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Dynamic behavior of flow during leaching of copper ores

Sainath, Narayana Rangaiah, M.S.

The University of Arizona, 1991

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**DYNAMIC BEHAVIOR OF FLOW DURING
LEACHING OF COPPER ORES**

by

Narayana Rangaiah Sainath

A Thesis Submitted to the Faculty of the
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In Partial Fulfillment of the Requirements
For the Degree of
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In the Graduate College
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1991

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TABLE OF CONTENTS

LIST OF FIGURES	6
LIST OF TABLES	8
ABSTRACT	9
1 INTRODUCTION	10
2 BACKGROUND	12
2.1 History of Copper Leaching	12
2.2 Occurrence of Copper Minerals	13
2.3 Chemistry of Leaching Copper	14
2.4 Methods of Leaching Copper	16
2.4.1 Dump Leaching	16
2.4.1 Heap Leaching	17
2.4.3 'In Place' Leaching	17
2.4.4 Vat Leaching	18
2.4.5 <i>In Situ</i> Leaching	18
2.5 Extraction of Copper from Pregnant Leach Solution	21
2.5.1 Iron Precipitation Process	21
2.5.2 Solvent Extraction and Electrowinning	23
2.6 <i>In Situ</i> Leaching Research	25
2.6.1 Need for Research	25
2.6.2 Experimental <i>In Situ</i> Leaching Projects	26
2.6.3 Purpose of Present Research	28
3 EXPERIMENTAL INVESTIGATION	31
3.1 Specimen Procurement and Preparation	31
3.2 Specimen Characterization	34
3.3 Lixiviant and the Method of Leaching	36
3.4 Sequence of Experiments	38
3.5 Measurement of Effective Porosity	39
3.6 Permeability Measurement	40
3.6.1 Permeability to Water	40
3.6.2 Gas Permeability	41
3.7 Experimental Setup	44

TABLE OF CONTENTS—(continued)

3.7.1	Water Permeability	44
3.7.2	Gas Permeability	49
3.8	Experimental Procedure	54
3.9	Estimation of Copper Recovery Rate	55
4	RESULTS AND DISCUSSION	56
4.1	Variation in Porosity	56
4.2	Variation in Permeability	59
4.3	Validity of Darcy's Law	62
4.4	Variation in Copper Recovery Rate	66
5	CONCLUSIONS AND RECOMMENDATIONS	71
5.1	Conclusions and Implications	71
5.5	Recommendations for future work	73
APPENDIX A :	SAMPLE CALCULATIONS	75
REFERENCES	80

LIST OF FIGURES

2.1	Cross section of a typical in situ leach mining system in which the ore is leached via a system of vertical wells	20
2.2	Generalized flowsheet for dump leaching and iron precipitation	22
2.3	Generalized flowsheet of solvent extraction and electrowinning process	24
2.4	Schematic vertical cross section of the in situ leaching operation at the Cyprus Casa Grande mine	29
3.1	A 1.5 inch diameter tactite specimen after it was prepared in the laboratory	32
3.2	A 4.0 inch diameter tactite specimen after it was prepared in the laboratory	33
3.3	Map of visible fractures on the surface of the specimen	35
3.4	A tactite specimen being leached in a beaker containing the lixiviant	37
3.5	Permeability of a core sample to hydrogen, nitrogen, and carbon dioxide at different pressures	42
3.6	Experimental panel that was constructed to perform the permeability experiments	45
3.7	Cross section of a triaxial cell	46
3.8	A triaxial cell holding an 1.5 inch diameter specimen, placed in a loading frame	47
3.9	Schematic of the experimental setup used to measure the permeability of a specimen using water	48
3.10	Experimental panel modified to be used in a permeability measurement experiments using a gas	50
3.11	Schematic of the experimental setup used to measure the permeability of a specimen using a gas.	51
3.12	Soap bubble flow meter	52
3.13	Complete experimental setup that was used to measure the permeability of the specimen using a gas	53
4.1	Saturation curve of the specimen	57
4.2	Variation in porosity with time as leaching progresses	58

LIST OF FIGURES — *(Continued)*

4.3	Permeability at various pressure gradients as a function of reciprocal of mean pressure	60
4.4	Variation of permeability of the specimen during leaching	61
4.5	A 1.5 inch diameter specimen that broke into two pieces after 80 days of leaching	63
4.6	A 4.0 inch diameter specimen that broke into a number of small pieces after 67 days of leaching	64
4.7	Total copper recovered from the specimen as leaching progresses	67
4.8	Amount of copper recovered per day of leaching.	68
4.9	Loss in weight of dry specimen and the total copper recovered from the specimen.	70
A.1	Permeability at Various Pressure Gradients as a Function of Reciprocal of Mean Pressure	78

LIST OF TABLES

A.1	Gas flow readings to measure permeability of a specimen using helium . .	77
A.2	Water flow readings to measure permeability of a specimen using water . .	79

ABSTRACT.

The objective of this investigation was to experimentally determine the variation in the flow characteristics of tactite copper ores during the leaching process. The laboratory work involved estimation of porosity and permeability of cores before leaching, and after various intervals of leaching. The tests were carried out using specimens of diameter 1.5 and 4.0 inches, prepared from boulders obtained from the Cyprus Casa Grande mine. A solution containing about 25 grams of sulfuric acid per liter was used as the lixiviant. Porosity was determined using the water saturation method. The permeability was estimated using either helium or water with the specimens stressed triaxially to simulate *in situ* conditions. The rate of copper recovery from the specimen during the leaching process was also determined by estimating the copper content in the solution used for leaching.

The results indicate that the permeability and porosity of the specimens increased with leaching, but both tend to remain constant after most of the soluble material in the core was dissolved. The rate of copper recovery was high initially but dropped as leaching progressed and the copper available in the core was depleted.

CHAPTER 1

INTRODUCTION

With fluctuating copper prices, the need to develop a low-cost, environmentally sound technology to mine copper is gaining importance. *In Situ* leaching of copper is being looked upon as a viable alternative to conventional methods of copper mining. This method consists of circulating dilute chemical solutions through an ore deposit to dissolve the copper minerals. The solutions containing the dissolved minerals are then pumped out of the ground to a processing plant for metal recovery. After recovery of the metals from the solution, the solution is recycled back to the orebody. Successful operation of an *in situ* leaching operation depends upon understanding the flow characteristics of the orebody, and the control of the flow of leach solution or the lixiviant within the orebody.

The flow characteristics of the lixiviant within the orebody depend upon a number of factors. These factors are the porosity and permeability of the rock matrix, the hydrologic condition of the orebody, that is, whether the orebody is saturated or unsaturated, the size and density of fractures, and the connectivity and permeability of these fractures. Most of these factors vary continuously over the life of an orebody depending upon mineral dissolution, precipitation, clay hydration, and physical sedimentation. Knowledge of the trends in the variation of these factors is essential in order to understand the flow characteristics of the solution within the orebody.

