.09E-07	6.88E-11
	17.24	6	0.04	180	2.10	2.10E-06	3.50E-08	2.75E-05	3.57E-07	6.30E-11
	17.24	6	0.04	240	2.00	2.00E-06	3.33E-08	2.70E-05	3.40E-07	6.09E-11
	17.24	6	0.04	300	2.50	2.50E-06	4.17E-08	2.91E-05	4.26E-07	7.07E-11
							Average	**2.83E-05**	**3.92E-07**	**6.68E-11**
							SD	**9.77E-07**	**3.99E-08**	**4.58E-12**
2000 Unload	13.79	6	0.04	0						
	13.79	6	0.04	60	3.00	3.00E-06	5.00E-08	3.10E-05	5.11E-07	7.99E-11
	13.79	6	0.04	120	3.00	3.00E-06	5.00E-08	3.10E-05	5.11E-07	7.99E-11
	13.79	6	0.04	180	3.00	3.00E-06	5.00E-08	3.10E-05	5.11E-07	7.99E-11
	13.79	6	0.04	240	3.00	3.00E-06	5.00E-08	3.10E-05	5.11E-07	7.99E-11
	13.79	6	0.04	300	3.00	3.00E-06	5.00E-08	3.10E-05	5.11E-07	7.99E-11
							Average	**3.10E-05**	**5.11E-07**	**7.99E-11**
							SD	**0.00E+00**	**0.00E+00**	**0.00E+00**

Table A.7 Test parameters and results of PWSS-01-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
1500 Unload	10.34	6	0.04	0						
	10.34	6	0.04	60	4.00	4.00E-06	6.67E-08	3.41E-05	6.81E-07	9.67E-11
	10.34	6	0.04	120	4.00	4.00E-06	6.67E-08	3.41E-05	6.81E-07	9.67E-11
	10.34	6	0.04	180	4.00	4.00E-06	6.67E-08	3.41E-05	6.81E-07	9.67E-11
	10.34	6	0.04	240	3.00	3.00E-06	5.00E-08	3.10E-05	5.11E-07	7.99E-11
	10.34	6	0.04	300	3.00	3.00E-06	5.00E-08	3.10E-05	5.11E-07	7.99E-11
							Average	**3.28E-05**	**6.13E-07**	**9.00E-11**
							SD	**1.71E-06**	**9.32E-08**	**9.25E-12**
1000 Unload	6.89	6	0.04	0						
	6.89	6	0.04	60	6.00	6.00E-06	1.00E-07	3.90E-05	1.02E-06	1.27E-10
	6.89	6	0.04	120	6.00	6.00E-06	1.00E-07	3.90E-05	1.02E-06	1.27E-10
	6.89	6	0.04	180	5.50	5.50E-06	9.17E-08	3.79E-05	9.36E-07	1.20E-10
	6.89	6	0.04	240	6.00	6.00E-06	1.00E-07	3.90E-05	1.02E-06	1.27E-10
	6.89	6	0.04	300	7.50	7.50E-06	1.25E-07	4.20E-05	1.28E-06	1.47E-10
							Average	**3.94E-05**	**1.06E-06**	**1.29E-10**
							SD	**1.55E-06**	**1.29E-07**	**1.04E-11**

Table A.7 Test parameters and results of PWSS-01-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
500 Unload	3.45	6	0.04	0						
	3.45	6	0.04	60	9.20	9.20E-06	1.53E-07	4.50E-05	1.57E-06	1.69E-10
	3.45	6	0.04	120	8.00	8.00E-06	1.33E-07	4.29E-05	1.36E-06	1.54E-10
	3.45	6	0.04	180	8.00	8.00E-06	1.33E-07	4.29E-05	1.36E-06	1.54E-10
	3.45	6	0.04	240	8.00	8.00E-06	1.33E-07	4.29E-05	1.36E-06	1.54E-10
	3.45	6	0.04	300	8.00	8.00E-06	1.33E-07	4.29E-05	1.36E-06	1.54E-10
							Average	**4.33E-05**	**1.40E-06**	**1.57E-10**
							SD	**9.16E-07**	**9.14E-08**	**6.71E-12**

Table A.8 Test parameters and results of PWSS-01-05.

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
500 Load	3.45	7	0.05	0						
	3.45	7	0.05	10	30.00	3.00E-05	3.00E-06	4.41E-05	1.80E-06	1.62E-10
	3.45	7	0.05	20	34.00	3.40E-05	3.40E-06	4.60E-05	2.04E-06	1.76E-10
	3.45	7	0.05	30	31.00	3.10E-05	3.10E-06	4.46E-05	1.86E-06	1.66E-10
	3.45	7	0.05	40	32.00	3.20E-05	3.20E-06	4.50E-05	1.92E-06	1.69E-10
	3.45	7	0.05	50	28.00	2.80E-05	2.80E-06	4.31E-05	1.68E-06	1.55E-10
							Average	**4.45E-05**	**1.86E-06**	**1.65E-10**
							SD	**1.07E-06**	**1.34E-07**	**7.97E-12**
1000 Load	6.89	7	0.05	0						
	6.89	7	0.05	10	25.00	2.50E-05	2.50E-06	4.15E-05	1.50E-06	1.43E-10
	6.89	7	0.05	20	25.00	2.50E-05	2.50E-06	4.15E-05	1.50E-06	1.43E-10
	6.89	7	0.05	30	26.00	2.60E-05	2.60E-06	4.20E-05	1.56E-06	1.47E-10
	6.89	7	0.05	40	25.00	2.50E-05	2.50E-06	4.15E-05	1.50E-06	1.43E-10
	6.89	7	0.05	50	25.00	2.50E-05	2.50E-06	4.15E-05	1.50E-06	1.43E-10
							Average	**4.16E-05**	**1.51E-06**	**1.44E-10**
							SD	**2.44E-07**	**2.69E-08**	**1.70E-12**

Table A.8 Test parameters and results of PWSS-01-05 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
1500 Load	10.34	7	0.05	0						
	10.34	7	0.05	20	28.00	2.80E-05	1.40E-06	3.42E-05	8.41E-07	9.74E-11
	10.34	7	0.05	40	27.00	2.70E-05	1.35E-06	3.38E-05	8.11E-07	9.51E-11
	10.34	7	0.05	60	27.00	2.70E-05	1.35E-06	3.38E-05	8.11E-07	9.51E-11
	10.34	7	0.05	80	24.00	2.40E-05	1.20E-06	3.25E-05	7.20E-07	8.79E-11
	10.34	7	0.05	100	28.00	2.80E-05	1.40E-06	3.42E-05	8.41E-07	9.74E-11
							Average	**3.37E-05**	**8.05E-07**	**9.46E-11**
							SD	**7.05E-07**	**4.93E-08**	**3.91E-12**
2000 Load	13.79	7	0.05	0						
	13.79	7	0.05	20	15.00	1.50E-05	7.50E-07	2.78E-05	4.50E-07	6.43E-11
	13.79	7	0.05	40	15.00	1.50E-05	7.50E-07	2.78E-05	4.50E-07	6.43E-11
	13.79	7	0.05	60	14.00	1.40E-05	7.00E-07	2.71E-05	4.20E-07	6.14E-11
	13.79	7	0.05	80	13.00	1.30E-05	6.50E-07	2.65E-05	3.90E-07	5.84E-11
	13.79	7	0.05	100	14.00	1.40E-05	7.00E-07	2.71E-05	4.20E-07	6.14E-11
							Average	**2.73E-05**	**4.26E-07**	**6.19E-11**
							SD	**5.39E-07**	**2.51E-08**	**2.44E-12**

Table A.8 Test parameters and results of PWSS-01-05 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
2500 Load	17.24	7	0.05	0						
	17.24	7	0.05	20	8.50	8.50E-06	4.25E-07	2.30E-05	2.55E-07	4.40E-11
	17.24	7	0.05	40	8.00	8.00E-06	4.00E-07	2.25E-05	2.40E-07	4.23E-11
	17.24	7	0.05	60	7.50	7.50E-06	3.75E-07	2.20E-05	2.25E-07	4.05E-11
	17.24	7	0.05	80	7.00	7.00E-06	3.50E-07	2.15E-05	2.10E-07	3.87E-11
	17.24	7	0.05	100	7.00	7.00E-06	3.50E-07	2.15E-05	2.10E-07	3.87E-11
							Average	**2.21E-05**	**2.28E-07**	**4.08E-11**
							SD	**6.28E-07**	**1.96E-08**	**2.33E-12**
3000 Load	20.68	7	0.05	0						
	20.68	7	0.05	30	7.00	7.00E-06	2.33E-07	1.88E-05	1.40E-07	2.95E-11
	20.68	7	0.05	60	6.50	6.50E-06	2.17E-07	1.84E-05	1.30E-07	2.81E-11
	20.68	7	0.05	90	6.50	6.50E-06	2.17E-07	1.84E-05	1.30E-07	2.81E-11
	20.68	7	0.05	120	6.00	6.00E-06	2.00E-07	1.79E-05	1.20E-07	2.66E-11
	20.68	7	0.05	150	5.50	5.50E-06	1.83E-07	1.74E-05	1.10E-07	2.51E-11
							Average	**1.82E-05**	**1.26E-07**	**2.75E-11**
							SD	**5.54E-07**	**1.14E-08**	**1.67E-12**

Table A.8 Test parameters and results of PWSS-01-05 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
2500 Unload	17.24	7	0.05	0						
	17.24	7	0.05	30	7.00	7.00E-06	2.33E-07	1.88E-05	1.40E-07	2.95E-11
	17.24	7	0.05	60	7.00	7.00E-06	2.33E-07	1.88E-05	1.40E-07	2.95E-11
	17.24	7	0.05	90	6.00	6.00E-06	2.00E-07	1.79E-05	1.20E-07	2.66E-11
	17.24	7	0.05	120	6.00	6.00E-06	2.00E-07	1.79E-05	1.20E-07	2.66E-11
	17.24	7	0.05	150	6.00	6.00E-06	2.00E-07	1.79E-05	1.20E-07	2.66E-11
							Average	**1.83E-05**	**1.28E-07**	**2.78E-11**
							SD	**5.16E-07**	**1.10E-08**	**1.58E-12**
2000 Unload	13.79	7	0.05	0						
	13.79	7	0.05	30	6.50	6.50E-06	2.17E-07	1.84E-05	1.30E-07	2.81E-11
	13.79	7	0.05	60	7.00	7.00E-06	2.33E-07	1.88E-05	1.40E-07	2.95E-11
	13.79	7	0.05	90	6.00	6.00E-06	2.00E-07	1.79E-05	1.20E-07	2.66E-11
	13.79	7	0.05	120	5.50	5.50E-06	1.83E-07	1.74E-05	1.10E-07	2.51E-11
	13.79	7	0.05	150	7.00	7.00E-06	2.33E-07	1.88E-05	1.40E-07	2.95E-11
							Average	**1.82E-05**	**1.28E-07**	**2.78E-11**
							SD	**6.29E-07**	**1.30E-08**	**1.90E-12**

Table A.8 Test parameters and results of PWSS-01-05 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**m^3/s**	**(m)**	**(m/s)**	**(m^2)**
1500 Unload	10.34	7	0.05	0						
	10.34	7	0.05	30	8.00	8.00E-06	2.67E-07	1.97E-05	1.60E-07	3.23E-11
	10.34	7	0.05	60	7.50	7.50E-06	2.50E-07	1.93E-05	1.50E-07	3.09E-11
	10.34	7	0.05	90	7.00	7.00E-06	2.33E-07	1.88E-05	1.40E-07	2.95E-11
	10.34	7	0.05	120	7.00	7.00E-06	2.33E-07	1.88E-05	1.40E-07	2.95E-11
	10.34	7	0.05	150	6.50	6.50E-06	2.17E-07	1.84E-05	1.30E-07	2.81E-11
							Average	**1.90E-05**	**1.44E-07**	**3.01E-11**
							SD	**4.99E-07**	**1.14E-08**	**1.58E-12**
1000 Unload	6.89	7	0.05	0						
	6.89	7	0.05	30	12.00	1.20E-05	4.00E-07	2.25E-05	2.40E-07	4.23E-11
	6.89	7	0.05	60	12.00	1.20E-05	4.00E-07	2.25E-05	2.40E-07	4.23E-11
	6.89	7	0.05	90	12.00	1.20E-05	4.00E-07	2.25E-05	2.40E-07	4.23E-11
	6.89	7	0.05	120	12.00	1.20E-05	4.00E-07	2.25E-05	2.40E-07	4.23E-11
	6.89	7	0.05	150	12.00	1.20E-05	4.00E-07	2.25E-05	2.40E-07	4.23E-11
							Average	**2.25E-05**	**2.40E-07**	**4.23E-11**
							SD	**0.00E+00**	**0.00E+00**	**0.00E+00**

Table A.8 Test parameters and results of PWSS-01-05 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
500 Unload	3.45	7	0.05	0						
	3.45	7	0.05	30	23.00	2.30E-05	7.67E-07	2.80E-05	4.60E-07	6.52E-11
	3.45	7	0.05	60	22.00	2.20E-05	7.33E-07	2.76E-05	4.40E-07	6.33E-11
	3.45	7	0.05	90	22.00	2.20E-05	7.33E-07	2.76E-05	4.40E-07	6.33E-11
	3.45	7	0.05	120	22.00	2.20E-05	7.33E-07	2.76E-05	4.40E-07	6.33E-11
	3.45	7	0.05	150	24.00	2.40E-05	8.00E-07	2.84E-05	4.80E-07	6.71E-11
							Average	**2.78E-05**	**4.52E-07**	**6.45E-11**
							SD	**3.63E-07**	**1.79E-08**	**1.69E-12**

Table A.9 Test parameters and results of PWSS-01-06.

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
500 Load	3.45	7	0.05	0						
	3.45	7	0.05	10	9.50	9.50E-06	9.50E-07	2.93E-05	4.59E-07	7.16E-11
	3.45	7	0.05	20	10.00	1.00E-05	1.00E-06	2.98E-05	4.83E-07	7.40E-11
	3.45	7	0.05	30	8.00	8.00E-06	8.00E-07	2.77E-05	3.87E-07	6.38E-11
	3.45	7	0.05	40	8.50	8.50E-06	8.50E-07	2.82E-05	4.11E-07	6.64E-11
	3.45	7	0.05	50	8.50	8.50E-06	8.50E-07	2.82E-05	4.11E-07	6.64E-11
	3.45	7	0.05	60	9.00	9.00E-06	9.00E-07	2.88E-05	4.35E-07	6.90E-11
	3.45	7	0.05	70	8.00	8.00E-06	8.00E-07	2.77E-05	3.87E-07	6.38E-11
	3.45	7	0.05	80	8.00	8.00E-06	8.00E-07	2.77E-05	3.87E-07	6.38E-11
							Average	**2.84E-05**	**4.20E-07**	**6.74E-11**
							SD	**8.09E-07**	**3.64E-08**	**3.86E-12**

Table A.9 Test parameters and results of PWSS-01-06 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**m^3/s**	**(m)**	**(m/s)**	**(m^2)**
1000 Load	6.89	7	0.05	0						
	6.89	7	0.05	20	6.00	6.00E-06	3.00E-07	2.00E-05	1.45E-07	3.32E-11
	6.89	7	0.05	40	5.50	5.50E-06	2.75E-07	1.94E-05	1.33E-07	3.13E-11
	6.89	7	0.05	60	4.60	4.60E-06	2.30E-07	1.83E-05	1.11E-07	2.78E-11
	6.89	7	0.05	80	5.00	5.00E-06	2.50E-07	1.88E-05	1.21E-07	2.94E-11
	6.89	7	0.05	100	4.70	4.70E-06	2.35E-07	1.84E-05	1.14E-07	2.82E-11
	6.89	7	0.05	120	4.70	4.70E-06	2.35E-07	1.84E-05	1.14E-07	2.82E-11
	6.89	7	0.05	140	4.50	4.50E-06	2.25E-07	1.81E-05	1.09E-07	2.74E-11
	6.89	7	0.05	160	4.50	4.50E-06	2.25E-07	1.81E-05	1.09E-07	2.74E-11
							Average	**1.87E-05**	**1.19E-07**	**2.91E-11**
							SD	**6.62E-07**	**1.31E-08**	**2.10E-12**
1500 Load	10.34	7	0.05	0						
	10.34	7	0.05	60	1.40	1.40E-06	2.33E-08	8.52E-06	1.13E-08	6.05E-12
	10.34	7	0.05	120	1.50	1.50E-06	2.50E-08	8.72E-06	1.21E-08	6.33E-12
	10.34	7	0.05	180	1.10	1.10E-06	1.83E-08	7.86E-06	8.86E-09	5.15E-12
	10.34	7	0.05	240	1.00	1.00E-06	1.67E-08	7.61E-06	8.05E-09	4.83E-12
	10.34	7	0.05	300	1.00	1.00E-06	1.67E-08	7.61E-06	8.05E-09	4.83E-12
							Average	**8.06E-06**	**9.67E-09**	**5.44E-12**
							SD	**5.19E-07**	**1.89E-09**	**7.05E-13**