The work discussed in this thesis investigates the changes in the flow characteristics of tectite copper ore by measuring the variation in the porosity and permeability of the rock specimens as they are leached in the laboratory. The rate of recovery of copper from these specimens during the leaching process is also measured. The knowledge of the trends in

the variation of porosity and permeability of rock specimens is important in order to predict the flow rates both in injection and recovery wells of an *in situ* leaching operation. Since the nature of deposits differs from one deposit to another, the trends in the variation of porosity and permeability would also be different for different deposits. Similar type of experiments can, however, be performed on specimens/cores from the deposits to be leached *in situ* to gain information regarding the variation in flow characteristics. The rate of copper recovery from the specimens, and the percent of total copper that can be recovered from a specimen through leaching gives the required information to decide the size of *in situ* leaching blocks, and estimates of the total time required to leach each block for the desired recovery.

Chapter 2 of this thesis discusses the background to the present work. This includes an introduction to copper leaching, chemistry involved in leaching, and the different methods of leaching copper ores. The need for research in the area of *in situ* leaching and the purpose of the present study are also presented in the second chapter. Chapter 3 describes the different experiments that were performed on each rock specimen to study the variation in the porosity and permeability of the specimen during the leaching process. Experiments to measure the rate of copper recovery from the specimens during the leaching process are also discussed in this chapter. An analysis and summary of the experimental results are presented in chapter 4. Finally, Chapter 5 gives the conclusions, discussion of some implications, and recommendations for future research.

CHAPTER 2

BACKGROUND

2.1 History of Copper Leaching

Recovering copper by leaching the rock mineral is not new. This method of recovering copper from ore by acid leaching was first used in ancient times, probably in Cyprus, Armenia, Egypt, and other places (Agricola, 1950). Dump or heap leaching began in Germany in the 16th century, and rapidly spread to other parts of Europe. Rio Tinto mine in Spain has been using large scale heap leaching to extract copper from cupreous pyrite ores since the early 17th century (Taylor and Whelan, 1942).

In the United States, precipitation of copper from mine waters began in around 1890 at Butte, Montana (Ballard, 1966). Extensive underground mining by stope and drift left large areas of the mine filled with waste rock containing some copper minerals. The oxidation of these minerals due to exposure to air made them soluble in mine water thus increasing the copper content of the mine water and enabling copper extraction. After this success in the Butte district, effort was made to bring the acid mine water in contact with old filled stopes, and wherever possible, parts of the mine were flooded. Water was subsequently pumped to the surface and passed through a copper precipitating plant, and copper was recovered.

The first significant application of the leaching technique to rock 'in place' was at the Ohio Copper mine in Utah, in 1922 (Anderson and Cameron, 1926). After mining by block caving method terminated, an inverted cone of broken rock containing about 38 million tons of ore remained in the ground. Water was applied to the top of the broken rock and was allowed to percolate down through the broken rock. This was then collected

in an adit below, and copper was successfully recovered from this solution. After the success at the Ohio Copper mine, leaching was generally attempted, and often succeeded, on large masses of broken copper bearing rock that remained after large scale mining operations were terminated. Heap leaching has also been extensively used to extract gold and silver from low-grade ores (Ahlness and Pojar, 1983). *In Situ* leach mining has been used on a commercial basis since mid 1970's to produce uranium from porous sandstone deposits in Texas and Wyoming (Larson, 1978).

2.2 Occurrence of Copper Minerals

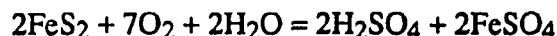
Copper minerals are widely distributed in the crust of the earth. Most copper is first deposited in the earth's crust as a sulfide mineral. Weathering processes, either in the present or former geologic periods, alter the near surface sulfide minerals to oxide, carbonate, silicate, or sulfate minerals. In copper mining, the term "oxide ore" usually implies copper ores that have been oxidized due to exposure to air. These oxide ores, therefore, refer to rock containing combinations of oxide, carbonate, silicate, or sulfate copper minerals. Copper present in the oxide form is amenable to extraction through leaching. The term "sulfide ore" is used in the copper industry to indicate rock containing copper minerals that are not readily soluble in dilute sulfuric acid, and can usually be recovered by the flotation process. Some sulfide minerals can, however, be dissolved in an acidic solution by using an oxidizing agent such as ferric sulfate.

Deposits containing "oxide copper ore" are suitable for *in situ* mining operation since copper can be extracted from these minerals by leaching. Another factor determining the leachability of a deposit is the nature of the host rock in which the minerals are present. Copper is found in rock types ranging from carbonate to silicate in sedimentary, metamorphic, or igneous rocks. Deposits in carbonate rocks are difficult to leach with acid

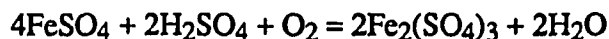
as gangue consumes excessive amounts of acid. Deposits in certain crystalline rocks like granite, monzonite, tactite, hornfel, and schist are suitable for *in situ* leaching.

2.3 Chemistry of Leaching Copper

Copper from oxidized copper ores, or mixed oxide-sulfide ores, can be extracted by leaching. In case of mixed oxide-sulfide ores, or where pyrite is associated with the ore minerals, water can be used as the leach solution or the lixiviant. But in the absence of pyrite or sulfide minerals within the orebody, dilute sulfuric acid is used as the leach solution. The reactions shown here, which relate to how specific copper minerals are dissolved while leaching either with water or sulfuric acid, were given by Van Arsdale (1953). When water and air, or water containing dissolved air, is percolated through broken rock containing pyrite, sulfuric acid is formed. The chemical reaction is shown as:



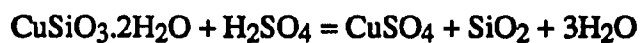
In the presence of abundant oxygen and sulfuric acid, the ferrous sulfate is oxidized to ferric sulfate as shown below:



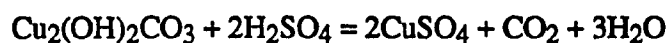
Ferric sulfate in the presence of sulfuric acid forms a solution that can dissolve most copper minerals. Most deposits contain varying amounts of pyrite associated with the copper minerals, and hence, acid is formed within the orebody when water percolates through it. But if a deposit does not contain adequate amount of pyrite to form sulfuric acid, acid must

be used as the leach solution. Some of the basic reactions involved in the dissolution of various copper minerals are:

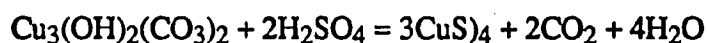
Chrysocolla, $\text{CuSiO}_3 \cdot 2\text{H}_2\text{O}$



Malachite, $\text{Cu}_2(\text{OH})_2\text{CO}_3$



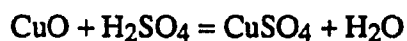
Azurite, $\text{Cu}_3(\text{OH})_2(\text{CO}_3)_2$



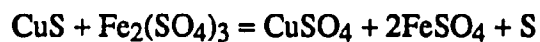
Cuprite, Cu_2O



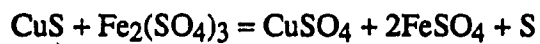
Tenorite, CuO



Chalcocite, Cu_2S (in two stages)



Covellite, CuS



2.4 Methods of Leaching

The principal methods of leaching used at present are dump, heap, 'in place', and vat leaching. These methods are interrelated, and many factors considered necessary for effective leaching by one method are also applicable to other methods. The choice of a leaching method depends upon a number of factors, some of which are the chemical and physical characteristics of the ore rock, the grade of the ore, the solubility of copper minerals, the amount of acid consuming gangue material present with the ore, and the mode of occurrence of the copper bearing minerals. In the following sections, the various leaching methods are discussed briefly.