Table A.9 Test parameters and results of PWSS-01-06 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
2000 Load	13.79	7	0.05	0						
	13.79	7	0.05	60	0.70	7.00E-07	1.17E-08	6.76E-06	5.64E-09	3.81E-12
	13.79	7	0.05	120	0.60	6.00E-07	1.00E-08	6.42E-06	4.83E-09	3.44E-12
	13.79	7	0.05	180	0.50	5.00E-07	8.33E-09	6.04E-06	4.03E-09	3.04E-12
	13.79	7	0.05	240	0.50	5.00E-07	8.33E-09	6.04E-06	4.03E-09	3.04E-12
	13.79	7	0.05	300	0.40	4.00E-07	6.67E-09	5.61E-06	3.22E-09	2.62E-12
							Average	**6.18E-06**	**4.35E-09**	**3.19E-12**
							SD	**4.35E-07**	**9.18E-10**	**4.50E-13**
2500 Load	17.24	7	0.05	0						
	17.24	7	0.05	60	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
	17.24	7	0.05	120	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
	17.24	7	0.05	180	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
	17.24	7	0.05	240	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
	17.24	7	0.05	300	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
							Average	**5.10E-06**	**2.42E-09**	**2.17E-12**
							SD	**2.00E-20**	**2.83E-23**	**1.70E-26**

Table A.9 Test parameters and results of PWSS-01-06 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**m^3/s**	**(m)**	**(m/s)**	**(m^2)**
3000 Load	20.68	7	0.05	0						
	20.68	7	0.05	60	0.20	2.00E-07	3.33E-09	4.45E-06	1.61E-09	1.65E-12
	20.68	7	0.05	120	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
	20.68	7	0.05	180	0.20	2.00E-07	3.33E-09	4.45E-06	1.61E-09	1.65E-12
	20.68	7	0.05	240	0.20	2.00E-07	3.33E-09	4.45E-06	1.61E-09	1.65E-12
	20.68	7	0.05	300	0.20	2.00E-07	3.33E-09	4.45E-06	1.61E-09	1.65E-12
							Average	**4.58E-06**	**1.77E-09**	**1.75E-12**
							SD	**2.88E-07**	**3.60E-10**	**2.29E-13**
2500 Unload	17.24	7	0.05	0						
	17.24	7	0.05	60	0.20	2.00E-07	3.33E-09	4.45E-06	1.61E-09	1.65E-12
	17.24	7	0.05	120	0.20	2.00E-07	3.33E-09	4.45E-06	1.61E-09	1.65E-12
	17.24	7	0.05	180	0.20	2.00E-07	3.33E-09	4.45E-06	1.61E-09	1.65E-12
	17.24	7	0.05	240	0.20	2.00E-07	3.33E-09	4.45E-06	1.61E-09	1.65E-12
	17.24	7	0.05	300	0.20	2.00E-07	3.33E-09	4.45E-06	1.61E-09	1.65E-12
							Average	**4.45E-06**	**1.61E-09**	**1.65E-12**
							SD	**2.60E-20**	**2.83E-23**	**1.94E-26**

Table A.9 Test parameters and results of PWSS-01-06 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
2000 Unload	13.79	7	0.05	0						
	13.79	7	0.05	60	0.20	2.00E-07	3.33E-09	4.45E-06	1.61E-09	1.65E-12
	13.79	7	0.05	120	0.20	2.00E-07	3.33E-09	4.45E-06	1.61E-09	1.65E-12
	13.79	7	0.05	180	0.20	2.00E-07	3.33E-09	4.45E-06	1.61E-09	1.65E-12
	13.79	7	0.05	240	0.20	2.00E-07	3.33E-09	4.45E-06	1.61E-09	1.65E-12
	13.79	7	0.05	300	0.20	2.00E-07	3.33E-09	4.45E-06	1.61E-09	1.65E-12
							Average	**4.45E-06**	**1.61E-09**	**1.65E-12**
							SD	**2.60E-20**	**2.83E-23**	**1.94E-26**
1500 Unload	10.34	7	0.05	0						
	10.34	7	0.05	60	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
	10.34	7	0.05	120	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
	10.34	7	0.05	180	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
	10.34	7	0.05	240	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
	10.34	7	0.05	300	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
							Average	**5.10E-06**	**2.42E-09**	**2.17E-12**
							SD	**1.21E-20**	**1.74E-23**	**1.03E-26**

Table A.9 Test parameters and results of PWSS-01-06 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**m^3/s**	**(m)**	**(m/s)**	**(m^2)**
1000 Unload	6.89	7	0.05	0						
	6.89	7	0.05	60	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
	6.89	7	0.05	120	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
	6.89	7	0.05	180	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
	6.89	7	0.05	240	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
	6.89	7	0.05	300	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
							Average	**5.10E-06**	**2.42E-09**	**2.17E-12**
							SD	**1.21E-20**	**1.74E-23**	**1.03E-26**
500 Unload	3.45	7	0.05	0						
	3.45	7	0.05	60	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
	3.45	7	0.05	120	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
	3.45	7	0.05	180	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
	3.45	7	0.05	240	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
	3.45	7	0.05	300	0.30	3.00E-07	5.00E-09	5.10E-06	2.42E-09	2.17E-12
							Average	**5.10E-06**	**2.42E-09**	**2.17E-12**
							SD	**1.21E-20**	**1.74E-23**	**1.03E-26**

Table A.10 Test parameters and results of SKSS-01-01.

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**m^3/s**	**(m)**	**(m/s)**	**(m^2)**
500 Load	3.45	10	0.07	0						
	3.45	10	0.07	30	19.50	1.95E-05	6.50E-07	2.55E-05	3.10E-07	5.42E-11
	3.45	10	0.07	60	17.50	1.75E-05	5.83E-07	2.46E-05	2.79E-07	5.04E-11
	3.45	10	0.07	90	18.50	1.85E-05	6.17E-07	2.51E-05	2.94E-07	5.23E-11
	3.45	10	0.07	120	15.50	1.55E-05	5.17E-07	2.36E-05	2.47E-07	4.65E-11
							Average	**2.47E-05**	**2.83E-07**	**5.09E-11**
							SD	**8.04E-07**	**2.72E-08**	**3.29E-12**
1000 Load	6.89	10	0.07	0						
	6.89	10	0.07	60	12.30	1.23E-05	2.05E-07	1.74E-05	9.79E-08	2.51E-11
	6.89	10	0.07	120	10.30	1.03E-05	1.72E-07	1.64E-05	8.20E-08	2.23E-11
	6.89	10	0.07	180	10.40	1.04E-05	1.73E-07	1.64E-05	8.28E-08	2.25E-11
	6.89	10	0.07	240	10.00	1.00E-05	1.67E-07	1.62E-05	7.96E-08	2.19E-11
							Average	**1.66E-05**	**8.56E-08**	**2.29E-11**
							SD	**5.24E-07**	**8.33E-09**	**1.47E-12**

Table A.10 Test parameters and results of SKSS-01-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
1500 Load	10.34	10	0.07	0						
	10.34	10	0.07	60	4.50	4.50E-06	7.50E-08	1.24E-05	3.58E-08	1.28E-11
	10.34	10	0.07	120	4.50	4.50E-06	7.50E-08	1.24E-05	3.58E-08	1.28E-11
	10.34	10	0.07	180	4.00	4.00E-06	6.67E-08	1.19E-05	3.18E-08	1.19E-11
	10.34	10	0.07	240	3.70	3.70E-06	6.17E-08	1.16E-05	2.94E-08	1.13E-11
	10.34		0.00	300	3.60	3.60E-06	6.00E-08	1.15E-05	2.87E-08	1.11E-11
							Average	**1.20E-05**	**3.23E-08**	**1.20E-11**
							SD	**4.21E-07**	**3.40E-09**	**8.42E-13**
2000 Load	13.79	10	0.07	0						
	13.79	10	0.07	60	2.20	2.20E-06	3.67E-08	9.78E-06	1.75E-08	7.97E-12
	13.79	10	0.07	120	2.00	2.00E-06	3.33E-08	9.47E-06	1.59E-08	7.48E-12
	13.79	10	0.07	180	2.00	2.00E-06	3.33E-08	9.47E-06	1.59E-08	7.48E-12
	13.79	10	0.07	240	2.00	2.00E-06	3.33E-08	9.47E-06	1.59E-08	7.48E-12
	13.79	10	0.07	300	1.90	1.90E-06	3.17E-08	9.31E-06	1.51E-08	7.23E-12
							Average	**9.50E-06**	**1.61E-08**	**7.53E-12**
							SD	**1.70E-07**	**8.72E-10**	**2.70E-13**

Table A.10 Test parameters and results of SKSS-01-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
2500 Load	17.24	10	0.07	0						
	17.24	10	0.07	60	1.40	1.40E-06	2.33E-08	8.41E-06	1.11E-08	5.90E-12
	17.24	10	0.07	120	1.30	1.30E-06	2.17E-08	8.21E-06	1.03E-08	5.61E-12
	17.24	10	0.07	180	1.30	1.30E-06	2.17E-08	8.21E-06	1.03E-08	5.61E-12
	17.24	10	0.07	240	1.30	1.30E-06	2.17E-08	8.21E-06	1.03E-08	5.61E-12
	17.24	10	0.07	300	1.20	1.20E-06	2.00E-08	7.99E-06	9.55E-09	5.32E-12
							Average	**8.21E-06**	**1.03E-08**	**5.61E-12**
							SD	**1.49E-07**	**5.63E-10**	**2.04E-13**
3000 Load	20.68	10	0.07	0						
	20.68	10	0.07	60	0.20	2.00E-07	3.33E-09	4.40E-06	1.59E-09	1.61E-12
	20.68	10	0.07	120	0.10	1.00E-07	1.67E-09	3.49E-06	7.96E-10	1.02E-12
	20.68	10	0.07	180	0.10	1.00E-07	1.67E-09	3.49E-06	7.96E-10	1.02E-12
	20.68	10	0.07	240	0.10	1.00E-07	1.67E-09	3.49E-06	7.96E-10	1.02E-12
	20.68	10	0.07	300	0.10	1.00E-07	1.67E-09	3.49E-06	7.96E-10	1.02E-12
							Average	**3.67E-06**	**9.55E-10**	**1.13E-12**
							SD	**4.06E-07**	**3.56E-10**	**2.67E-13**

Table A.10 Test parameters and results of SKSS-01-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**m^3/s**	**(m)**	**(m/s)**	**(m^2)**
2500 Unload	17.24	10	0.07	0						
	17.24	10	0.07	60	0.10	1.00E-07	1.67E-09	3.49E-06	7.96E-10	1.02E-12
	17.24	10	0.07	120	0.10	1.00E-07	1.67E-09	3.49E-06	7.96E-10	1.02E-12
	17.24	10	0.07	180	0.10	1.00E-07	1.67E-09	3.49E-06	7.96E-10	1.02E-12
	17.24	10	0.07	240	0.10	1.00E-07	1.67E-09	3.49E-06	7.96E-10	1.02E-12
	17.24	10	0.07	300	0.10	1.00E-07	1.67E-09	3.49E-06	7.96E-10	1.02E-12
							Average	**3.49E-06**	**7.96E-10**	**1.02E-12**
							SD	**3.88E-20**	**2.66E-23**	**2.27E-26**
2000 Unload	13.79	10	0.07	0						
	13.79	10	0.07	60	0.10	1.00E-07	1.67E-09	3.49E-06	7.96E-10	1.02E-12
	13.79	10	0.07	120	0.10	1.00E-07	1.67E-09	3.49E-06	7.96E-10	1.02E-12
	13.79	10	0.07	180	0.10	1.00E-07	1.67E-09	3.49E-06	7.96E-10	1.02E-12
	13.79	10	0.07	240	0.10	1.00E-07	1.67E-09	3.49E-06	7.96E-10	1.02E-12
	13.79	10	0.07	300	0.10	1.00E-07	1.67E-09	3.49E-06	7.96E-10	1.02E-12
							Average	**3.49E-06**	**7.96E-10**	**1.02E-12**
							SD	**3.88E-20**	**2.66E-23**	**2.27E-26**

Table A.10 Test parameters and results of SKSS-01-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
1500 Unload	10.34	10	0.07	0						
	10.34	10	0.07	60	0.20	2.00E-07	3.33E-09	4.40E-06	1.59E-09	1.61E-12
	10.34	10	0.07	120	0.20	2.00E-07	3.33E-09	4.40E-06	1.59E-09	1.61E-12
	10.34	10	0.07	180	0.10	1.00E-07	1.67E-09	3.49E-06	7.96E-10	1.02E-12
	10.34	10	0.07	240	0.20	2.00E-07	3.33E-09	4.40E-06	1.59E-09	1.61E-12
	10.34	10	0.07	300	0.20	2.00E-07	3.33E-09	4.40E-06	1.59E-09	1.61E-12
							Average	**4.22E-06**	**1.43E-09**	**1.49E-12**
							SD	**4.06E-07**	**3.56E-10**	**2.67E-13**
1000 Unload	6.89	10	0.07	0						
	6.89	10	0.07	60	2.00	2.00E-06	3.33E-08	9.47E-06	1.59E-08	7.48E-12
	6.89	10	0.07	120	1.90	1.90E-06	3.17E-08	9.31E-06	1.51E-08	7.23E-12
	6.89	10	0.07	180	1.90	1.90E-06	3.17E-08	9.31E-06	1.51E-08	7.23E-12
	6.89	10	0.07	240	1.90	1.90E-06	3.17E-08	9.31E-06	1.51E-08	7.23E-12
	6.89	10	0.07	300	1.80	1.80E-06	3.00E-08	9.15E-06	1.43E-08	6.97E-12
							Average	**9.31E-06**	**1.51E-08**	**7.23E-12**
							SD	**1.16E-07**	**5.63E-10**	**1.79E-13**

Table A.10 Test parameters and results of SKSS-01-01 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	m^3/s	(m)	(m/s)	(m^2)
500 Unload	3.45	10	0.07	0						
	3.45	10	0.07	60	2.20	2.20E-06	3.67E-08	9.78E-06	1.75E-08	7.97E-12
	3.45	10	0.07	120	2.20	2.20E-06	3.67E-08	9.78E-06	1.75E-08	7.97E-12
	3.45	10	0.07	180	2.30	2.30E-06	3.83E-08	9.93E-06	1.83E-08	8.21E-12
	3.45	10	0.07	240	1.80	1.80E-06	3.00E-08	9.15E-06	1.43E-08	6.97E-12
	3.45	10	0.07	300	2.10	2.10E-06	3.50E-08	9.63E-06	1.67E-08	7.73E-12
							Average	**9.65E-06**	**1.69E-08**	**7.77E-12**
							SD	**3.01E-07**	**1.53E-09**	**4.78E-13**

Table A.11 Test parameters and results of SKSS-02-03.

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	(m^3/s)	(m)	(m/s)	(m^2)
500 Load	3.45	7	0.05	0						
	3.45	7	0.05	30	13.20	1.32E-05	4.40E-07	2.41E-05	3.10E-07	4.84E-11
	3.45	7	0.05	60	11.40	1.14E-05	3.80E-07	2.30E-05	2.67E-07	4.39E-11
	3.45	7	0.05	90	10.40	1.04E-05	3.47E-07	2.23E-05	2.44E-07	4.13E-11
	3.45	7	0.05	120	9.00	9.00E-06	3.00E-07	2.12E-05	2.11E-07	3.75E-11
							Average	**2.26E-05**	**2.58E-07**	**4.28E-11**
							SD	**1.21E-06**	**4.14E-08**	**4.58E-12**
1000 Load	6.89	7	0.05	0						
	6.89	7	0.05	30	3.50	3.50E-06	1.17E-07	1.55E-05	8.21E-08	2.00E-11
	6.89	7	0.05	60	3.40	3.40E-06	1.13E-07	1.53E-05	7.97E-08	1.96E-11
	6.89	7	0.05	90	3.10	3.10E-06	1.03E-07	1.49E-05	7.27E-08	1.84E-11
	6.89	7	0.05	120	2.80	2.80E-06	9.33E-08	1.44E-05	6.57E-08	1.72E-11
	6.89	7	0.05	150	2.70	2.70E-06	9.00E-08	1.42E-05	6.33E-08	1.68E-11
	6.89	7	0.05	180	2.50	2.50E-06	8.33E-08	1.38E-05	5.86E-08	1.60E-11
	6.89	7	0.05	210	2.40	2.40E-06	8.00E-08	1.37E-05	5.63E-08	1.55E-11
	6.89	7	0.05	240	2.20	2.20E-06	7.33E-08	1.33E-05	5.16E-08	1.47E-11
	6.89	7	0.05	270	2.20	2.20E-06	7.33E-08	1.33E-05	5.16E-08	1.47E-11
							Average	**1.43E-05**	**6.46E-08**	**1.70E-11**
							SD	**8.34E-07**	**1.14E-08**	**2.00E-12**

Table A.11 Test parameters and results of SKSS-02-03 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	(m^3/s)	(m)	(m/s)	(m^2)
1500 Load	10.34	7	0.05	0						
	10.34	7	0.05	30	0.70	7.00E-07	2.33E-08	9.05E-06	1.64E-08	6.83E-12
	10.34	7	0.05	60	0.60	6.00E-07	2.00E-08	8.60E-06	1.41E-08	6.16E-12
	10.34	7	0.05	90	0.50	5.00E-07	1.67E-08	8.09E-06	1.17E-08	5.46E-12
	10.34	7	0.05	120	0.50	5.00E-07	1.67E-08	8.09E-06	1.17E-08	5.46E-12
	10.34	7	0.05	150	0.50	5.00E-07	1.67E-08	8.09E-06	1.17E-08	5.46E-12
	10.34	7	0.05	180	0.40	4.00E-07	1.33E-08	7.51E-06	9.38E-09	4.70E-12
	10.34	7	0.05	210	0.40	4.00E-07	1.33E-08	7.51E-06	9.38E-09	4.70E-12
	10.34	7	0.05	240	0.40	4.00E-07	1.33E-08	7.51E-06	9.38E-09	4.70E-12
	10.34	7	0.05	270	0.30	3.00E-07	1.00E-08	6.83E-06	7.04E-09	3.88E-12
							Average	**7.92E-06**	**1.12E-08**	**5.26E-12**
							SD	**6.64E-07**	**2.82E-09**	**8.82E-13**

Table A.11 Test parameters and results of SKSS-02-03 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	(m^3/s)	(m)	(m/s)	(m^2)
2000 Load	13.79	7	0.05	0						
	13.79	7	0.05	60	0.30	3.00E-07	5.00E-09	5.42E-06	3.52E-09	2.45E-12
	13.79	7	0.05	120	0.10	1.00E-07	1.67E-09	3.76E-06	1.17E-09	1.18E-12
	13.79	7	0.05	180	0.10	1.00E-07	1.67E-09	3.76E-06	1.17E-09	1.18E-12
	13.79	7	0.05	240	0.10	1.00E-07	1.67E-09	3.76E-06	1.17E-09	1.18E-12
	13.79	7	0.05	360	0.20	2.00E-07	1.67E-09	3.76E-06	1.17E-09	1.18E-12
	13.79	7	0.05	480	0.15	1.50E-07	1.25E-09	3.41E-06	8.79E-10	9.71E-13
	13.79	7	0.05	600	0.15	1.50E-07	1.25E-09	3.41E-06	8.79E-10	9.71E-13
							Average	**3.90E-06**	**1.42E-09**	**1.30E-12**
							SD	**6.90E-07**	**9.34E-10**	**5.15E-13**
2500 Load	17.24	7	0.05	0						
	17.24	7	0.05	300	0.20	2.00E-07	6.67E-10	2.77E-06	4.69E-10	6.38E-13
	17.24	7	0.05	600	0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	17.24	7	0.05	900	0.15	1.50E-07	5.00E-10	2.51E-06	3.52E-10	5.27E-13
	17.24	7	0.05	1200	0.05	5.00E-08	1.67E-10	1.74E-06	1.17E-10	2.53E-13
							Average	**1.76E-06**	**2.35E-10**	**3.55E-13**
							SD	**1.25E-06**	**2.14E-10**	**2.87E-13**

Table A.11 Test parameters and results of SKSS-02-03 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	**MPa**	**psi**	**MPa**	**(s)**	**cm^3**	**m^3**	**(m^3/s)**	**(m)**	**(m/s)**	**(m^2)**
3000 Load	20.68	7	0.05	0						
	20.68	7	0.05	300	0.10	1.00E-07	3.33E-10	2.20E-06	2.35E-10	4.02E-13
	20.68	7	0.05	600	0.05	5.00E-08	1.67E-10	1.74E-06	1.17E-10	2.53E-13
	20.68	7	0.05	900	0.15	1.50E-07	5.00E-10	2.51E-06	3.52E-10	5.27E-13
							Average	**2.15E-06**	**2.35E-10**	**3.94E-13**
							SD	**3.88E-07**	**1.17E-10**	**1.37E-13**
2500 Unload	17.24	15	0.10	0						
	17.24	15	0.10	300	0.05	5.00E-08	1.67E-10	1.74E-06	1.17E-10	2.53E-13
	17.24	15	0.10	600	0.10	1.00E-07	3.33E-10	2.20E-06	2.35E-10	4.02E-13
							Average	**1.97E-06**	**1.76E-10**	**3.28E-13**
							SD	**3.20E-07**	**8.29E-11**	**1.05E-13**
2000 Unload	13.79	15	0.10	0						
	13.79	15	0.10	300	0.10	1.00E-07	3.33E-10	2.20E-06	2.35E-10	4.02E-13
	13.79	15	0.10	600	0.10	1.00E-07	3.33E-10	2.20E-06	2.35E-10	4.02E-13
							Average	**2.20E-06**	**2.35E-10**	**4.02E-13**
							SD	**3.86E-20**	**1.24E-23**	**1.41E-26**

Table A.11 Test parameters and results of SKSS-02-03 (Continued).

P_c		P_i		Time	Outflow		q	e_c	K	k
psi	MPa	psi	MPa	(s)	cm^3	m^3	(m^3/s)	(m)	(m/s)	(m^2)
1500 Unload	10.34	15	0.10	0						
	10.34	15	0.10	300	0.10	1.00E-07	3.33E-10	2.20E-06	2.35E-10	4.02E-13
	10.34	15	0.10	600	0.10	1.00E-07	3.33E-10	2.20E-06	2.35E-10	4.02E-13
							Average	**2.20E-06**	**2.35E-10**	**4.02E-13**
							SD	**3.86E-20**	**1.24E-23**	**1.41E-26**
1000 Unload	6.89	15	0.10	0						
	6.89	15	0.10	300	0.15	1.50E-07	5.00E-10	2.51E-06	3.52E-10	5.27E-13
	6.89	15	0.10	600	0.15	1.50E-07	5.00E-10	2.51E-06	3.52E-10	5.27E-13
							Average	**2.51E-06**	**3.52E-10**	**5.27E-13**
							SD	**2.55E-20**	**1.06E-23**	**1.06E-26**
500 Unload	3.45	15	0.10	0						
	3.45	15	0.10	300	1.60	1.60E-06	5.33E-09	5.54E-06	3.75E-09	2.55E-12
	3.45	15	0.10	600	1.50	1.50E-06	5.00E-09	5.42E-06	3.52E-09	2.45E-12
							Average	**5.48E-06**	**3.64E-09**	**2.50E-12**
							SD	**8.33E-08**	**1.66E-10**	**7.60E-14**

APPENDIX B

RESULT FROM FALLING HEAD FLOW TEST UNDER NORMAL STRESSES

Table B.1 Test parameters and results of PKSS-F-01.

STRESS		TIME	HEAD	e	K_j
(psi)	(MPa)	(s)	(m)	(m)	(m/s)
50	0.34	0	1.0950		
	0.34	60	1.0100	2.27E-14	3.75E-22
	0.34	120	0.9320	2.26E-14	3.71E-22
	0.34	180	0.8620	2.19E-14	3.50E-22
	0.34	240	0.7950	2.27E-14	3.76E-22
	0.34	300	0.7340	2.24E-14	3.66E-22
			Average	**2.25E-14**	**3.68E-22**
			SD	**3.24E-16**	**1.06E-23**
100	0.69	0	1.1050		
	0.69	60	1.0670	9.82E-15	7.03E-23
	0.69	120	1.0300	9.91E-15	7.15E-23
	0.69	180	0.9950	9.70E-15	6.87E-23
	0.69	240	0.9600	1.01E-14	7.37E-23
	0.69	300	0.9250	1.04E-14	7.92E-23
			Average	**9.98E-15**	**7.27E-23**
			SD	**2.78E-16**	**4.09E-24**
150	1.03	0	1.1250		
	1.03	60	1.0800	1.15E-14	9.57E-23
	1.03	120	1.0670	3.40E-15	8.42E-24
	1.03	180	1.0530	3.71E-15	1.00E-23
	1.03	240	1.0410	3.22E-15	7.55E-24
	1.03	300	1.0280	3.53E-15	9.07E-24
			Average	**5.06E-15**	**2.62E-23**
			SD	**3.58E-15**	**3.89E-23**
200	1.38	0	1.0200		
	1.38	60	1.0140	1.66E-15	2.00E-24
	1.38	120	1.0090	1.39E-15	1.40E-24
	1.38	180	1.0050	1.11E-15	9.06E-25
	1.38	240	1.0010	1.12E-15	9.14E-25
	1.38	300	0.9970	1.12E-15	9.21E-25
			Average	**1.28E-15**	**1.23E-24**
			SD	**2.40E-16**	**4.80E-25**

Table B.1 Test parameters and results of PKSS-F-01 (Continued).

STRESS		TIME	HEAD	e	K_j
(psi)	**(MPa)**	**(s)**	**(m)**	**(m)**	**(m/s)**
250	1.72	0	0.9880		
	1.72	60	0.9860	5.69E-16	2.36E-25
	1.72	120	0.9840	5.70E-16	2.37E-25
	1.72	180	0.9820	5.71E-16	2.38E-25
	1.72	240	0.9800	5.72E-16	2.39E-25
	1.72	300	0.9780	5.73E-16	2.40E-25
			Average	**5.71E-16**	**2.38E-25**
			SD	**1.84E-18**	**1.53E-27**
300	2.07	0	0.9760		
	2.07	60	0.9750	2.88E-16	6.04E-26
	2.07	120	0.9740	2.88E-16	6.05E-26
	2.07	180	0.9730	2.88E-16	6.06E-26
	2.07	240	0.9720	2.89E-16	6.07E-26
	2.07	300	0.9710	2.89E-16	6.09E-26
			Average	**2.88E-16**	**6.06E-26**
			SD	**4.68E-19**	**1.97E-28**
250	1.72	0	0.9700		
	1.72	60	0.9690	2.90E-16	6.11E-26
	1.72	120	0.9680	2.90E-16	6.12E-26
	1.72	180	0.9670	2.90E-16	6.14E-26
	1.72	240	0.9660	2.90E-16	6.15E-26
	1.72	300	0.9650	2.91E-16	6.16E-26
			Average	**2.90E-16**	**6.14E-26**
			SD	**4.74E-19**	**2.01E-28**
200	1.38	0	0.9640		
	1.38	60	0.9630	2.91E-16	6.19E-26
	1.38	120	0.9620	2.92E-16	6.20E-26
	1.38	180	0.9610	2.92E-16	6.21E-26
	1.38	240	0.9600	2.92E-16	6.23E-26
	1.38	300	0.9590	2.93E-16	6.24E-26
			Average	**2.92E-16**	**6.21E-26**
			SD	**4.80E-19**	**2.04E-28**

Table B.1 Test parameters and results of PKSS-F-01 (Continued).

STRESS		TIME	HEAD	e	K_j
(psi)	(MPa)	(s)	(m)	(m)	(m/s)
150	1.03	0	0.9600		
	1.03	60	0.9590	2.93E-16	6.24E-26
	1.03	120	0.9580	2.93E-16	6.25E-26
	1.03	180	0.9570	2.93E-16	6.27E-26
	1.03	240	0.9560	2.93E-16	6.28E-26
	1.03	300	0.9550	2.94E-16	6.29E-26
			Average	**2.93E-16**	**6.27E-26**
			SD	**4.84E-19**	**2.07E-28**
100	0.69	0	0.9530		
	0.69	60	0.9520	2.95E-16	6.33E-26
	0.69	120	0.9510	2.95E-16	6.34E-26
	0.69	180	0.9500	2.95E-16	6.36E-26
	0.69	240	0.9490	2.96E-16	6.37E-26
	0.69	300	0.9480	2.96E-16	6.38E-26
			Average	**2.95E-16**	**6.36E-26**
			SD	**4.91E-19**	**2.12E-28**
50	0.34	0	0.9470		
	0.34	60	0.9460	2.97E-16	6.41E-26
	0.34	120	0.9450	2.97E-16	6.43E-26
	0.34	180	0.9440	2.97E-16	6.44E-26
	0.34	240	0.9430	2.97E-16	6.45E-26
	0.34	300	0.9420	2.98E-16	6.47E-26
			Average	**2.97E-16**	**6.44E-26**
			SD	**4.97E-19**	**2.16E-28**

Table B.2 Test parameters and results of PKSS-F-02.

STRESS		TIME	HEAD	e	K_j
(psi)	(MPa)	(s)	(m)	(m)	(m/s)
50	0.34	0	1.0500		
	0.34	60	1.0050	1.23E-14	1.10E-22
	0.34	120	0.9600	1.29E-14	1.21E-22
	0.34	180	0.9170	1.29E-14	1.21E-22
	0.34	240	0.8770	1.25E-14	1.14E-22
	0.34	300	0.8380	1.28E-14	1.19E-22
			Average	**1.27E-14**	**1.17E-22**
			SD	**2.48E-16**	**4.55E-24**
100	0.69	0	1.1300		
	0.69	60	1.1180	3.00E-15	6.55E-24
	0.69	120	1.1060	3.03E-15	6.69E-24
	0.69	180	1.0950	2.81E-15	5.74E-24
	0.69	240	1.0830	3.09E-15	6.98E-24
	0.69	300	1.0730	2.60E-15	4.94E-24
			Average	**2.91E-15**	**6.18E-24**
			SD	**2.00E-16**	**8.29E-25**
150	1.03	0	1.1300		
	1.03	60	1.1260	9.95E-16	7.22E-25
	1.03	120	1.1220	9.99E-16	7.27E-25
	1.03	180	1.1180	1.00E-15	7.33E-25
	1.03	240	1.1150	7.54E-16	4.15E-25
	1.03	300	1.1110	1.01E-15	7.42E-25
			Average	**9.52E-16**	**6.68E-25**
			SD	**1.11E-16**	**1.42E-25**
200	1.38	0	1.1500		
	1.38	60	1.1470	7.33E-16	3.92E-25
	1.38	120	1.1450	4.90E-16	1.75E-25
	1.38	180	1.1430	4.91E-16	1.76E-25
	1.38	240	1.1410	4.92E-16	1.76E-25
	1.38	300	1.1390	4.92E-16	1.77E-25
			Average	**5.40E-16**	**2.19E-25**
			SD	**1.08E-16**	**9.66E-26**

Table B.2 Test parameters and results of PKSS-F-02 (Continued).

STRESS		TIME	HEAD	e	K_j
(psi)	(MPa)	(s)	(m)	(m)	(m/s)
250	1.72	0	1.1400		
	1.72	60	1.1390	2.46E-16	4.42E-26
	1.72	120	1.1380	2.47E-16	4.43E-26
	1.72	180	1.1370	2.47E-16	4.44E-26
	1.72	240	1.1360	2.47E-16	4.45E-26
	1.72	300	1.1350	2.47E-16	4.46E-26
			Average	**2.47E-16**	**4.44E-26**
			SD	**3.43E-19**	**1.23E-28**
300	2.07	0	1.1500		
	2.07	60	1.1496	9.76E-17	6.95E-27
	2.07	120	1.1492	9.77E-17	6.96E-27
	2.07	180	1.1488	9.77E-17	6.96E-27
	2.07	240	1.1484	9.77E-17	6.97E-27
	2.07	300	1.1480	9.78E-17	6.97E-27
			Average	**9.77E-17**	**6.96E-27**
			SD	**5.38E-20**	**7.66E-30**
250	1.72	0	1.1700		
	1.72	60	1.1696	9.60E-17	6.72E-27
	1.72	120	1.1692	9.60E-17	6.72E-27
	1.72	180	1.1688	9.60E-17	6.73E-27
	1.72	240	1.1684	9.61E-17	6.73E-27
	1.72	300	1.1680	9.61E-17	6.73E-27
			Average	**9.60E-17**	**6.73E-27**
			SD	**5.20E-20**	**7.28E-30**
200	1.38	0	1.1800		
	1.38	60	1.1794	1.43E-16	1.49E-26
	1.38	120	1.1788	1.43E-16	1.49E-26
	1.38	180	1.1782	1.43E-16	1.49E-26
	1.38	240	1.1776	1.43E-16	1.49E-26
	1.38	300	1.1770	1.43E-16	1.49E-26
			Average	**1.43E-16**	**1.49E-26**
			SD	**1.15E-19**	**2.40E-29**

Table B.2 Test parameters and results of PKSS-F-02 (Continued).

STRESS		**TIME**	**HEAD**	**e**	**K_j**
(psi)	**(MPa)**	**(s)**	**(m)**	**(m)**	**(m/s)**
150	1.03	0	1.1800		
	1.03	60	1.1794	1.43E-16	1.49E-26
	1.03	120	1.1788	1.43E-16	1.49E-26
	1.03	180	1.1782	1.43E-16	1.49E-26
	1.03	240	1.1776	1.43E-16	1.49E-26
	1.03	300	1.1770	1.43E-16	1.49E-26
			Average	**1.43E-16**	**1.49E-26**
			SD	**1.15E-19**	**2.40E-29**
100	0.69	0	1.1700		
	0.69	60	1.1694	1.44E-16	1.51E-26
	0.69	120	1.1688	1.44E-16	1.51E-26
	0.69	180	1.1682	1.44E-16	1.51E-26
	0.69	240	1.1676	1.44E-16	1.52E-26
	0.69	300	1.1670	1.44E-16	1.52E-26
			Average	**1.44E-16**	**1.51E-26**
			SD	**1.17E-19**	**2.46E-29**
50	0.34	0	1.1670		
	0.34	60	1.1664	1.44E-16	1.52E-26
	0.34	120	1.1658	1.44E-16	1.52E-26
	0.34	180	1.1652	1.44E-16	1.52E-26
	0.34	240	1.1646	1.45E-16	1.52E-26
	0.34	300	1.1640	1.45E-16	1.53E-26
			Average	**1.44E-16**	**1.52E-26**
			SD	**1.18E-19**	**2.48E-29**

Table B.3 Test parameters and results of PPSS-F-01.