2.4.1 Dump Leaching

Dump leaching is used to extract copper from low-grade and waste material stripped during mining operations. Run-of-mine material containing copper in amounts less than the cut-off grade is leached by this method. Most dumps are deposited upon existing topography. The locations of the dumps are selected to assure impermeable surfaces utilizing the natural slopes of ridges and valleys for the recovery and collection of the pregnant leach solution. Pregnant leach solution is the lixiviant or the leach solution with dissolved copper. Since the material placed in leach dumps is run-of-mine material, the size varies from large boulders, a couple of feet in diameter, to fine particles. The shape of most leach dumps is that of a truncated cone. The dumps have slopes with angle of repose dependent upon the type, and size of the material. Large dumps are usually raised in lifts of 50 to 100 feet. The tonnage of major leach dumps varies from a few million tons to a few billion tons. Some of the mining operations where dump leaching is practised are Bagdad and Inspiration Copper mines, both in Arizona.

2.4.2 Heap Leaching

Heap leaching is employed to dissolve copper from oxide ore that has been placed on specially prepared surface. Heap leaching is similar to dump leaching in most respects, but differs in that the ore material is leached instead of the waste. In this method, the oxide copper ore is placed in a heap for leaching. Copper ores containing sulfide minerals, ores containing large amounts of carbonate, and other acid soluble gangue material, are generally not used in this method of leaching. Leach heaps are deposited on the ground after it has been specially prepared for the purpose. Preparation of the ground surface for heap leaching includes clearing the vegetation and cementing of the ground. Sometimes this cemented layer is covered with polyethylene plastic material, generally known as leach pads, for enhancing the recovery of the pregnant leach solution. Acid is not generated within the heaps because of the absence of pyrite in the oxidized ore. Dilute sulfuric acid is, therefore, used as the leach solution in this method of leaching. The volume of leach material in the heaps is considerably less than that of leach dumps. Because of the higher grade of the material in the heaps, and the ready solubility of oxidized copper minerals, pregnant solutions produced in heap leaching contain much more copper than the pregnant solutions obtained from dump leaching.

2.4.3 'In Place' Leaching

'In Place' leaching is a method of leaching commonly employed to leach oxide and sulfide copper ores left behind in the ground after block caving or other mining operations are terminated. Leach solution, applied either on the ground surface or in the stopes, is allowed to percolate through the ore material left in the ground. Slow percolation of the leach solution promotes the oxidizing conditions deemed favorable for continued and rapid dissolution of copper sulfide minerals. Adequate preparation is necessary to collect the

resultant copper bearing leach solution. After collection of the leach solution, usually in the adits of underground workings, it is pumped to the surface treatment plant for recovery of copper.

The Miami Copper mine in Arizona is an example of a current 'in place' leaching operation. The mine leaches copper from underground ore bodies which were previously mined by block caving operation (Ahlness and Pojar, 1983). Acid is added to tailings water from the precipitation plant, and the solution is distributed by sprays on to the surface area which overlies the former block caving operation. The leach solution percolates downward through the mixture of ore and waste material to the 1000 ft level of the mine in three to four weeks. The leach solution with dissolved copper is collected in a reservoir located in the 1000 ft level, and then pumped to the surface for recovery of copper.

2.4.4 Vat Leaching

Vat leaching is employed to extract copper from oxide or mixed oxide-sulfide ores containing more than 0.5 percent acid-soluble copper. This method is used in preference to heap leaching if the ore material is not porous, and crushing is necessary to permit adequate contact between the leach solution and the copper minerals. In spite of increased costs due to crushing and screening of the ore, vat leaching has certain advantages like higher copper recovery, higher copper content of the leach solution, and also shorter time period required for leaching. Loss of leach solution with this method is negligible.

2.4.5 In Situ Leaching

With need to reduce the cost of mining copper, *in situ* leaching is being looked upon as a viable alternative to conventional methods of mining copper. The mechanics of *in situ* leaching involves flow of a solution through an undisturbed orebody to dissolve the

required mineral and recovery of this solution with dissolved mineral by a collecting system. Figure 2.1 shows a cross section of a typical *in situ* leach mining system in which the ore is leached via a system of vertical wells. Leach solution is forced down the injection wells and the leachant with dissolved copper minerals is recovered through the recovery wells. Extraction of the metal from the leachant and the treatment of the leachant for reuse is carried out at the processing plant.

In Situ leach mining offers several advantages over conventional methods of mining copper. The process requires relatively smaller capital investment, and the start-up time for production is considerably less. The method eliminates the process of extraction, crushing, and milling, thereby reducing the production costs. Additional advantage is that the miners are not exposed to the hazards of underground mining thus resulting in fewer health and safety risks. The technique disrupts the environment significantly less than conventional mining since the process only removes the target metals from the ground. The site is easily reclaimed to its original condition by treating the groundwater, capping the wells, and dismantling the processing plant. The overall advantages provide two important benefits to the mine operators. These are:

- 1) considerable reduction in the cost of producing copper, and
- 2) copper can be recovered from small and low grade deposits that are currently not economical to mine by conventional methods.