STRESS		TIME	HEAD	e	K_j
(psi)	**(MPa)**	**(s)**	**(m)**	**(m)**	**(m/s)**
50	0.34	0	2.4350		
	0.34	60	1.9900	5.66E-14	2.34E-21
	0.34	120	1.5400	7.20E-14	3.77E-21
	0.34	180	1.0800	9.96E-14	7.23E-21
	0.34	240	0.6300	1.51E-13	1.67E-20
	0.34	300	0.1700	3.68E-13	9.86E-20
			Average	**1.49E-13**	**2.57E-20**
			SD	**1.27E-13**	**4.11E-20**
100	0.69	0	1.5250		
	0.69	60	1.2400	5.81E-14	2.46E-21
	0.69	120	0.9550	7.33E-14	3.92E-21
	0.69	180	0.6700	9.95E-14	7.22E-21
	0.69	240	0.3850	1.56E-13	1.76E-20
	0.69	300	0.1000	3.78E-13	1.04E-19
			Average	**1.53E-13**	**2.71E-20**
			SD	**1.31E-13**	**4.36E-20**
150	1.03	0	1.1500		
	1.03	60	0.9730	4.69E-14	1.60E-21
	1.03	120	0.7980	5.57E-14	2.26E-21
	1.03	180	0.6230	6.95E-14	3.52E-21
	1.03	240	0.4530	8.94E-14	5.83E-21
	1.03	300	0.2880	1.27E-13	1.18E-20
			Average	**7.77E-14**	**5.00E-21**
			SD	**3.19E-14**	**4.12E-21**
200	1.38	0	1.1900		
	1.38	60	1.0850	2.59E-14	4.90E-22
	1.38	120	0.9900	2.57E-14	4.82E-22
	1.38	180	0.9020	2.61E-14	4.98E-22
	1.38	240	0.8250	2.50E-14	4.57E-22
	1.38	300	0.7500	2.68E-14	5.22E-22
			Average	**2.59E-14**	**4.90E-22**
			SD	**6.21E-16**	**2.34E-23**

Table B.3 Test parameters and results of PPSS-F-01 (Continued).

STRESS		TIME	HEAD	e	K_j
(psi)	(MPa)	(s)	(m)	(m)	(m/s)
250	1.72	0	1.1400		
	1.72	60	1.0700	1.78E-14	2.31E-22
	1.72	120	1.0050	1.76E-14	2.26E-22
	1.72	180	0.9450	1.73E-14	2.18E-22
	1.72	240	0.8850	1.84E-14	2.47E-22
	1.72	300	0.8350	1.63E-14	1.94E-22
			Average	**1.75E-14**	**2.23E-22**
			SD	**7.67E-16**	**1.94E-23**
300	2.07	0	1.1300		
	2.07	60	1.0800	1.27E-14	1.18E-22
	2.07	120	1.0300	1.33E-14	1.29E-22
	2.07	180	0.9850	1.25E-14	1.15E-22
	2.07	240	0.9400	1.31E-14	1.26E-22
	2.07	300	0.9000	1.22E-14	1.09E-22
			Average	**1.28E-14**	**1.19E-22**
			SD	**4.44E-16**	**8.27E-24**
250	1.72	0	1.1400		
	1.72	60	1.0880	1.31E-14	1.25E-22
	1.72	120	1.0400	1.27E-14	1.17E-22
	1.72	180	0.9900	1.38E-14	1.39E-22
	1.72	240	0.9480	1.22E-14	1.08E-22
	1.72	300	0.9000	1.46E-14	1.55E-22
			Average	**1.33E-14**	**1.29E-22**
			SD	**9.55E-16**	**1.87E-23**
200	1.38	0	1.1200		
	1.38	60	1.0650	1.41E-14	1.46E-22
	1.38	120	1.0150	1.35E-14	1.33E-22
	1.38	180	0.9650	1.42E-14	1.47E-22
	1.38	240	0.9220	1.28E-14	1.19E-22
	1.38	300	0.8750	1.47E-14	1.57E-22
			Average	**1.39E-14**	**1.40E-22**
			SD	**7.29E-16**	**1.46E-23**

Table B.3 Test parameters and results of PPSS-F-01 (Continued).

STRESS		TIME	HEAD	e	K_j
(psi)	(MPa)	(s)	(m)	(m)	(m/s)
150	1.03	0	1.1400		
	1.03	60	1.0780	1.57E-14	1.80E-22
	1.03	120	1.0200	1.55E-14	1.76E-22
	1.03	180	0.9700	1.41E-14	1.45E-22
	1.03	240	0.9150	1.64E-14	1.96E-22
	1.03	300	0.8650	1.58E-14	1.81E-22
			Average	**1.55E-14**	**1.76E-22**
			SD	**8.42E-16**	**1.86E-23**
100	0.69	0	1.1800		
	0.69	60	1.1000	1.97E-14	2.83E-22
	0.69	120	1.0300	1.85E-14	2.48E-22
	0.69	180	0.9600	1.98E-14	2.85E-22
	0.69	240	0.9000	1.81E-14	2.39E-22
	0.69	300	1.0420	-4.11E-14	1.23E-21
			Average	**6.98E-15**	**4.58E-22**
			SD	**2.69E-14**	**4.34E-22**
50	0.34	0	1.2000		
	0.34	60	1.0800	2.96E-14	6.38E-22
	0.34	120	0.9750	2.87E-14	6.01E-22
	0.34	180	0.8800	2.88E-14	6.04E-22
	0.34	240	0.7950	2.85E-14	5.93E-22
	0.34	300	0.7150	2.98E-14	6.46E-22
			Average	**2.91E-14**	**6.16E-22**
			SD	**5.64E-16**	**2.40E-23**

Table B.4 Test parameters and results of PPSS-F-02.

STRESS		TIME	HEAD	e	K_j
(psi)	(MPa)	(s)	(m)	(m)	(m/s)
50	0.34	0	1.0800		
	0.34	60	0.9950	2.30E-14	3.86E-22
	0.34	120	0.9180	2.26E-14	3.73E-22
	0.34	180	0.8500	2.16E-14	3.40E-22
	0.34	240	0.7850	2.23E-14	3.64E-22
	0.34	300	0.7200	2.43E-14	4.29E-22
			Average	**2.28E-14**	**3.78E-22**
			SD	**9.83E-16**	**3.29E-23**
100	0.69	0	1.0700		
	0.69	60	1.0180	1.40E-14	1.43E-22
	0.69	120	0.9680	1.41E-14	1.46E-22
	0.69	180	0.9240	1.31E-14	1.24E-22
	0.69	240	0.8780	1.43E-14	1.50E-22
	0.69	300	0.8360	1.38E-14	1.38E-22
			Average	**1.39E-14**	**1.40E-22**
			SD	**4.92E-16**	**9.81E-24**
150	1.03	0	1.1000		
	1.03	60	1.0750	6.45E-15	3.04E-23
	1.03	120	1.0520	6.07E-15	2.69E-23
	1.03	180	1.0290	6.20E-15	2.81E-23
	1.03	240	1.0070	6.07E-15	2.68E-23
	1.03	300	0.9850	6.20E-15	2.80E-23
			Average	**6.20E-15**	**2.80E-23**
			SD	**1.57E-16**	**1.43E-24**

Table B.4 Test parameters and results of PPSS-F-02 (Continued).

STRESS		**TIME**	**HEAD**	**e**	**K_j**
(psi)	**(MPa)**	**(s)**	**(m)**	**(m)**	**(m/s)**
200	1.38	0	1.1200		
	1.38	60	1.1070	3.28E-15	7.83E-24
	1.38	120	1.0930	3.57E-15	9.30E-24
	1.38	180	1.0800	3.36E-15	8.22E-24
	1.38	240	1.0680	3.14E-15	7.17E-24
	1.38	300	1.0560	3.17E-15	7.33E-24
			Average	**3.30E-15**	**7.97E-24**
			SD	**1.74E-16**	**8.53E-25**
250	1.72	0	1.0350		
	1.72	60	1.0270	2.18E-15	3.46E-24
	1.72	120	1.0190	2.19E-15	3.51E-24
	1.72	180	1.0120	1.93E-15	2.73E-24
	1.72	240	1.0050	1.95E-15	2.77E-24
	1.72	300	0.9970	2.24E-15	3.67E-24
			Average	**2.10E-15**	**3.23E-24**
			SD	**1.47E-16**	**4.44E-25**
300	2.07	0	0.9800		
	2.07	60	0.9750	1.44E-15	1.50E-24
	2.07	120	0.9700	1.44E-15	1.52E-24
	2.07	180	0.9660	1.16E-15	9.81E-25
	2.07	240	0.9610	1.46E-15	1.55E-24
	2.07	300	0.9560	1.46E-15	1.56E-24
			Average	**1.39E-15**	**1.42E-24**
			SD	**1.30E-16**	**2.48E-25**

Table B.4 Test parameters and results of PPSS-F-02 (Continued).

STRESS		TIME	HEAD	e	K_j
(psi)	**(MPa)**	**(s)**	**(m)**	**(m)**	**(m/s)**
250	1.72	0	0.9450		
	1.72	60	0.9400	1.49E-15	1.62E-24
	1.72	120	0.9360	1.20E-15	1.04E-24
	1.72	180	0.9310	1.50E-15	1.65E-24
	1.72	240	0.9260	1.51E-15	1.67E-24
	1.72	300	0.9220	1.22E-15	1.08E-24
			Average	**1.38E-15**	**1.41E-24**
			SD	**1.62E-16**	**3.20E-25**
200	1.38	0	0.8950		
	1.38	60	0.8910	1.26E-15	1.15E-24
	1.38	120	0.8870	1.26E-15	1.16E-24
	1.38	180	0.8830	1.27E-15	1.17E-24
	1.38	240	0.8780	1.59E-15	1.85E-24
	1.38	300	0.8740	1.28E-15	1.20E-24
			Average	**1.33E-15**	**1.31E-24**
			SD	**1.46E-16**	**3.05E-25**
150	1.03	0	0.8520		
	1.03	60	0.8480	1.32E-15	1.27E-24
	1.03	120	0.8430	1.66E-15	2.01E-24
	1.03	180	0.8380	1.67E-15	2.03E-24
	1.03	240	0.8340	1.34E-15	1.32E-24
	1.03	300	0.8300	1.35E-15	1.33E-24
			Average	**1.47E-15**	**1.59E-24**
			SD	**1.79E-16**	**3.93E-25**

Table B.4 Test parameters and results of PPSS-F-02 (Continued).

STRESS		TIME	HEAD	e	K_j
(psi)	**(MPa)**	**(s)**	**(m)**	**(m)**	**(m/s)**
100	0.69	0	0.8120		
	0.69	60	0.8060	2.08E-15	3.16E-24
	0.69	120	0.8010	1.75E-15	2.22E-24
	0.69	180	0.7960	1.76E-15	2.25E-24
	0.69	240	0.7910	1.77E-15	2.28E-24
	0.69	300	0.7860	1.78E-15	2.31E-24
			Average	**1.83E-15**	**2.45E-24**
			SD	**1.43E-16**	**4.01E-25**
50	0.34	0	0.7640		
	0.34	60	0.7560	2.95E-15	6.36E-24
	0.34	120	0.7500	2.24E-15	3.65E-24
	0.34	180	0.7440	2.25E-15	3.71E-24
	0.34	240	0.7370	2.65E-15	5.13E-24
	0.34	300	0.7320	1.91E-15	2.66E-24
			Average	**2.40E-15**	**4.30E-24**
			SD	**4.06E-16**	**1.45E-24**

Table B.5 Test parameters and results of PWSS-F-01.

STRESS (psi)	STRESS (MPa)	TIME (s)	HEAD (m)	e (m)	K_j (m/s)
50	0.34	0	1.1000		
	0.34	60	1.0630	9.60E-15	6.72E-23
	0.34	120	1.0270	9.67E-15	6.82E-23
	0.34	180	0.9950	8.88E-15	5.76E-23
	0.34	240	0.9640	8.88E-15	5.75E-23
	0.34	300	0.9340	8.87E-15	5.74E-23
			Average	**9.18E-15**	**6.16E-23**
			SD	**4.15E-16**	**5.60E-24**
100	0.69	0	1.1100		
	0.69	60	1.0600	1.29E-14	1.22E-22
	0.69	120	1.0100	1.36E-14	1.34E-22
	0.69	180	0.9620	1.37E-14	1.36E-22
	0.69	240	0.9200	1.25E-14	1.14E-22
	0.69	300	0.8800	1.25E-14	1.14E-22
			Average	**1.30E-14**	**1.24E-22**
			SD	**5.60E-16**	**1.07E-23**
150	1.03	0	1.0900		
	1.03	60	1.0500	1.05E-14	8.03E-23
	1.03	120	1.0180	8.69E-15	5.50E-23
	1.03	180	0.9830	9.82E-15	7.03E-23
	1.03	240	0.9500	9.58E-15	6.70E-23
	1.03	300	0.9180	9.62E-15	6.74E-23
			Average	**9.64E-15**	**6.80E-23**
			SD	**6.47E-16**	**9.03E-24**
200	1.38	0	1.0200		
	1.38	60	0.9900	8.38E-15	5.12E-23
	1.38	120	0.9600	8.64E-15	5.44E-23
	1.38	180	0.9350	7.41E-15	4.00E-23
	1.38	240	0.9080	8.22E-15	4.93E-23
	1.38	300	0.8850	7.20E-15	3.78E-23
			Average	**7.97E-15**	**4.65E-23**
			SD	**6.30E-16**	**7.25E-24**

Table B.5 Test parameters and results of PWSS-F-01 (Continued).

STRESS		TIME	HEAD	e	K_j
(psi)	**(MPa)**	**(s)**	**(m)**	**(m)**	**(m/s)**
250	1.72	0	1.0100		
	1.72	60	0.9850	7.03E-15	3.61E-23
	1.72	120	0.9630	6.34E-15	2.93E-23
	1.72	180	0.9400	6.78E-15	3.36E-23
	1.72	240	0.9200	6.04E-15	2.66E-23
	1.72	300	0.9000	6.17E-15	2.77E-23
			Average	**6.47E-15**	**3.07E-23**
			SD	**4.22E-16**	**4.03E-24**
300	2.07	0	1.0800		
	2.07	60	1.0600	5.25E-15	2.01E-23
	2.07	120	1.0400	5.35E-15	2.08E-23
	2.07	180	1.0200	5.45E-15	2.17E-23
	2.07	240	1.0020	5.00E-15	1.82E-23
	2.07	300	0.9850	4.80E-15	1.68E-23
			Average	**5.17E-15**	**1.95E-23**
			SD	**2.65E-16**	**1.98E-24**
250	1.72	0	1.0500		
	1.72	60	1.0300	5.40E-15	2.12E-23
	1.72	120	1.0120	4.95E-15	1.79E-23
	1.72	180	0.9940	5.04E-15	1.85E-23
	1.72	240	0.9750	5.42E-15	2.14E-23
	1.72	300	0.9570	5.23E-15	1.99E-23
			Average	**5.21E-15**	**1.98E-23**
			SD	**2.10E-16**	**1.59E-24**
200	1.38	0	1.0800		
	1.38	60	1.0600	5.25E-15	2.01E-23
	1.38	120	1.0400	5.35E-15	2.08E-23
	1.38	180	1.0250	4.08E-15	1.21E-23
	1.38	240	1.0040	5.81E-15	2.46E-23
	1.38	300	0.9860	5.08E-15	1.88E-23
			Average	**5.11E-15**	**1.93E-23**
			SD	**6.39E-16**	**4.55E-24**

Table B.5 Test parameters and results of PWSS-F-01 (Continued).

STRESS		TIME	HEAD	e	K_j
(psi)	**(MPa)**	**(s)**	**(m)**	**(m)**	**(m/s)**
150	1.03	0	1.0200		
	1.03	60	1.0000	5.56E-15	2.25E-23
	1.03	120	0.9840	4.53E-15	1.49E-23
	1.03	180	0.9650	5.47E-15	2.18E-23
	1.03	240	0.9460	5.58E-15	2.27E-23
	1.03	300	0.9250	6.30E-15	2.89E-23
			Average	**5.49E-15**	**2.22E-23**
			SD	**6.32E-16**	**4.97E-24**
100	0.69	0	1.0100		
	0.69	60	0.9900	5.61E-15	2.30E-23
	0.69	120	0.9740	4.57E-15	1.52E-23
	0.69	180	0.9550	5.53E-15	2.23E-23
	0.69	240	0.9350	5.94E-15	2.57E-23
	0.69	300	0.9180	5.15E-15	1.93E-23
			Average	**5.36E-15**	**2.11E-23**
			SD	**5.23E-16**	**3.99E-24**
50	0.34	0	1.0000		
	0.34	60	0.9700	8.55E-15	5.33E-23
	0.34	120	0.9420	8.22E-15	4.93E-23
	0.34	180	0.9150	8.16E-15	4.86E-23
	0.34	240	0.8900	7.78E-15	4.41E-23
	0.34	300	0.8650	8.00E-15	4.66E-23
			Average	**8.14E-15**	**4.84E-23**
			SD	**2.86E-16**	**3.41E-24**

Table B.6 Test parameters and results of PWSS-F-02.

STRESS (psi)	STRESS (MPa)	TIME (s)	HEAD (m)	e (m)	K_j (m/s)
50	0.34	0	1.1250		
	0.34	60	1.0630	1.59E-14	1.85E-22
	0.34	120	1.0150	1.30E-14	1.23E-22
	0.34	180	0.9700	1.27E-14	1.18E-22
	0.34	240	0.9280	1.24E-14	1.13E-22
	0.34	300	0.8870	1.27E-14	1.17E-22
			Average	**1.33E-14**	**1.31E-22**
			SD	**1.45E-15**	**3.02E-23**
100	0.69	0	1.1250		
	0.69	60	1.0830	1.07E-14	8.32E-23
	0.69	120	1.0480	9.22E-15	6.20E-23
	0.69	180	1.0150	8.98E-15	5.88E-23
	0.69	240	0.9850	8.42E-15	5.17E-23
	0.69	300	0.9550	8.68E-15	5.50E-23
			Average	**9.20E-15**	**6.21E-23**
			SD	**8.82E-16**	**1.24E-23**
150	1.03	0	1.0050		
	1.03	60	0.9800	7.07E-15	3.64E-23
	1.03	120	0.9550	7.25E-15	3.84E-23
	1.03	180	0.9350	5.94E-15	2.57E-23
	1.03	240	0.9150	6.07E-15	2.69E-23
	1.03	300	0.8900	7.78E-15	4.41E-23
			Average	**6.82E-15**	**3.43E-23**
			SD	**7.91E-16**	**7.84E-24**
200	1.38	0	1.0750		
	1.38	60	1.0550	5.27E-15	2.03E-23
	1.38	120	1.0300	6.73E-15	3.30E-23
	1.38	180	1.0100	5.50E-15	2.21E-23
	1.38	240	0.9900	5.61E-15	2.30E-23
	1.38	300	0.9700	5.73E-15	2.39E-23
			Average	**5.77E-15**	**2.45E-23**
			SD	**5.63E-16**	**4.98E-24**

Table B.6 Test parameters and results of PWSS-F-02 (Continued).

STRESS		TIME	HEAD	e	K_j
(psi)	(MPa)	(s)	(m)	(m)	(m/s)
250	1.72	0	1.0550		
	1.72	60	1.0350	5.37E-15	2.10E-23
	1.72	120	1.0150	5.48E-15	2.19E-23
	1.72	180	0.9950	5.59E-15	2.28E-23
	1.72	240	0.9750	5.70E-15	2.37E-23
	1.72	300	0.9550	5.82E-15	2.47E-23
			Average	**5.59E-15**	**2.28E-23**
			SD	**1.76E-16**	**1.44E-24**
300	2.07	0	1.0100		
	2.07	60	0.9920	5.05E-15	1.86E-23
	2.07	120	0.9750	4.85E-15	1.72E-23
	2.07	180	0.9580	4.94E-15	1.78E-23
	2.07	240	0.9400	5.32E-15	2.07E-23
	2.07	300	0.9250	4.51E-15	1.49E-23
			Average	**4.93E-15**	**1.78E-23**
			SD	**2.95E-16**	**2.11E-24**
250	1.72	0	1.0250		
	1.72	60	1.0080	4.69E-15	1.61E-23
	1.72	120	0.9900	5.06E-15	1.86E-23
	1.72	180	0.9750	4.29E-15	1.34E-23
	1.72	240	0.9580	4.94E-15	1.78E-23
	1.72	300	0.9400	5.32E-15	2.07E-23
			Average	**4.86E-15**	**1.73E-23**
			SD	**3.93E-16**	**2.75E-24**
200	1.38	0	1.0350		
	1.38	60	1.0200	4.10E-15	1.22E-23
	1.38	120	1.0030	4.72E-15	1.62E-23
	1.38	180	0.9880	4.23E-15	1.30E-23
	1.38	240	0.9720	4.58E-15	1.53E-23
	1.38	300	0.9550	4.95E-15	1.79E-23
			Average	**4.52E-15**	**1.49E-23**
			SD	**3.51E-16**	**2.31E-24**

Table B.6 Test parameters and results of PWSS-F-02 (Continued).

STRESS (psi)	STRESS (MPa)	TIME (s)	HEAD (m)	e (m)	K_j (m/s)
150	1.03	0	1.0750		
	1.03	60	1.0600	3.94E-15	1.13E-23
	1.03	120	1.0430	4.54E-15	1.50E-23
	1.03	180	1.0280	4.07E-15	1.21E-23
	1.03	240	1.0120	4.40E-15	1.41E-23
	1.03	300	0.9970	4.19E-15	1.28E-23
			Average	**4.23E-15**	**1.31E-23**
			SD	**2.42E-16**	**1.50E-24**
100	0.69	0	1.0450		
	0.69	60	1.0300	4.06E-15	1.20E-23
	0.69	120	1.0150	4.12E-15	1.24E-23
	0.69	180	1.0000	4.18E-15	1.27E-23
	0.69	240	0.9850	4.24E-15	1.31E-23
	0.69	300	0.9700	4.31E-15	1.35E-23
			Average	**4.18E-15**	**1.28E-23**
			SD	**9.85E-17**	**6.01E-25**
50	0.34	0	1.0950		
	0.34	60	1.0800	3.87E-15	1.09E-23
	0.34	120	1.0650	3.93E-15	1.12E-23
	0.34	180	1.0450	5.32E-15	2.06E-23
	0.34	240	1.0150	8.18E-15	4.87E-23
	0.34	300	1.0020	3.62E-15	9.54E-24
			Average	**4.98E-15**	**2.02E-23**
			SD	**1.91E-15**	**1.65E-23**

Table B.7 Test parameters and results of SKSS-F-01.

STRESS		TIME	HEAD	e	K_j
(psi)	**(MPa)**	**(s)**	**(m)**	**(m)**	**(m/s)**
50	0.34	0	1.0450		
	0.34	60	0.8950	4.35E-14	1.38E-21
	0.34	120	0.7650	4.41E-14	1.41E-21
	0.34	180	0.6020	6.73E-14	3.30E-21
	0.34	240	0.4450	8.48E-14	5.25E-21
	0.34	300	0.2900	1.20E-13	1.05E-20
			Average	**7.20E-14**	**4.37E-21**
			SD	**3.20E-14**	**3.79E-21**
100	0.69	0	1.1000		
	0.69	60	0.9980	2.73E-14	5.44E-22
	0.69	120	0.9100	2.59E-14	4.89E-22
	0.69	180	0.8250	2.75E-14	5.52E-22
	0.69	240	0.7540	2.53E-14	4.65E-22
	0.69	300	0.6880	2.57E-14	4.82E-22
			Average	**2.63E-14**	**5.07E-22**
			SD	**1.01E-15**	**3.91E-23**
150	1.03	0	1.1300		
	1.03	60	1.0780	1.32E-14	1.27E-22
	1.03	120	1.0320	1.22E-14	1.09E-22
	1.03	180	0.9900	1.17E-14	9.92E-23
	1.03	240	0.9480	1.22E-14	1.08E-22
	1.03	300	0.9070	1.24E-14	1.12E-22
			Average	**1.23E-14**	**1.11E-22**
			SD	**5.66E-16**	**1.03E-23**
200	1.38	0	1.0800		
	1.38	60	1.0560	6.31E-15	2.90E-23
	1.38	120	1.0340	5.91E-15	2.55E-23
	1.38	180	1.0120	6.04E-15	2.66E-23
	1.38	240	0.9900	6.17E-15	2.77E-23
	1.38	300	0.9680	6.31E-15	2.90E-23
			Average	**6.15E-15**	**2.76E-23**
			SD	**1.74E-16**	**1.55E-24**

Table B.7 Test parameters and results of SKSS-F-01 (Continued).

STRESS		TIME	HEAD	e	K_j
(psi)	**(MPa)**	**(s)**	**(m)**	**(m)**	**(m/s)**
250	1.72	0	0.8640		
	1.72	60	0.8550	2.94E-15	6.30E-24
	1.72	120	0.8450	3.30E-15	7.95E-24
	1.72	180	0.8360	3.01E-15	6.59E-24
	1.72	240	0.8260	3.38E-15	8.32E-24
	1.72	300	0.8180	2.73E-15	5.44E-24
			Average	**3.07E-15**	**6.92E-24**
			SD	**2.67E-16**	**1.19E-24**
300	2.07	0	0.8860		
	2.07	60	0.8810	1.59E-15	1.84E-24
	2.07	120	0.8770	1.28E-15	1.19E-24
	2.07	180	0.8720	1.60E-15	1.88E-24
	2.07	240	0.8680	1.29E-15	1.21E-24
	2.07	300	0.8640	1.30E-15	1.23E-24
			Average	**1.41E-15**	**1.47E-24**
			SD	**1.69E-16**	**3.56E-25**
250	1.72	0	0.8350		
	1.72	60	0.8310	1.35E-15	1.32E-24
	1.72	120	0.8280	1.02E-15	7.51E-25
	1.72	180	0.8240	1.36E-15	1.35E-24
	1.72	240	0.8200	1.37E-15	1.36E-24
	1.72	300	0.8170	1.03E-15	7.72E-25
			Average	**1.22E-15**	**1.11E-24**
			SD	**1.84E-16**	**3.19E-25**
200	1.38	0	0.7980		
	1.38	60	0.7950	1.06E-15	8.15E-25
	1.38	120	0.7920	1.06E-15	8.21E-25
	1.38	180	0.7880	1.42E-15	1.47E-24
	1.38	240	0.7850	1.07E-15	8.36E-25
	1.38	300	0.7820	1.07E-15	8.42E-25
			Average	**1.14E-15**	**9.57E-25**
			SD	**1.59E-16**	**2.88E-25**

Table B.7 Test parameters and results of SKSS-F-01 (Continued).

STRESS (psi)	STRESS (MPa)	TIME (s)	HEAD (m)	e (m)	K_j (m/s)
150	1.03	0	0.9970		
	1.03	60	0.9930	1.13E-15	9.28E-25
	1.03	120	0.9880	1.42E-15	1.46E-24
	1.03	180	0.9840	1.14E-15	9.45E-25
	1.03	240	0.9800	1.14E-15	9.53E-25
	1.03	300	0.9760	1.15E-15	9.61E-25
			Average	**1.20E-15**	**1.05E-24**
			SD	**1.24E-16**	**2.31E-25**
100	0.69	0	0.9470		
	0.69	60	0.9430	1.19E-15	1.03E-24
	0.69	120	0.9380	1.49E-15	1.62E-24
	0.69	180	0.9340	1.20E-15	1.05E-24
	0.69	240	0.9290	1.51E-15	1.66E-24
	0.69	300	0.9250	1.21E-15	1.07E-24
			Average	**1.32E-15**	**1.29E-24**
			SD	**1.65E-16**	**3.24E-25**
50	0.34	0	0.9020		
	0.34	60	0.8970	1.56E-15	1.77E-24
	0.34	120	0.8920	1.57E-15	1.79E-24
	0.34	180	0.8880	1.26E-15	1.16E-24
	0.34	240	0.8830	1.58E-15	1.83E-24
	0.34	300	0.8780	1.59E-15	1.85E-24
			Average	**1.51E-15**	**1.68E-24**
			SD	**1.42E-16**	**2.94E-25**

Table B.8 Test parameters and results of SKSS-F-02.

STRESS		TIME	HEAD	e	K_j
(psi)	**(MPa)**	**(s)**	**(m)**	**(m)**	**(m/s)**
50	0.34	0	2.6350		
	0.34	60	2.1150	6.17E-14	2.78E-21
	0.34	120	1.5900	8.01E-14	4.68E-21
	0.34	180	1.0650	1.12E-13	9.23E-21
	0.34	240	0.5500	1.85E-13	2.51E-20
	0.34	300	0.0500	6.73E-13	3.30E-19
			Average	**2.23E-13**	**7.44E-20**
			SD	**2.56E-13**	**1.43E-19**
100	0.69	0	2.1300		
	0.69	60	1.6800	6.66E-14	3.24E-21
	0.69	120	1.3100	6.98E-14	3.55E-21
	0.69	180	0.8900	1.08E-13	8.58E-21
	0.69	240	0.4700	1.79E-13	2.34E-20
	0.69	300	0.0500	6.29E-13	2.88E-19
			Average	**2.11E-13**	**6.54E-20**
			SD	**2.38E-13**	**1.25E-19**
150	1.03	0	1.8450		
	1.03	60	1.4750	6.28E-14	2.88E-21
	1.03	120	1.1100	7.98E-14	4.64E-21
	1.03	180	0.7400	1.14E-13	9.44E-21
	1.03	240	0.3800	1.87E-13	2.55E-20
	1.03	300	0.0500	5.69E-13	2.36E-19
			Average	**2.03E-13**	**5.58E-20**
			SD	**2.10E-13**	**1.01E-19**
200	1.38	0	1.4700		
	1.38	60	1.1800	6.17E-14	2.77E-21
	1.38	120	0.9050	7.45E-14	4.04E-21
	1.38	180	0.6150	1.08E-13	8.57E-21
	1.38	240	0.3350	1.71E-13	2.12E-20
	1.38	300	0.0500	5.34E-13	2.08E-19
			Average	**1.90E-13**	**4.89E-20**
			SD	**1.97E-13**	**8.91E-20**

Table B.8 Test parameters and results of SKSS-F-02 (Continued).

STRESS		TIME	HEAD	e	K_j
(psi)	**(MPa)**	**(s)**	**(m)**	**(m)**	**(m/s)**
250	1.72	0	1.1650		
	1.72	60	0.9400	6.02E-14	2.65E-21
	1.72	120	0.7150	7.68E-14	4.30E-21
	1.72	180	0.4900	1.06E-13	8.20E-21
	1.72	240	0.2700	1.67E-13	2.04E-20
	1.72	300	0.0500	4.73E-13	1.63E-19
			Average	**1.77E-13**	**3.98E-20**
			SD	**1.71E-13**	**6.94E-20**
300	2.07	0	1.0500		
	2.07	60	0.8650	5.44E-14	2.16E-21
	2.07	120	0.6750	6.96E-14	3.53E-21
	2.07	180	0.4950	8.71E-14	5.53E-21
	2.07	240	0.3200	1.22E-13	1.09E-20
	2.07	300	0.1530	2.07E-13	3.13E-20
			Average	**1.08E-13**	**1.07E-20**
			SD	**6.09E-14**	**1.20E-20**
250	1.72	0	1.1100		
	1.72	60	0.9350	4.82E-14	1.69E-21
	1.72	120	0.7630	5.71E-14	2.37E-21
	1.72	180	0.5910	7.17E-14	3.75E-21
	1.72	240	0.4290	8.99E-14	5.90E-21
	1.72	300	0.2610	1.39E-13	1.42E-20
			Average	**8.13E-14**	**5.58E-21**
			SD	**3.62E-14**	**5.07E-21**
200	1.38	0	0.9900		
	1.38	60	0.8300	4.95E-14	1.78E-21
	1.38	120	0.6550	6.65E-14	3.22E-21
	1.38	180	0.4850	8.43E-14	5.19E-21
	1.38	240	0.3150	1.21E-13	1.07E-20
	1.38	300	0.1400	2.28E-13	3.78E-20
			Average	**1.10E-13**	**1.17E-20**
			SD	**7.10E-14**	**1.49E-20**

Table B.8 Test parameters and results of SKSS-F-02 (Continued).

STRESS		TIME	HEAD	e	K_j
(psi)	**(MPa)**	**(s)**	**(m)**	**(m)**	**(m/s)**
150	1.03	0	1.1400		
	1.03	60	0.9300	5.71E-14	2.38E-21
	1.03	120	0.7200	7.18E-14	3.76E-21
	1.03	180	0.5250	8.87E-14	5.73E-21
	1.03	240	0.3300	1.30E-13	1.24E-20
	1.03	300	0.1250	2.72E-13	5.41E-20
			Average	**1.24E-13**	**1.57E-20**
			SD	**8.74E-14**	**2.18E-20**
100	0.69	0	1.1400		
	0.69	60	0.9200	6.02E-14	2.64E-21
	0.69	120	0.7000	7.67E-14	4.29E-21
	0.69	180	0.4800	1.06E-13	8.18E-21
	0.69	240	0.2550	1.78E-13	2.30E-20
	0.69	300	0.0350	5.57E-13	2.27E-19
			Average	**1.96E-13**	**5.29E-20**
			SD	**2.07E-13**	**9.74E-20**
50	0.34	0	1.5250		
	0.34	60	1.2350	5.92E-14	2.56E-21
	0.34	120	0.9500	7.36E-14	3.95E-21
	0.34	180	0.6600	1.02E-13	7.62E-21
	0.34	240	0.3700	1.62E-13	1.92E-20
	0.34	300	0.0500	5.62E-13	2.30E-19
			Average	**1.92E-13**	**5.27E-20**
			SD	**2.11E-13**	**9.94E-20**

APPENDIX C

TECHNICAL PUBLICATION

TECHNICAL PUBLICATION

Akkrachattrarat, N., Suanprom, P., Buaboocha, J. and Fuenkajorn, K., 2009. **Flow testing of sandstone fractures under normal and shear stresses**, In Proceedings of the Second Thailand Symposium on Rock Mechanics (ThaiRock 2009), Jomtien Palm Beach Hotel & Resort, Chonburi, 12-13 March 2009, pp. 319 - 334.

Rock Mechanics, Fuenkajorn & Phien-wej (eds) © 2009. ISBN 978 974 533 624 7

Flow testing of sandstone fractures under normal and shear stresses

N. Akkrachattrarat, P. Suanprom, J. Buaboocha & K. Fuenkajorn
Geomechanics Research Unit, Suranaree University of Technology, Thailand

Keywords: Permeability, fracture, aperture, shear stress, deviatoric stress

ABSTRACTS: Flow tests have been performed to determine hydraulic conductivity of intact sandstone specimens under confining pressures and deviatoric stresses, and of tension-induced fractures under normal and shear stresses. The results indicate that the intact sandstone permeability decreases with increasing volumetric strain before dilation strength probably due to the closure of voids and micro-cracks, and increases with the specimen dilation after the dilation strength probably due to the initiation and propagation of cracks and fractures. The physical aperture e_p and hydraulic aperture e_h increase with shearing displacement, particularly under high normal stresses. The magnitudes of fracture permeability under no shear and under peak shear stress are similar. The K_p is about an order of magnitude greater than K_h, particularly in the residual shear region. Both tend to decrease exponentially with increasing normal stress. The difference between the permeability under residual shear stress and that under peak stress becomes larger under higher normal stresses. The fracture hydraulic conductivities exponentially decrease from 10000×10^{-6} m/s to 100×10^{-6} m/s as the normal stresses are increased from 0.35 MPa to 2.06 MPa. Under normal stress alone a permanent fracture closure is usually observed after unloading as evidenced by the permanent reduction of the measured flow rates.