In spite of the obvious advantages, *in situ* leaching technique has certain drawbacks. In the past, experimental *in situ* leach mining programs were carried out to determine the feasibility of a commercial operation (D'Andrea et al.,1977). The results of these tests, however, were not very encouraging. The problems encountered were, and to some extent still are, low rates of leach solution recovery and low copper content of the pregnant leach solution. Because of this, the percentage recovery of metal from the

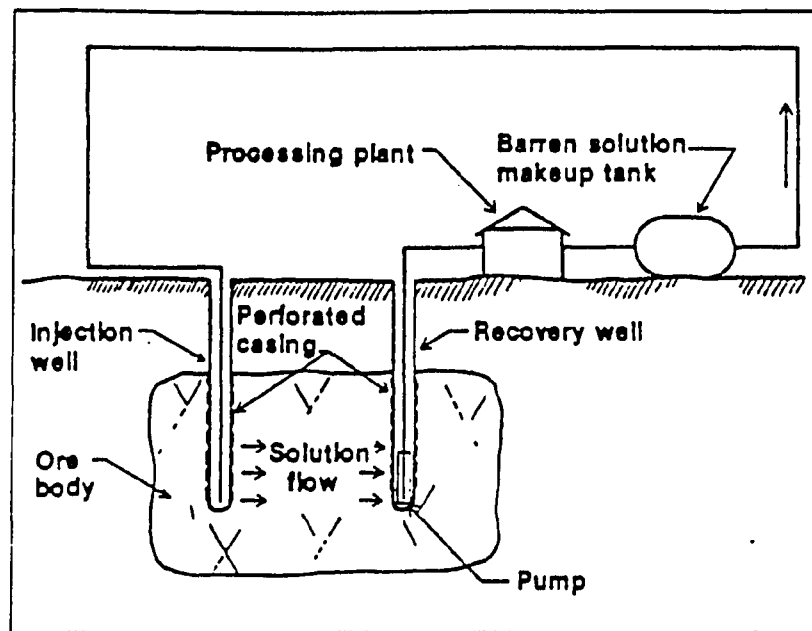


Figure 2.1. Cross section of a typical *in situ* leach mining system in which the ore is leached via a system of vertical wells (after Chamberlain and Pojar, 1981).

orebody was very low. Another disadvantage of this method, which is also a major environmental concern, is the lack of technology to contain the leach solution within the orebody.

2.5 Extraction of Copper from Pregnant Leach Solution

Extraction of copper from the pregnant leach solution is done by either of the following two methods:

- 1) iron precipitation followed by smelting, and refining, or
- 2) solvent extraction and electrowinning

2.5.1 Iron Precipitation Process

Iron precipitation process was extensively used to extract copper from the pregnant leach solution before the perfection of the solvent extraction and electrowinning process. In this process, metallic iron is used to precipitate copper from the pregnant leach solution. The reaction involved in this process is shown below:

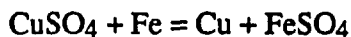


Figure 2.2 shows a generalized flowsheet for dump leaching and iron precipitation. As seen from the flow sheet, the leach solution is sprayed on to the emplaced dump and pregnant leach solution with dissolved copper is recovered from the dump and treated in precipitation launders. In precipitation launders, iron (usually scrap iron) is used to precipitate copper in the solution. This precipitated copper, known as cement copper, is dried and shipped for smelting. The tailing solution from precipitation launders is treated for reuse by adding acid.

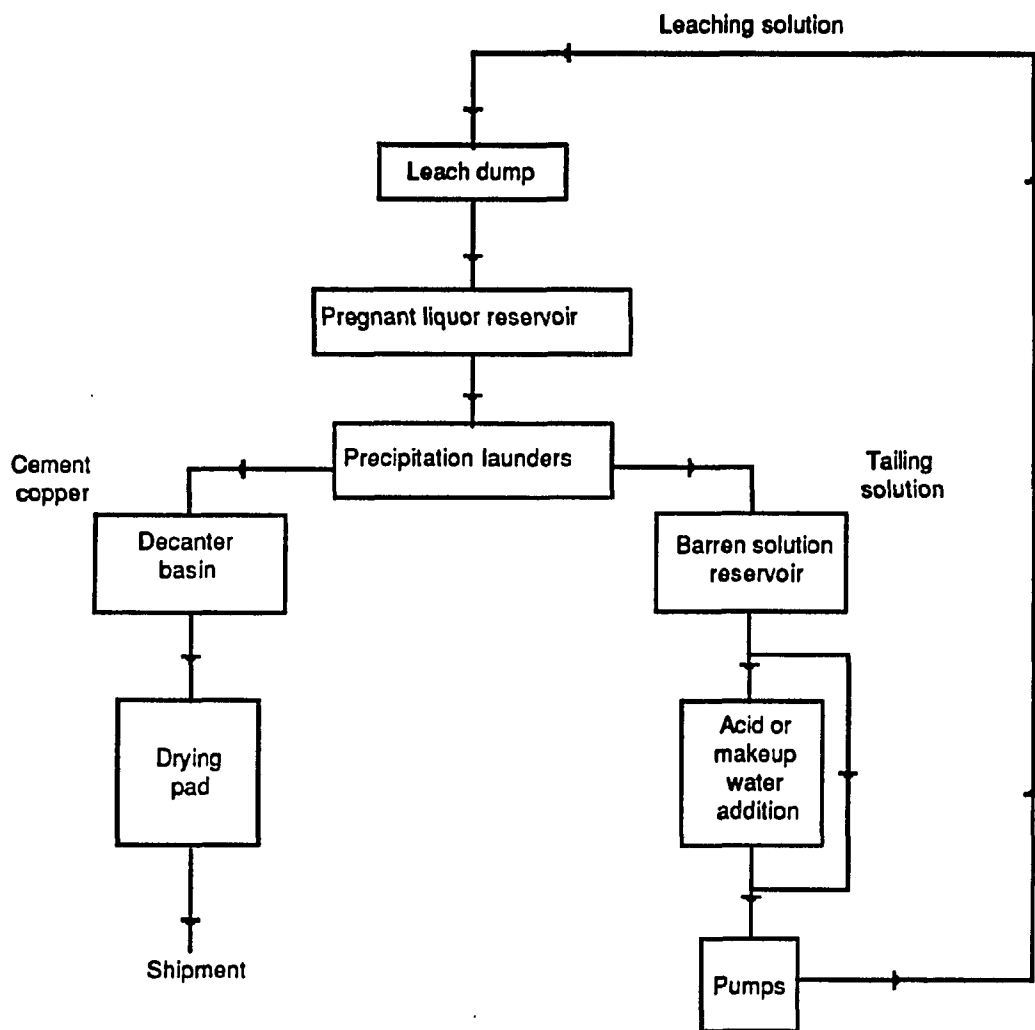


Figure 2.2. Generalized flowsheet for dump leaching and iron precipitation.

2.5.2 Solvent Extraction and Electrowinning

Solvent extraction and electrowinning process, usually called the SX/EW process, is a relatively new method of extracting copper from the pregnant leach solution. It is a simple and inexpensive process, and produces practically pure copper from the pregnant leach solution. The SX/EW process consists of 3 steps, as shown on the flow sheet in Figure 2.3. The three steps involved in this process are extraction, stripping, and electrowinning. Two interdependent process solution streams transfer the copper from one step to the next.

In the extraction process, the pregnant leach solution is mixed vigorously with an equal volume of kerosene based solvent that contains an organic chemical to extract copper. After the solutions have been mixed for about two minutes, the mixture is allowed to settle. The leach solution, which has given up its copper to the organic chemical, is the heavier of the two solutions, and sinks to the bottom. This solution, which is the same as the original lixiviant is pumped back to the leach dumps to begin another cycle. The solvent containing the copper laden organic chemical, called "loaded organic," floats to the top and is pumped to the next process. In the stripping process, the loaded organic is mixed with a copper bearing sulfuric acid solution, called the electrolyte. The copper migrates from the organic to the electrolyte. The mixed solutions are then allowed to settle. The solvent that has been stripped of its copper, now called the "barren organic," floats to the top and is sent back to the extraction process to pick up another load of copper. The electrolyte containing copper settles to the bottom and is pumped to the final step - the electrowinning process. In this final step, the rich electrolyte is pumped through a series of tanks. Hanging in the tanks are insoluble lead plates alternating with sheets of copper. Each lead plate serves as the anode pole of an electric circuit; each cathode pole begins as a thin 'starter sheet' of pure copper. A direct current is passed through the electrolyte, reducing some of copper ions to copper

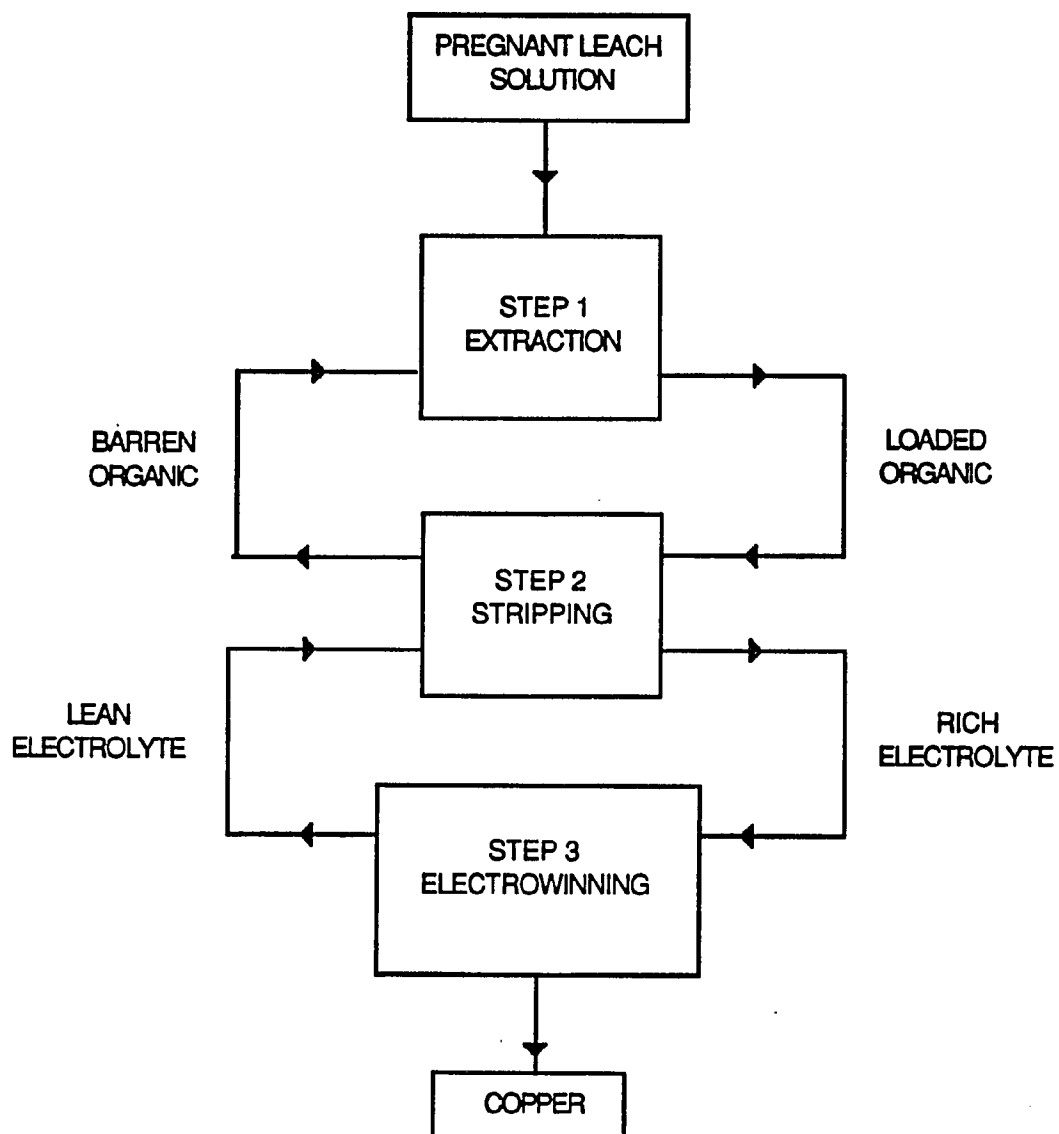


Figure 2.3. Generalized flowsheet of solvent extraction and electrowinning process.

metal. These copper atoms accumulate on the starter sheet. After sufficient amount of copper has been accumulated on the starter sheet, these are removed and replaced with new starter sheets. The copper cathodes removed from the tanks are virtually pure copper and are ready for further processing into other copper products. The electrolyte, that has passed through the electrowinning tanks, is partially depleted of its copper, and is returned to the stripping process to have its copper content upgraded once again.

2.6 *In Situ* Leaching Research

2.6.1 Need for Research

With fluctuating copper prices, the need to develop a low-cost, environmentally sound technology to mine copper is gaining importance. But as mentioned in section 2.4.5, *in situ* leaching has certain drawbacks like low rates of leach solution recovery, low percentage recovery of metal from the orebody, and containment of the leach solution within the orebody. Most of these are related to flow behavior of the copper bearing rock, and can be significantly improved by a thorough understanding of the flow characteristics of the solution.

The flow of solution in the orebody depends on a number of factors like the porosity and permeability of the rock matrix, size and density of fractures in the orebody, and the permeability of these fractures. These factors vary continuously over the life of an *in situ* leaching operation, depending upon mineral dissolution, precipitation, clay hydration, and physical sedimentation. Mineral dissolution may act to increase the size of the flow channels and thus increase the permeability. Sometimes, permeability may be adversely affected by any carbon dioxide that may be formed by the attack of acid on any carbonate minerals present in the orebody. When sulfuric acid is used as the leach solution, elevated sulfate (SO_4^{-2}) content in the leach solution may result in combining of

SO_4^{2-} ions with cations mobilized by mineral dissolution, or ion exchange, with clay minerals causing precipitation of the sulfate minerals and clogging the flow channels. Knowledge of the trends in the variation of the above factors is essential to properly understand the flow of leach solution in the orebody.