1 INTRODUCTION

Groundwater in rock mass is one of the key factors governing the mechanical stability of slope embankments, underground mines and tunnels. The lack of proper understanding of the water pressure and flow characteristics in rock mass makes it difficult to predict the water inflow for underground mines and tunnels under complex hydro-geological environments. Unlike those in the soil mass, permeability of rock mass is path dependent, controlling mainly by the system of fracture as the permeability of the intact rocks is normally low. For undisturbed rock mass (before excavation) the joint characteristics (e.g., roughness, aperture, spacing and orientation) that dictate the amount and direction of water flow, can be adequately determined by means of in-situ measurements, and are sometimes assisted by numerical modeling. Slope or underground excavations disturb the surrounding rock, alter the stress states on the fracture planes, and often cause relative displacements of the rock fractures. In most cases the excavations usually increase the surrounding rock mass permeability, sometimes by several orders of magnitude.

It has been experimentally found that permeability of intact rocks is affected by the confining pressures (Iscan et al., 2006; Shangxian & Shangxu, 2006) and by deviatoric stresses (Ferfera et al., 1997; Oda, 2002; Pusch & Weber, 1998; Heiland, 2003; Zhou & Shao, 2006). The rock permeability generally decreases logarithmically with increasing the confining pressures. Under deviatoric stresses the rock permeability first decreases due to a reduction of pore spaces, and starts to increase due to the damage growth after the rock is dilated under differential stresses.

Fracture apertures and hydraulic conductivity are the main factors governing the rock mass permeability. Xiao et al. (1999), Pyrak-Noltea & Morrisa (2000), Niemi et al. (1997), Indraratna & Ranjith (2001) and Baghbanan & Jing (2008) conclude from their experimental results that fracture permeability exponentially decreases with increasing normal stresses. The apertures and permeability of rock fractures are also affected by the shearing displacement (Auradou et al., 2006). The flow testing results on fractures in granite and marble by Lee & Cho (2002) indicate that the fracture permeability increases by up to two orders of magnitude as the shearing displacement increases. This finding is supported by the results of numerical simulations by Son et al. (2004).

The objective of this study is to experimentally determine the hydraulic conductivity of fractures in sandstone specimens under normal and shear stresses. Constant head flow tests are conducted to obtain data basis on the permeability of intact sandstones under hydrostatic pressures and deviatoric stresses. The rock permeability is correlated with the volumetric strain before failure and with the volumetric dilation after failure. Falling head tests are performed to determine the permeability of tension-induced fractures under normal and shear stresses. The flow rates are monitored from before peak shear strength through residual shear strength. The fracture hydraulic conductivities calculated from the physical, mechanical and hydraulic apertures are compared. The joint normal and shear stiffness parameters are determined.

2 ROCK SAMPLES

The tested sandstones are from four sources: Phu Phan, Phra Wihan, Phu Kradung and Sao Kua formations (hereafter designated as PP, PW, PK and SK sandstones). They belong to the Khorat group and widely expose in the north and northeast of Thailand. X-ray diffraction analyses have been performed to determine their mineral compositions. Table 1 summarizes the results. These fine-grained quartz sandstones are selected for this study primarily because they have highly uniform texture, grain size and density.

3 FLOW TESTING ON INTACT SANDSTONES

3.1 Permeability of Intact Sandstones under Confining Pressures

Constant head flow tests have been performed to assess the effects of hydrostatic pressures and deviatoric stresses on the intact sandstone permeability. Figure 1 shows the laboratory arrangement of the constant head flow test under various confining pressures. The sandstone specimens have a nominal dimension of 5 cm in diameter and 10 cm long. A constant diameter water pump is used to inject water pressure of 0.14 MPa (20 psi) to bottom end of the specimen while the specimen is confined in a triaxial cell. The injected water pressure is controlled by using a regulating valve at the top of nitrogen gas tank. The constant confining pressures vary from 3.45 (500 psi), 6.90, 10.34, 13.79, 17.24 to 20.69 MPa (3000 psi). A

Rock Mechanics, Fuenkajorn & Phien-wej (eds) © 2009. ISBN 978 974 533 624 7

Table 1. Mineral compositions of tested sandstones obtained from X-ray diffraction.

Rocks	Density (g/cc)	Grain Size (mm)	Sorting	Mineral Compositions				
				Quartz (%)	Albite (%)	Kaolinite (%)	Feldspar (%)	Mica (%)
PW	2.35	1.5-2.0	well	99.47	-	0.53	-	-
PP	2.45	1.5-2.0	well	98.40	-	-	-	1.60
PK	2.63	0.1-1.5	moderate	48.80	46.10	5.10	-	-
SK	2.37	0.1-1.0	poorly	57.00	39.50	-	2.90	0.60

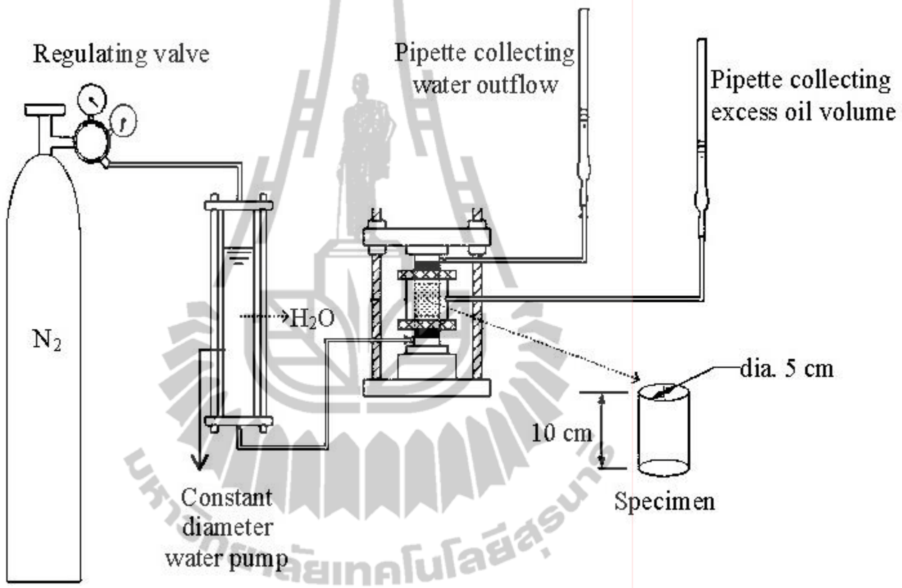


Figure 1. Laboratory arrangement for constant head flow tests.

high precision pipette collects the outflow of water at the top end of the specimen. The measured flow rates under each confining pressure are used to calculate the specimen permeability. The hydraulic conductivity (K) is calculated by assuming that the Darcy's law is valid (Indraratna & Ranjith, 2001):

$$K = 4q\mu / [\pi D^2(dp/dx)] \quad (1)$$

where q is water flow rate through the specimen (cm^2/s), μ is the dynamic viscosity of the water ($N{\cdot}s/cm^2$), D is the specimen diameter (cm^2), and dp/dx is the pressure gradient along the length of the specimen.

Figure 2 plots the hydraulic conductivity for eight PW sandstone specimens under confining pressures between 3.45 MPa and 20.7 MPa. The permeability decreases from about 100×10^{-9} m/s to about 50×10^{-9} m/s as the confining pressures increase from 3.45 MPa to 20.7 MPa. The flow rates measured during unloading show a permanent reduction of the rock permeability, suggesting that a permanent closure of the pore spaces has occurred.

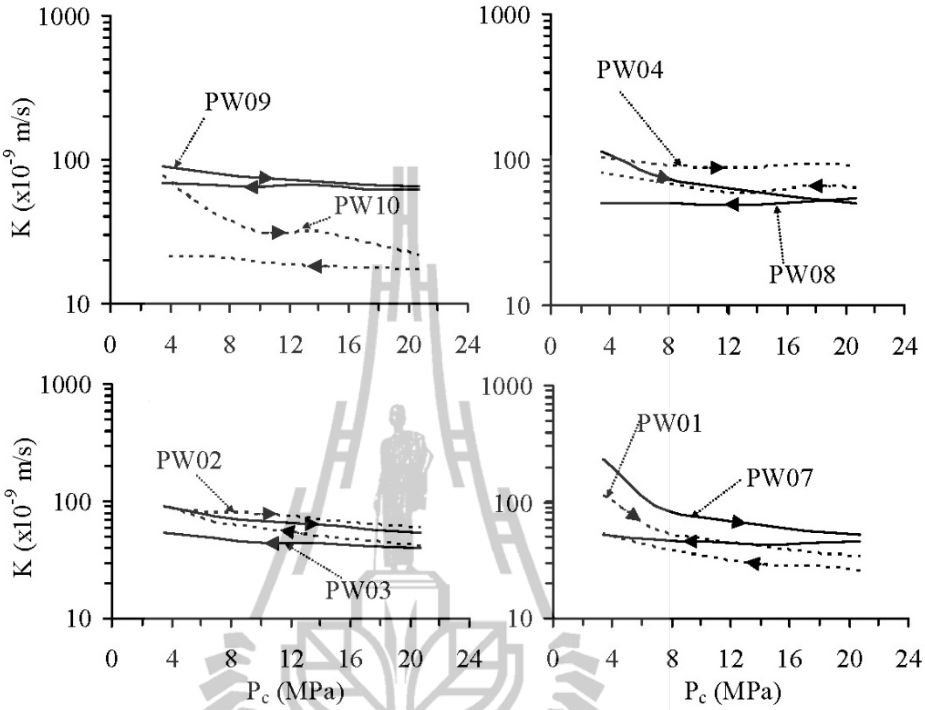


Figure 2. Hydraulic conductivity of eight PW sandstone specimens under hydrostatic stresses. Arrows indicate direction of loading and unloading.

3.2 Permeability of Intact Sandstones under Deviatoric Stresses

The laboratory arrangement for the flow testing of intact sandstone specimens under deviatoric stresses is similar to that of the testing under confining pressures. After the constant confining pressure is applied the axial stress is increased until failure occurs. The constant confining pressures varied from 1, 2, 3 to 6 MPa. The flow is measured every 6.9 MPa axial stress increment. The injected water pressure is maintained at 0.27 MPa (40 psi). A high precision pipette is used to collect the excess oil released from the triaxial cell by the specimen dilation. It will be used to calculate the volumetric strain (ε_V) of the specimen during loading:

$$\varepsilon_V = (V_O - V_S) / V_R \quad (2)$$

where V_O is the excess oil volume, V_S is the volume of oil displaced by loading platen, and V_R is the volume of rock specimen.

Figures 3 and 4 give the permeability results for PW and PP sandstone specimens as a function of volumetric strain (ε_V). They are compared with their corresponding stress-strain curves obtained under various confining pressures (σ_3). The hydraulic conductivity is calculated by using equation (1). Before dilation the permeability of PW sandstone decreases with increasing the deviatoric stress. This agrees with the experimental by Ferfera et al. (1997), Pusch & Weber (1998), Oda et al. (2002) and Heiland (2003). The PP sandstone permeability however tends to increase with the deviatoric stresses. This may be due to error

Rock Mechanics, Fuenkajorn & Phien-wej (eds) © 2009. ISBN 978 974 533 624 7

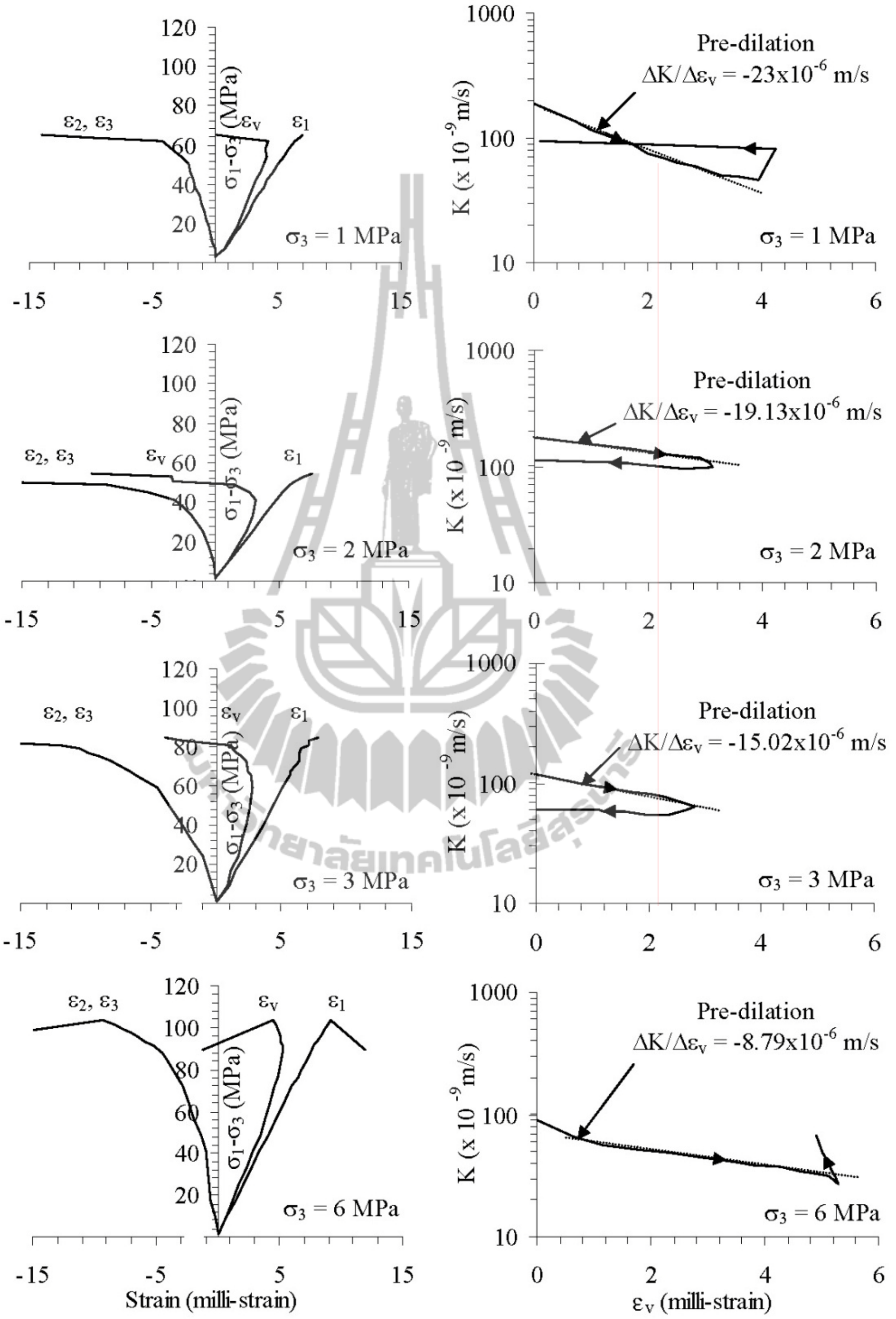


Figure 3. Permeability of PW sandstone specimens as a function of volumetric strain (ε_v) (right) and their corresponding stress-strain curves (left), for confining pressures (σ_3) from 1, 2, 3 to 6 MPa. Dotted lines represent curve fit for $\Delta K/\Delta\varepsilon_v$ ratio before failure.

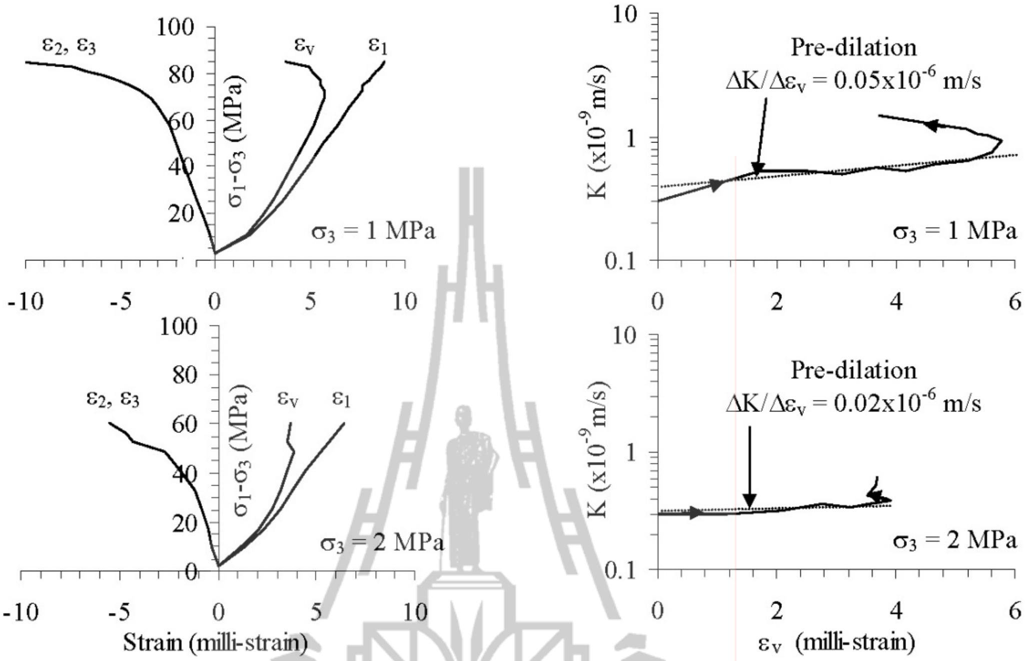


Figure 4. Permeability of PP sandstone specimens as a function of volumetric strain (ε_v) (right and their corresponding stress-strain curves (left), for confining pressures (σ_3) of and 2 MPa. Dotted lines represent curve fit for $\Delta K/\Delta\varepsilon_v$ ratio before failure.

of flow measurements. Table 2 summarizes the flow test result under deviatoric stresses. The permeability-to-volumetric strain ratio ($\Delta K/\Delta\varepsilon_V$) (before dilation strength) and the permeability-to-dilation strain ($\Delta K/\Delta\varepsilon_D$) ratio (after dilation strength) are calculated. Before dilation strength the permeability decreases with increasing volumetric strain. This is probably due to the contraction of the pore spaces in the specimen. Within this stage the $\Delta K/\Delta\varepsilon_V$ ratio decreases as increasing confining pressure. After dilation strength the rock permeability increases with specimen dilation probably because of the initiation and propagation of micro-cracks due to the applied axial stress approaching failure.

4 FLOW TESTING ON SANDSTONE FRACTURES UNDER SHEAR STRESSES

Falling head flow tests have been performed to determine the fracture permeability in sandstone specimens under shear stresses. Figure 5 shows the laboratory arrangement of the falling head flow test while the fracture is under normal and shear stresses. The maximum water head above the tested fracture is 1.23 m. The injection hole at the center of the lower block is 0.8 cm in diameter. The fractures are artificially made by applying a line load to induce a splitting tensile crack in 10×10×12 cm prismatic blocks of PW and PP sandstones (Figure 6). The fracture area is 10×10 cm. Their roughness is observed and classified by comparing with a reference profiles given by Barton (joint roughness coefficient – JRC, Barton, 1973). The constant normal stresses are 0.69, 1.38, 2.76, 3.45 and 4.14. MPa. The shear stress is applied while the shear displacement and head drop are monitored for every 0.5 mm shear displacement. The maximum shear displacement is 10 mm. The (physical) fracture aperture is measured to the nearest 0.01 mm before and after normal and shear stress application. The fracture dilations are also monitored during the shear test.

Rock Mechanics, Fuenkajorn & Phien-wej (eds) © 2009. ISBN 978 974 533 624 7

Table 2. Results of flow testing under deviatoric stresses.

	Sample No.	P_c (MPa)	E (GPa)	ν	Dilation Strength (MPa)	Ultimate Strength (MPa)	Pre-failure	Post-failure
							$\Delta k/\Delta\varepsilon_v$ ($\times 10^{-6}$ m/s)	$\Delta k/\Delta\varepsilon_d$ ($\times 10^{-6}$ m/s)
PW	PWSS-01	1	9.31	0.23	42	65	-23.00	-3.15
	PWSS-02	2	9.14	0.25	37	55	-19.13	-3.82
	PWSS-03	3	8.52	0.33	55	88	-15.02	-4.41
	PWSS-04	6	11.98	0.29	64	103	-8.79	-100
Mean±SD					49±12	78±25		
PP	PPSS-01	1	7.89	0.31	69	85	0.05	-0.21
	PPSS-02	2	8.66	0.31	49	60	0.02	-0.21
Mean±SD					59±10	72±13		

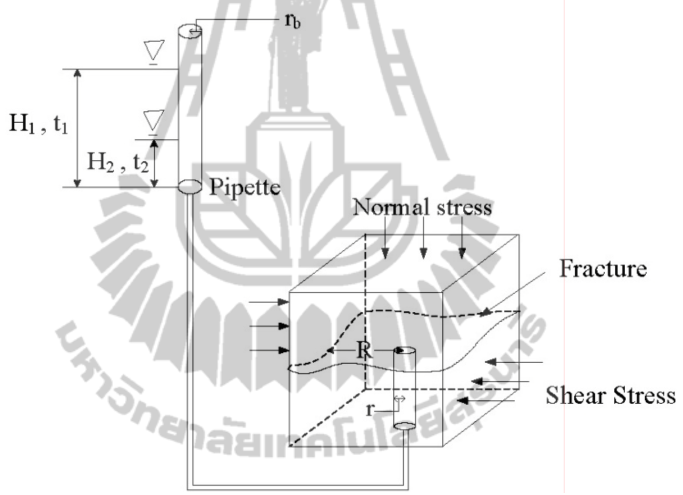


Figure 5. Laboratory arrangement for falling head test under normal and shear stresses.

The physical, mechanical and hydraulic apertures are used to calculate the hydraulic conductivity of the tested fractures. The physical aperture (e_p) is obtained from the actual measurements of the fractures before and during normal and shear stress applications. The measurement points are at the four corners of the shear box. The physical aperture at each shear displacement is an average from the four measurements. The mechanical aperture (e_m) in mm is calculated by (Barton & Bakhtar, 1983 and Bandis et al., 1983, 1985):

$$e_m = [JRC/5] / [0.2(\sigma_c/JCS) - 0.1] \quad (3)$$

where σ_c and JCS are the uniaxial compressive strength and joint compressive strength of the rock in MPa. Here σ_c and JCS are assumed to be equal.

The equivalent hydraulic aperture (e_h) for radial flow is calculated by (Maini, 1971):

$$e_h = [[\ln(H_1 / H_2)r_b^2 \ln(R / r)6\mu] / [(t_2 - t_1)\gamma]]^{1/3} \quad (4)$$

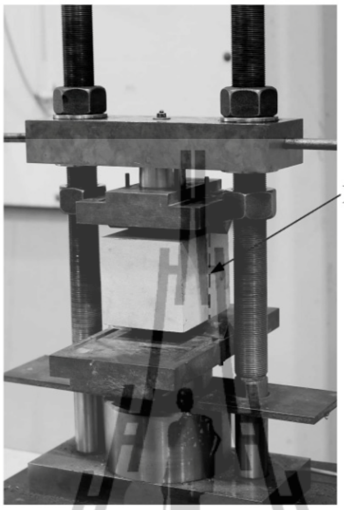


Figure 6. A 10×10×12 cm block of PW sandstone is line-loaded to induce tensile fracture in the mid-length of the block.

where γ is the unit weight of water (N/m^2), μ is the dynamic viscosity ($N \cdot s/m^2$), H_1 and H_2 are the water heads at t_1 and t_2, r_b is the pipette radius (m), R is the radius of flow path (m), and r is the radius of the radius injection hole (m).

The fracture permeability is calculated by (Zeigler, 1976):

$$K = \gamma e^2 / 12\mu \quad (5)$$

where K represents hydraulic conductivity between smooth and parallel plates and e is the parallel plate aperture. It is assumed here that the flow is isotropic across the fracture plane, and that the intact rock is impermeable. From section 3 the intact PW sandstone permeability is about 0.1×10^{-6} m/s which is very low compared to the fracture permeability. The other sandstone permeability is less than 0.0001×10^{-6} m/s (measurement limit).

Here the fracture conductivity is calculated for three types of fracture apertures: e_p, e_m and e_h, and differentiated by different symbols as K_p – physical, K_m – mechanical, and K_h – hydraulic conductivities.

The measured JRC values range from 11, 13 to 15, which are classified as rough and undulating; bedding and tectonic joints; and relief joints, respectively. From equation (3) the equivalent mechanical apertures for the above JRC values are 220, 260 and 300 micro-meters.

The fracture hydraulic conductivities are calculated for the three aperture measurements and plotted as a function of shear displacement (u) for normal stresses of 0.69, 2.75 and 4.14 MPa in Figures 7 and 8 for PW and PP sandstones. They are also compared with their corresponding shear stress-shear displacement diagram. Since the shear stresses after the peak value remain relatively consistent through 10 mm of displacement, up to 3 mm shear displacement is plotted in the figures.

Rock Mechanics, Fuenkajorn & Phien-wej (eds) © 2009. ISBN 978 974 533 624 7

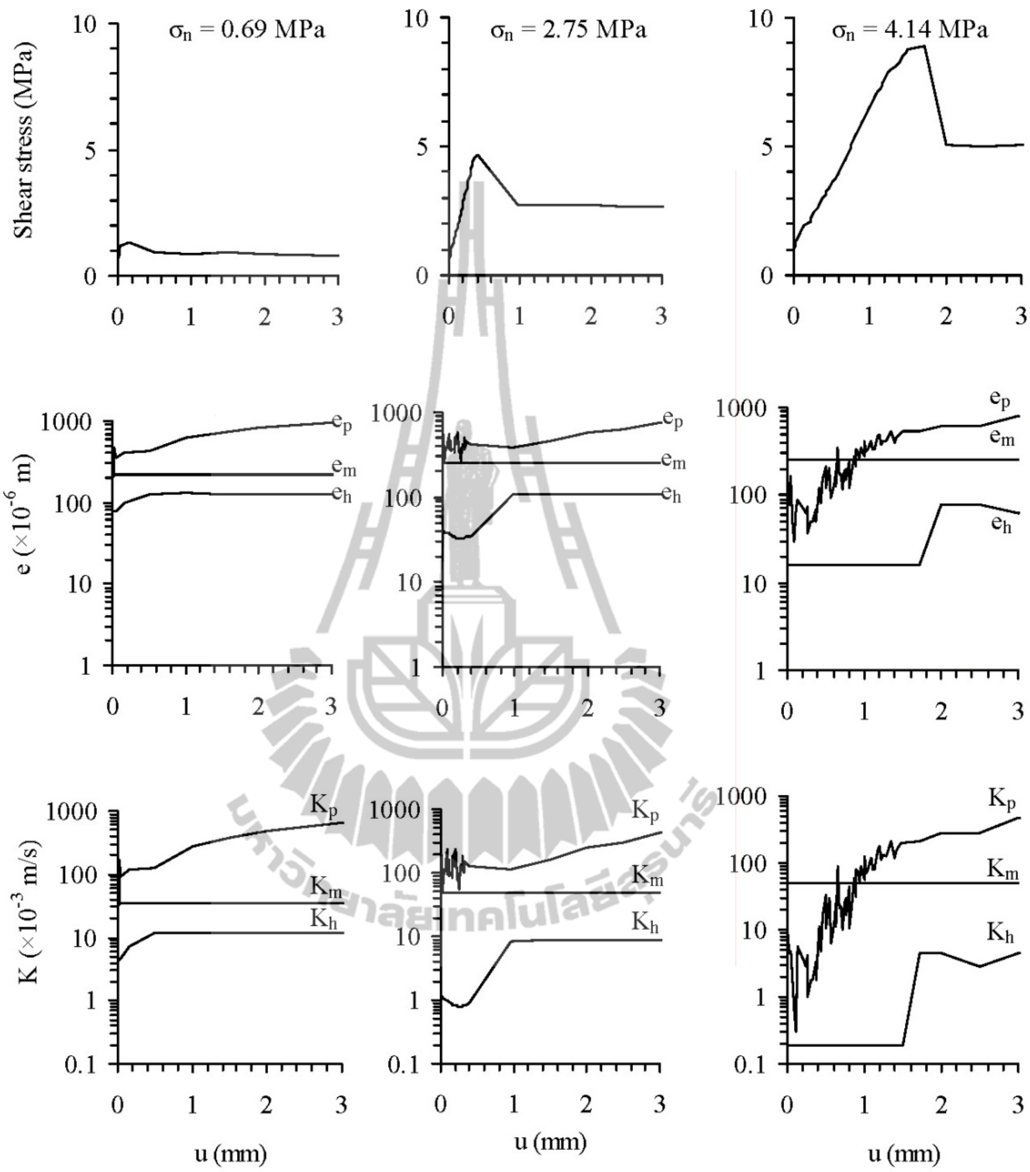


Figure 7. Shear stress, fracture aperture and hydraulic conductivity as a function of shear displacement (u) for PW sandstone fractures under normal stresses of 0.69 MPa (left), 2.75 MPa (middle) and 4.14 MPa (right).

Observations of pre– and post–test fracture areas suggest that no significant change has occurred in terms of fracture roughness. Even though some portion of fracture is sheared off the JRC's remain roughly the same. This is primarily because the applied normal stresses are relatively low. The mechanical aperture, e_m before, during and after shearing therefore remains constant during the shearing process. As a result the hydraulic conductivity K_m calculated from e_m is independent of the shearing displacement. An example of the post–test fracture for PW sandstone is shown in Figure 9.

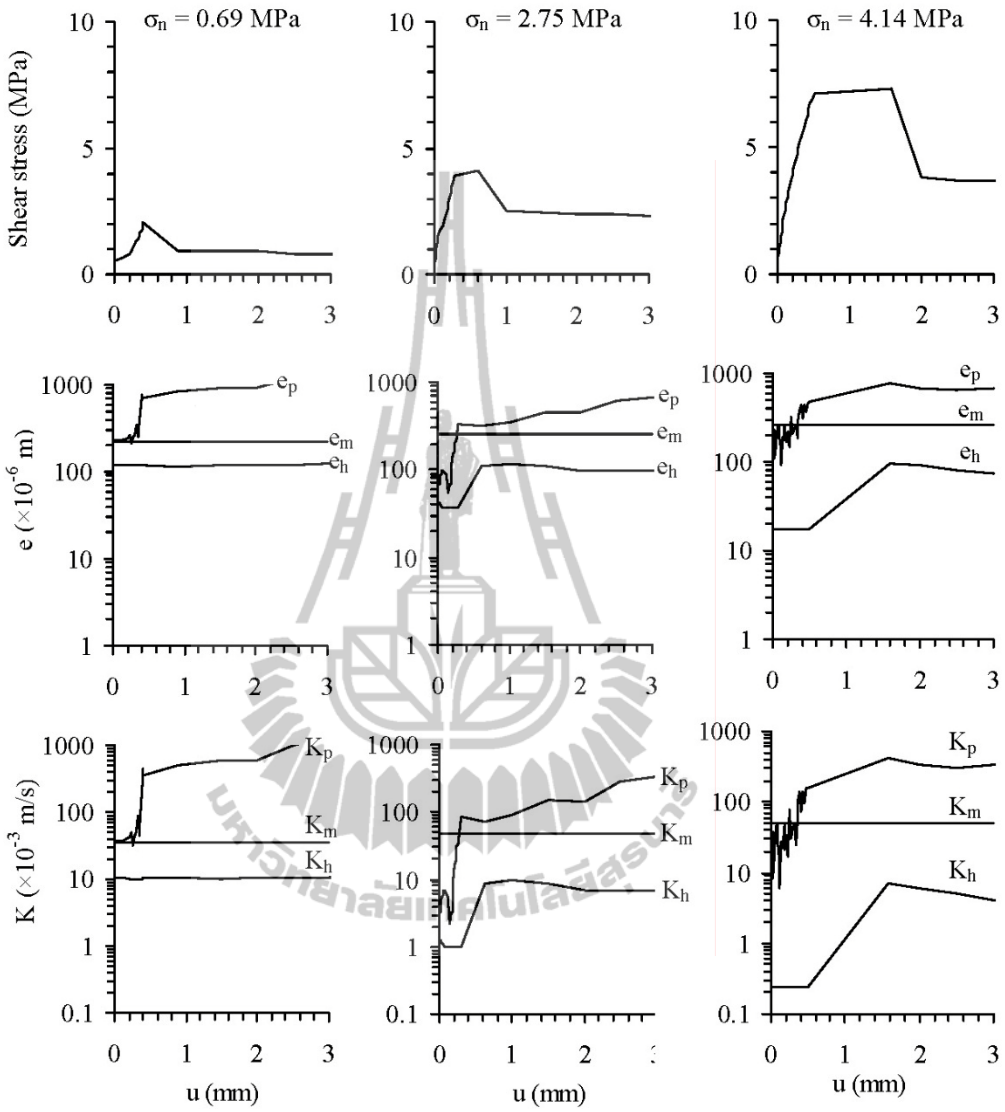


Figure 8. Shear stress, fracture aperture and hydraulic conductivity as a function of shear displacement (u) for PP sandstone fractures under normal stresses of 0.69 MPa (left), 2.75 MPa (middle) and 4.14 MPa (right).

For both PW and PP sandstones the physical aperture e_p tends to increase with shearing displacement. Its value fluctuates before the peak and tends to be more consistent in the residual stress region. The K_p values calculated from e_p subsequently show similar characteristics of the curves in the permeability-shear displacement diagram.

The hydraulic aperture e_h indirectly determined from the inflow rates also tends to increase with the shear displacement, particularly under high normal stresses. Even though K_p and K_h show similar characteristics of the curves in the permeability-shear displacement diagram, K_p is always about an order of magnitude greater than K_h, particularly in the residual shear region.

Rock Mechanics, Fuenkajorn & Phien-wej (eds) © 2009. ISBN 978 974 533 624 7

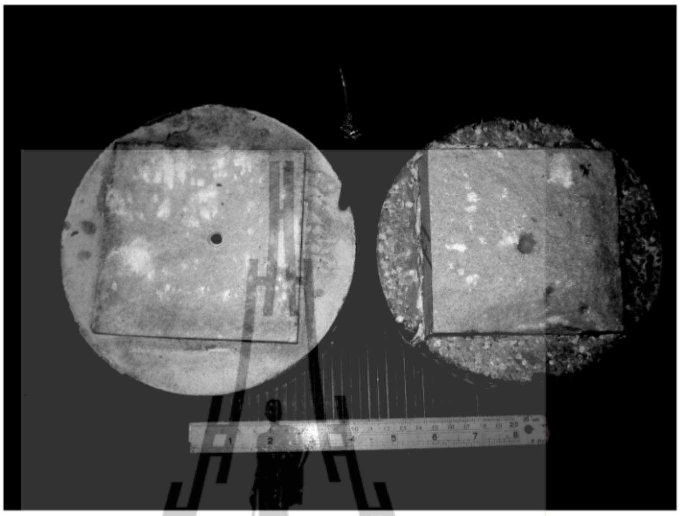


Figure 9. Example of post-test fracture surfaces in a PW sandstone specimen. The sheared surfaces are indicated by white areas.