The effectiveness and the efficiency of any *in situ* leaching operation depends upon a number of variables which can be classified into two main categories:

- 1) Chemical solution characteristics, injection pressure, and the rate of injection of leach solution, and
- 2) Orebody-rock characteristics

The variables in the first category can be altered or controlled during an *in situ* leaching operation. But the orebody-rock characteristics are a function of the *in situ* conditions and cannot be controlled significantly. The variation in the rock characteristics with time, as leaching progresses, needs to be studied in detail in order to understand the flow behavior in the orebody.

2.6.2 Experimental *In Situ* Leaching Projects

The U.S Bureau of mines is presently conducting two experimental *in situ* leaching operations of oxide ore deposits, both in Arizona. The first project is at the Santa Cruz site, 7 miles west of Casa Grande. This project is being carried out in cooperation with the Santa Cruz joint Venture, a mining partnership between ASARCO, Santa Cruz Inc., and Freeport Copper Co. The Santa Cruz site is undeveloped and contains a mineralized zone with chryscolla and atacamite as the predominant copper minerals present in granite and porphyry host rocks. A well field design of two connected five spot patterns will be used at this site (Ahlness and Millenacker, 1989). The corner wells in the pattern will serve the production needs, and the center wells will be used for injection. A sufficiently large area

will be leached in this operation to investigate copper recovery, copper loading in the pregnant leach solution, and residence time expected for a commercial operation.

The second project is at the Cyprus Casa Grande mine, Casa Grande, and is being carried out in cooperation with the Cyprus Casa Grande Corporation. An underground *in situ* leaching field investigation to carry out flow behavior and modeling studies is being carried out at this site. Underground *in situ* leaching is a method of *in situ* leaching which takes advantage of existing underground mine workings to gain preferential access to a deeply buried ore deposit. With this method of leaching, injection and recovery wells are collared in existing underground mine drifts and drilled into an undisturbed portion of the deposit. Maintaining acceptable rates of solution injection and recovery in wells, and distributing the injected leach solution effectively within the oxide ore zone are the primary concerns at this operation (Schmidt et al., 1990). The objective of this ongoing investigation is to better understand the hydrologic conditions underlying the efficient distribution and control of leach solutions during *in situ* leaching.

The deposit at the Cyprus Casa Grande mine is primarily of granitic composition and contains both oxide and sulfide mineralized zones. These zones are overlain by 600 to 1500 feet of tertiary fanglomerate, a formation of cemented, unmineralized gravels. The *in situ* leaching operation is being carried out on a part of the oxide orebody. This oxide ore is extensively fractured granodiorite porphyry, with chrysocolla being the predominant copper mineral. Fifty-eight wells have been constructed from a drift at 1100 ft level called the "tool crib" drift. The wells are drilled in 15 parallel fan patterns, located 12.5 ft apart along the drift. Each fan is composed of 3 to 5 wells drilled at angles ranging from 6 to 89 degrees from the horizontal. The wells penetrate the fanglomerate, oxide zone, and terminate at the top of the sulfide zone. Figure 2.4 shows a schematic vertical cross section of this leaching operation. A stainless steel pipe is inserted in each well bore. The pipe is

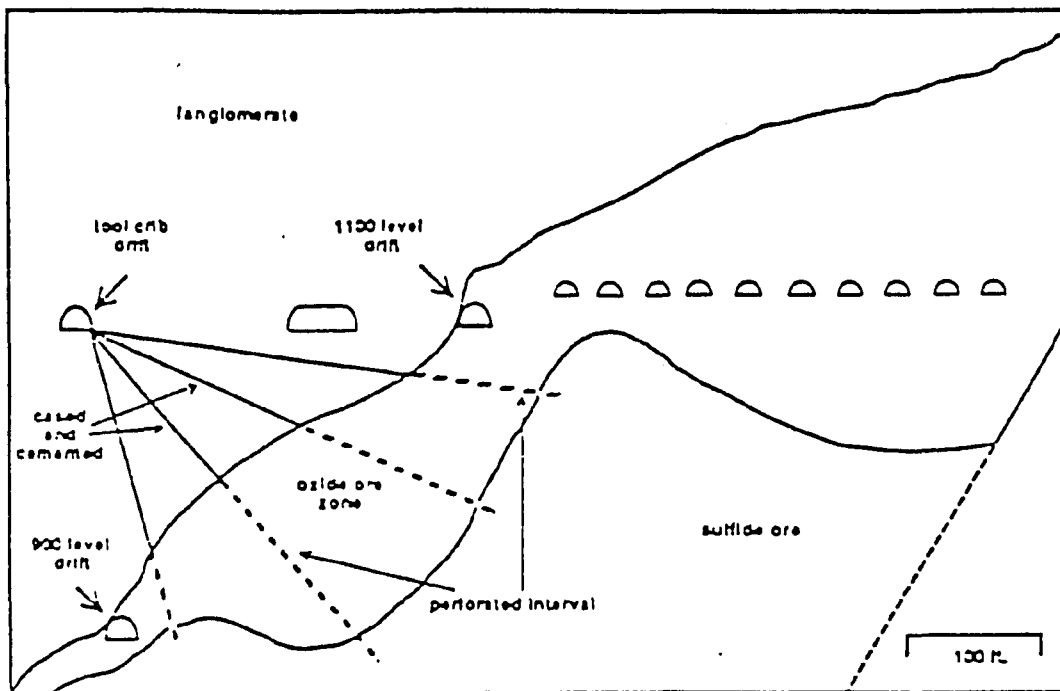


Figure 2.4. Schematic vertical cross section of the *in situ* leaching operation at the Cyprus Casa Grande mine (after Schmidt et al., 1990).

cemented in place in the interval between the top of the oxide zone and the well collar. Throughout the oxide ore interval, the pipe is perforated at one foot intervals. The pressure and flow data from these injection and recovery wells is being used to model the flow of solution in the orebody.

2.6.3 Purpose of the Present Research

To supplement the field research, laboratory leaching experiments on rock samples from oxide copper deposits are being carried out by various research institutions. Experiments on rock samples are being carried out to gain an understanding of the physical and chemical factors that have an impact on *in situ* mining, and also to develop techniques to evaluate a deposit for its amenability to *in situ* leaching. Previous research in this area has been done mostly using powdered or crushed rock samples (Cook, 1987). More recently, core leaching experiments are being carried out to better simulate the actual process involved in *in situ* copper leaching (Paulson and Kuhlman, 1989).

In the research presented in this thesis, experimental work was carried out using core samples to study the variations in the flow characteristics of tactite copper ore. This included measuring the variation in the porosity and permeability of tactite rock specimens as they were leached in the laboratory. The rate of copper recovery from these specimens during this leaching process was also studied. Experimental work of this kind is an inexpensive and easy way to gain qualitative information regarding the changes taking place while leaching an ore deposit. The values of permeability variations obtained from core leaching experiments, however, cannot be easily scaled to apply to the entire orebody, as the field permeability of a particular deposit will, most certainly, be quite different from that measured using core samples. This is due to the impact of large fractures and other preferential flow paths occurring in a deposit. However, correlation of permeability

changes during the experiments with data on fluid chemistry yields information that is useful in determining the potential impact of these mechanisms during actual *in situ* mining in the field. By incorporating the laboratory data with field data from a deposit, one can make predictions of what is actually occurring in a full-scale *in situ* mining operation. Experiments to estimate the rate of recovery of copper from core specimens yield information, such as copper content in the pregnant leach solution, fractional copper removal versus time, and the percent of total copper that can be recovered from the specimen through leaching. Such information is essential in assessing the feasibility of applying *in situ* mining to a deposit, and in designing an *in situ* leaching operation.

CHAPTER 3

EXPERIMENTAL INVESTIGATION

3.1 Specimen Procurement and Preparation

The rock specimens used for the experiments were prepared from rock boulders obtained from the Cyprus Casa Grande mine at Casa Grande, Arizona. These boulders were primarily tactite copper ore. The primary mineralization in these rocks appeared to be chrysocolla, seen as a blue-green material mostly along the fractures indicating that most of the copper mineralization in this rock type is present along the fractures in the rock.

Two sizes of core specimens were used for the experiments. These were 1.5 inch and 4.0 inch diameter specimens. These cores were prepared from rock boulders using a coring machine. The ends of these specimens were ground parallel using a surface grinder. In accordance with the International Society of Rock Mechanics (ISRM) testing procedures (Obert and Duvall, 1967) effort was made to keep the length of the specimen twice the specimen diameter. Therefore, the length of 1.5 inch diameter cores varied between 2 to 3 inches, but the length of 4 inch diameter cores ranged from 4 to 8 inches due to difficulty in preparing longer core specimens as the rock boulders had extensive fractures in them. Figure 3.1 shows a 1.5 inch diameter specimen after it was prepared in the laboratory and Figure 3.2 shows a 4.0 inch diameter specimen.

Cylindrical rock specimens, rather than crushed rock material were used for the leaching experiments. This permitted stressing the specimens in a hoek cell to simulate *in situ* stresses while performing the permeability measurements. Subjecting the specimen to stresses while measuring the permeability is important as the permeability of the rock specimens can vary by a few orders of magnitude when the stress on the specimen is

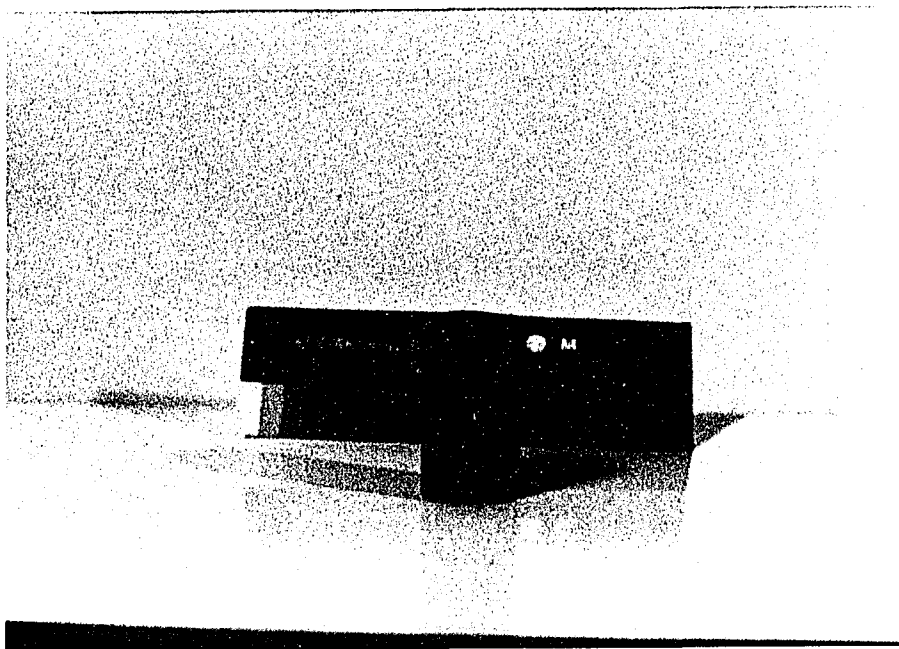


Figure 3.1. A 1.5 inch diameter tactite specimen after it was prepared in the laboratory.

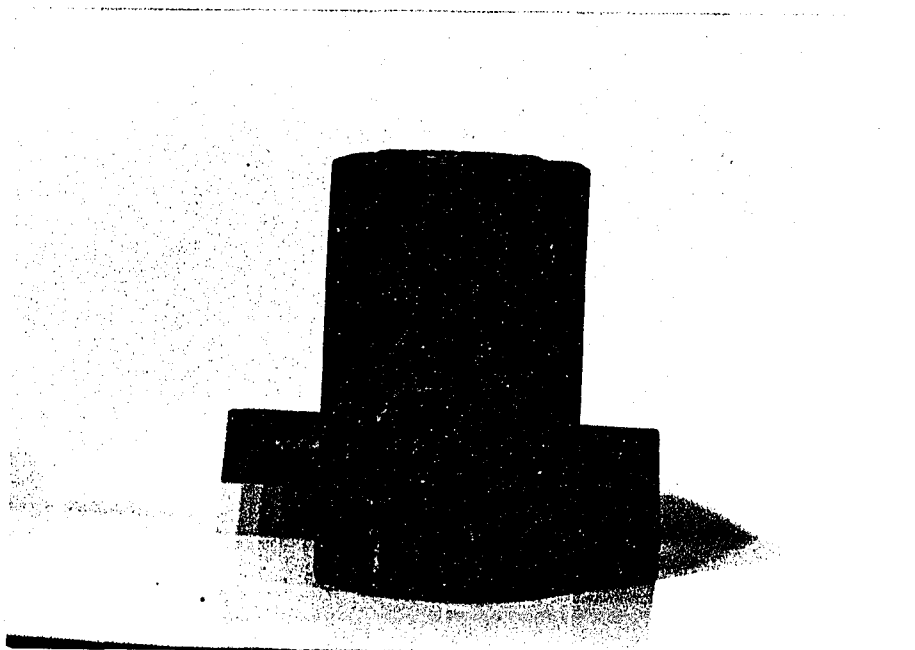


Figure 3.2. A 4.0 inch diameter tactite specimen after it was prepared in the laboratory.

varied. The use of cylindrical specimens also allowed evaluation of the changes in the permeability and the porosity taking place due to the leaching process. The solution travels along fractures, both *in situ* and in core leaching experiments. Core leaching experiments, therefore, more closely simulate the nature of the solution/rock interface *in situ* than column leaching experiments commonly used. Thus the variation in the flow characteristics within the specimen, and the copper content in the lixiviant resulting from such experiments, are similar to those occurring during *in situ* mining. Experiments performed with crushed rock material expose a much greater proportion of gangue mineralization to the leach solution than that expected in core leaching experiments. This could result in a leachant chemistry significantly different from that generated during *in situ* mining.