Figures 10 and 11 plot the hydraulic conductivity derived from e_h as a function of normal stress σ_n. The fracture permeability values under no shear stress, immediately before the peak stress, and under the residual shear stress are compared. The fracture permeability under residual shear region is greater than that under no shear and that immediately before peak stress. It is not very sensitive to the normal stress – showing a slightly decrease with increasing the normal stress. The magnitudes of fracture permeability under no shear and under peak stress are similar. Both tend to decrease exponentially with the normal stress. As a result the difference between the permeability under residual shear stress and that under peak stress becomes larger as the normal stress increases. The results agree reasonably well with those obtained by Lee & Cho (2002) and Son et al. (2004).

This suggests that under a given normal stress, the fracture permeability immediately before peak stress will remain similar to that under no shear stress. After the fracture is displaced beyond the peak stress its permeability will however notably increase particularly under high normal stresses. The change of the fracture permeability with the normal stress will be presented in the next section.

From the shear stress-displacement diagrams as shown in Figures 7 and 8, the joint shear stiffness for various normal stresses has been calculated at the 50% peak stress using an equation (Indraratna & Ranjith, 2001):

$$k_s = \tau_s/\delta_s \qquad (6)$$

where k_s is the joint shear stiffness (MPa/m), τ_s is the shear stress (MPa), δ_s is the shear displacement (m). Table 3 summarizes the results for PW and PP sandstones. The joint shear stiffness tends to increase with the normal stresses.

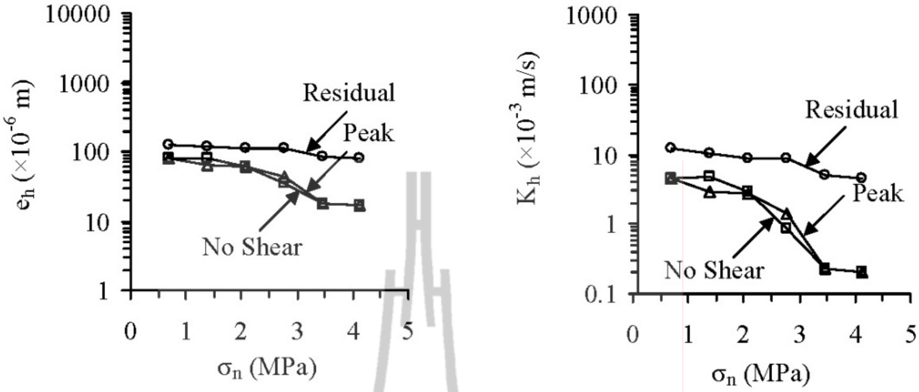


Figure 10. Hydraulic aperture (left) and hydraulic conductivity (right) as a function of applied normal stress for PW sandstone specimens.

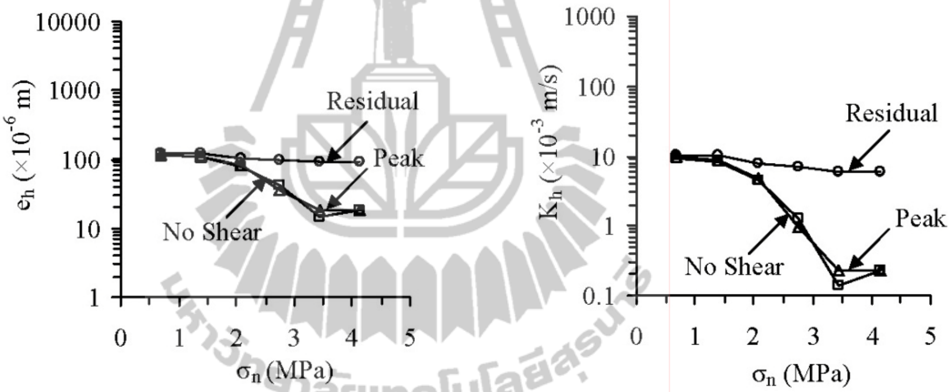


Figure 11. Hydraulic aperture (left) and hydraulic conductivity (right) as a function of applied normal stress for PP sandstone specimens.

Table 3. Joint shear stiffness for PP and PW sandstones.

PP	K_s(GPa/m)	PW	K_s(GPa/m)
PPSS-DS-01	5.17	PWSS-DS-01	11.49
PPSS-DS-02	6.47	PWSS-DS-02	12.93
PPSS-DS-03	11.34	PWSS-DS-03	10.34
PPSS-DS-04	14.13	PWSS-DS-04	8.08
PPSS-DS-05	8.62	PWSS-DS-05	6.47
PPSS-DS-06	9.42	PWSS-DS-06	6.90
Average	9.19±3.25	Average	9.37±2.62

5 FLOW TESTING ON SANDSTONE FRACTURES UNDER NORMAL STRESSES

Falling head flow tests have been performed to determine the fracture permeability in PW, PP, PK and SK sandstone specimens under normal stresses. One cycle of loading and unloading has been made during the flow test. During loading the normal stresses are

Rock Mechanics, Fuenkajorn & Phien-wej (eds) © 2009. ISBN 978 974 533 624 7

progressively increased from 0.35, 0.69, 1.03, 1.39, 1.72 to 2.06 MPa. During unloading the normal stresses are reduced from the maximum to the minimum while the flow rates are continuously measured. The tested fractures are tension-induced fractures with a nominal area of 15×15 cm. The flow test arrangement is similar to the flow test under shear stresses. A minimum of 3 specimens have been tested for each sandstone type.

The hydraulic aperture e_h and hydraulic conductivity K_h of the fractures are plotted as a function of the normal stress in Figure 12. They are calculated by using equations (4) and (6). For all sandstone types the fracture hydraulic conductivities exponentially decrease with increasing the normal stresses. Their permeability is in the range between 100×10^{-6} m/s and 10000×10^{-6} m/s. A permanent fracture closure is usually observed after unloading as evidenced by the permanent reduction of the fracture permeability (flow rate). The joint normal stiffness is calculated by an equation (Indraratna & Ranjith, 2001):

$$k_n=\sigma_n/\delta_n \tag{7}$$

where k_n is the joint normal stiffness (MPa/m), σ_n is the normal stress (MPa), δ_n is the joint deformation or closure (m). Table 4 summarizes the results. Due to the permanent closure of the fracture under the normal stresses the normal stiffness determined from the loading curves is significantly less than that from the unloading curves.

6 DISCUSSIONS AND CONCLUSIONS

The hydraulic conductivities of the intact PW and PP sandstones decreases with increasing volumetric strain before dilation strength probably due to the closure of voids and micro-cracks, and increases with the dilation strain after the dilation strength due to the initiation and propagation of cracks and fractures. The hydraulic conductivity of the PW sandstone decreases from about 100×10^{-9} m/s to about 50×10^{-9} m/s as the confining pressures increase from 3.45 MPa to 20.7 MPa. The flow rates measured during unloading show a permanent reduction of the rock permeability, suggesting that a permanent collapse of the pore spaces has occurred.

Both physical and hydraulic apertures (e_p and e_h) increase with shearing displacement, particularly under high normal stresses. The hydraulic conductivity derived from the actual aperture measurement (K_p) is about an order of magnitude greater than that indirectly determined from the flow rate (K_h), particularly in the residual shear region. The magnitudes of fracture permeability under no shear and under peak stress are similar. The K_h values in the residual shear region are greater than that immediately before peak stress. Both tend to decrease exponentially with the normal stress. The difference between the permeability under residual shear stress and that under peak stress becomes larger as the normal stress increases. For all sandstones tested here the fracture hydraulic conductivities exponentially decrease with increasing the normal stresses. Their permeability is in the range between 100×10^{-6} m/s and 10000×10^{-6} m/s. A permanent fracture closure is usually observed after unloading as evidenced by the permanent reduction of the flow rate.

More testing is required to develop mathematical relationships between the fracture hydraulic conductivity (or hydraulic apertures) with the applied normal stresses for the peak and the residual regions. Such relations would be useful in predicting the fracture permeability in rock mass around underground excavations or in the slope embankments where displacement of fractures usually occur.

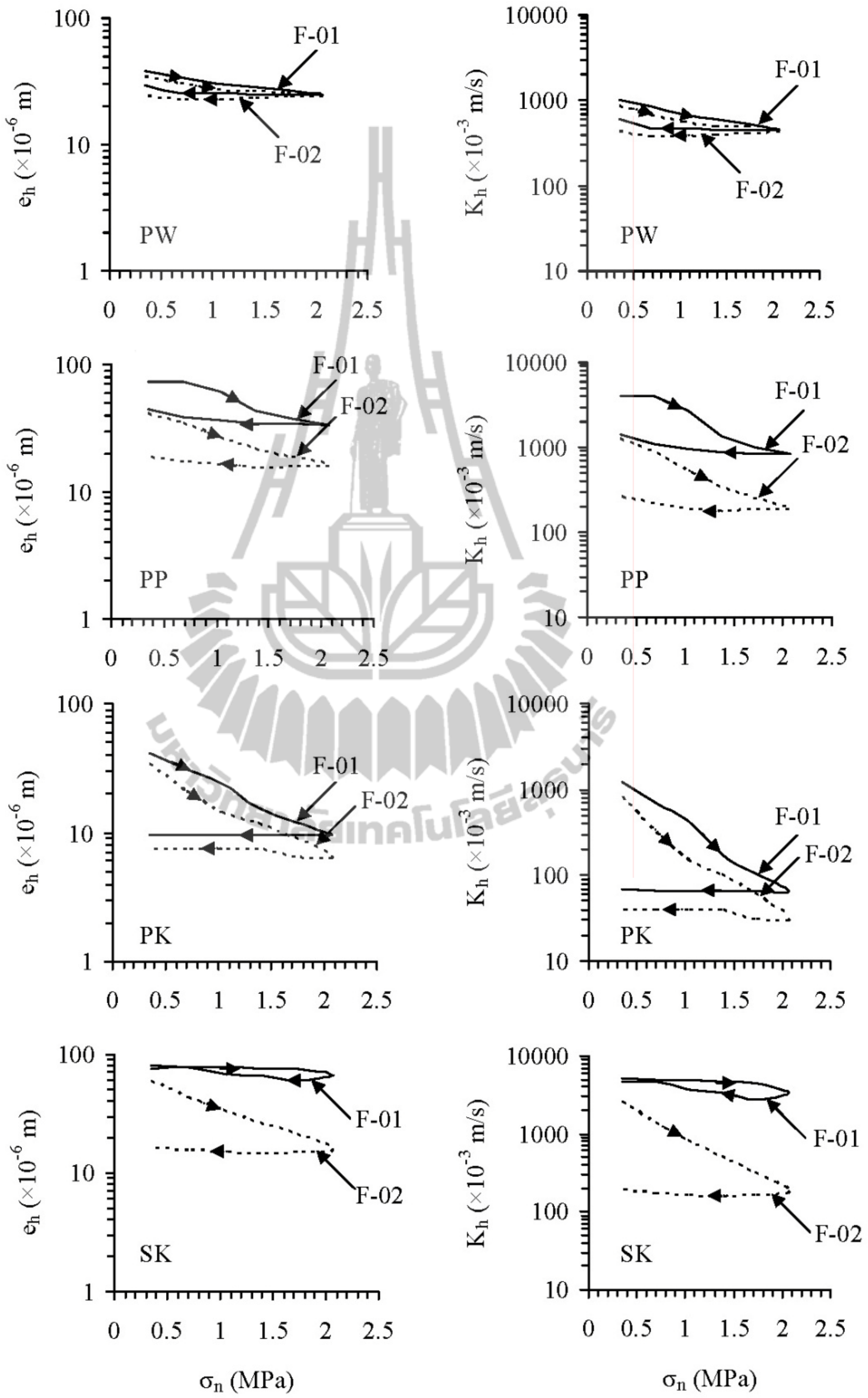


Figure 12. Hydraulic aperture (e_h) and hydraulic conductivity (K_h) as a function of normal stress (σ_n) for fracture in PW, PP, PK and SK sandstones.

Rock Mechanics, Fuenkajorn & Phien-wej (eds) © 2009. ISBN 978 974 533 624 7

Table 4. Joint normal stiffness for PW, PP, PK and SK sandstones.

K_n (GPa/m)	PW	PP	PK	SK
Loading	427.2±533.7	85.2±43.2	72.3±45.1	48.5±20.3
Unloading	1548.9±1817.4	1837.9±3875.5	18504.3±4296.8	211±905.9

ACKNOWLEDGTMENT

This research is funded by Suranaree University of Technology. Permission to publish this paper is gratefully acknowledged.

REFERENCES

Auradou, A., Drazer, G., Boschan, A., Hulin, J.P. & Koplik, J., 2006. Flow channeling in a single fracture induced by shear displacement. *Geothermics*. 35(5-6): 576–588.

Baghbanan, A. & Jing, L., 2008. Stress effects on permeability in a fractured rock mass with correlated fracture length and aperture. *International Journal of Rock Mechanics & Mining Sciences*. 45(8): 1320-1334.

Bandis, S.C., Barton, N.R. & Christianson, M., 1985. Application of a new numerical model of joint behaviour to rock mechanics problems. *Proc. Int. Symps. On Fundamentals of Rock Joints*, Bjorkliden.

Bandis, S.C., Lumsden, A.C. & Barton, N.R., 1983. Fundamentals of rock joint deformation. *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.* 20: 249-268.

Barton, N. & Bakhtar, K., 1983. Rock joint description and modeling for the hydrothermomechanical design of nuclear waste repositories (Contract Report, submitted to CANMET). *Mining Research Laboratory*, Ottawa, Parts 1-4: 270; Part 5: 105.

Ferfera, F.M.R., Sarda, J-P., Bouteca, M. & Vincke, O., 1997. Experimental study of monophasic permeability changes under various stress paths. *Int. J. Rock Mech. & Min. Sci.* 34: 3-4.

Heiland, J., 2003. Permeability of triaxially compressed sandstone: Influence of deformation and strain-rate on permeability. *Pure appl. Geophys.* 160: 889-908.

Indraratna, B. & Ranjith, P.G., 2001. Laboratory measurement of two-phase flow parameters in rock joints based on high pressure triaxial testing. *Journal of Geotechnical and Geoenvironmental Engineering*. 127(6): 530-542.

Indraratna, B., & Ranjith, P., 2001. *Hydromechanical Aspects and Unsaturated Flow in Joints Rock*. Lisse: A. A. Balkema.

Iscan, A.G., Kok, M.V., & Bagc, A.S., 2006. Estimation of permeability ans rock mechanical properties of limestone reservoir rocks under stress conditions by strain gauge. *Journal of Petroleum Science and Engineering*. 53: 13-24.

Lee, H. S. & Cho, T.F., 2002. Hydraulic characteristics of rough fractures in linear flow under normal and shear load. *Rock Mechanics and Rock Engineering*. Springer-Verlag Wien. 35(4): 299-318.

Maini, Y.N.T., 1971. *In situ hydraulic parameters in jointed rock-their measurement and interpretation*. Ph.D. Thesis. Imperial College, London. 321 p.

Niemi, A.P., Vaittinen, T.A., Vuopio, J.A. & Polla, J.P., 1997. Simulation of heterogeneous flow in a natural fracture under varying normal stress. *International of Rock Mechanics and Mining Sciences*. 34(3-4): 565.

Oda, M., Takemura, T., & Aoki, T., 2002. Damage growth and permeability change in triaxial compression tests of Inada granite. *Mechanics of Materials 34 (2002)* 313–331.

Pusch, G. & Weber, J.R., 1998. Correlation of rock permeability and anisotropic stress conditions for the integration of rock mechanical and hydraulic flow models. *SCA Paper 9826*.

Pyrak-Noltea, L.J. & Morrisa, J.P., 2000. Single fractures under normal stress: The relation between fracture specific stiffness and fluid flow. *International Journal of Rock Mechanics and Mining Sciences*. 37(1): 245-262.

Shangxian, Y. & Shangxu W., 2006. Effect and mechanism of stresses on rock permeability at different scales. *Science in China: Series D Earth Sciences 2006*. 49(7): 714-723.

Son, B. K., Lee, Y. K. & Lee, C.I., 2004. Elasto-plastic simulation of a direct shear test on rough rock joints. *International Journal of Rock Mechanics & Mining Sciences*. 41: 1-6.

Xiao, Y.X., Lee, C.F. & Wang, S.J., 1999. Assessment of an equivalent porous medium for coupled stress and fluid flow in fractured rock. *International of Rock Mechanics and Mining Sciences*. 36(7): 871-881.

Zeigler, B. 1976. *Theory of Modelling and Simulation*. New York: John Wiley and Sons.

Zhou, J. J. & Shao, J. F., 2006. micromechanical study of damage growth and permeability variation in brittle rocks. *Studia Geotechnica et Mechanica*. Vol. 28, No. 1, 2006.

Zhu, W., Montési, Laurent G. J. & Wong, T.F., 2002. Effects of stress on the anisotropic development of permeability during mechanical compaction of porous sandstones. *Geological Society, London, Special Publications*; 2002; v. 200; p. 119-136.

.

BIOGRAPHY

Ms. Jiraporn Buaboocha was born on May 19, 1983 in Bangkok, Thailand. She received her Bachelor's Degree in Engineering (Geotechnology) from Suranaree University of Technology in 2006. For her post-graduate, she continued to study with a Master's Degree in the Geological Engineering Program, Institute of Engineering, Suranaree University of Technology. She published technical paper related to rock mechanics, titled **"Flow Testing of Sandstone Fractures under Normal and Shear Stresses"** in the Proceedings of the Second Thailand Symposium on Rock Mechanics, Chonburi, Thailand.