3.2 Specimen Characterization

In most of the specimens used for the experiments, mineralization was present along the fractures. As a part of the initial specimen characterization, fractures on the specimens were mapped on a matt acetate sheet. This was done by wrapping the matt acetate sheet around the specimen, and carefully marking the paths of the fractures on the surface of the specimen. Figure 3.3 shows the mapped fractures on the surface of a 1.5 inch diameter specimen. The figure indicates the approximate nature and extent of fractures on the surface of the specimen used for experimental work. The distribution appears to be quite random. However, since most of the flow in a core specimen is expected to take place along the fractures, it is important to know the extent of the fractures in the specimens. It was found that the permeability of the specimens generally increased with increase in the extent of the fracture network visible on the surface of specimen. But in some cases, specimens with very few fractures had relatively high permeabilities. This might be due to the large apertures of the fractures, or the fracture distribution within the

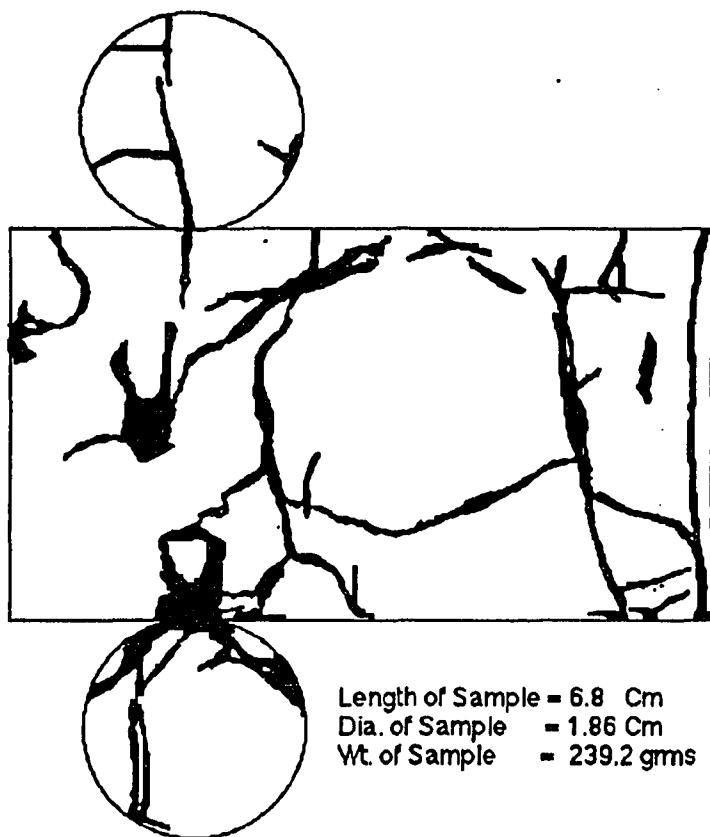


Figure 3.3. Map of the visible fractures on the surface of the specimen.

specimen. With continued leaching, most specimens eventually cracked along these fractures as the minerals were dissolved by the acid. As discussed later, soluble minerals included copper as well as non-copper material.

3.3 Lixiviant and the Method of Leaching

The lixiviant used for leaching the specimens was dilute sulfuric acid solution obtained from the Cyprus Casa Grande mine. This is the "leach field feed" which is used to leach the oxide ore body at the mine site. The lixiviant contains about 25 grams of sulfuric acid per liter of the solution.

The specimens used in the experiments were leached by placing the specimens in a beaker containing the lixiviant for different periods of time which ranged from 8 to 15 days. Figure 3.4 shows a tactite specimen being leached in a beaker containing the lixiviant. The lixiviant in the beaker was not changed during this leaching period. Evaporation of the lixiviant during this leaching period was minimized by covering the beaker containing the specimen and the lixiviant with aluminum foil.

It is well realized that the flow of the solution in the specimen was of the diffusion type since there was no pressure gradient across it. However, it was felt that this affects only the rate of flow because diffusional flow is significantly slower than viscous, or Darcian, flow. The resulting change in permeability and porosity would still be similar, but slower. Flowing the solution through the specimen with a pressure gradient across it was not possible with this experimental setup due to the acidic nature of the solution.

3.4 Sequence of Experiments

The objective of this experimental investigation was to estimate the porosity and permeability of the specimen during various intervals of leaching. The rate of recovery of

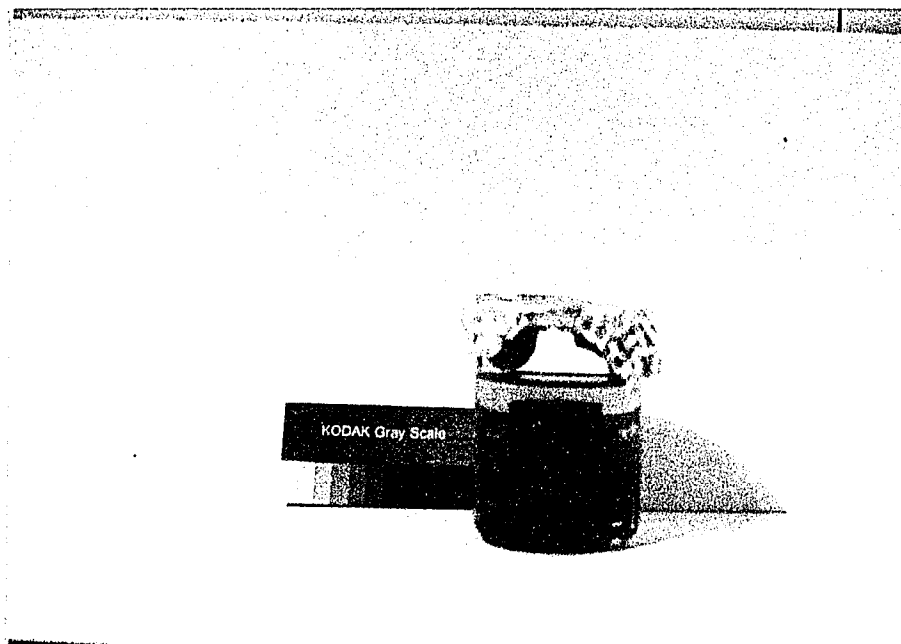


Figure 3.4. A tactite specimen being leached in a beaker containing the lixiviant.

copper from the specimen during this process was also measured. To obtain all of this information, the following sequence of experiments was carried out for each specimen.

- 1) After the specimen was prepared, it was placed in the oven at 105 °C until its weight stabilized; the specimen was then weighed.
- 2) The permeability of the specimen was measured using either helium or distilled water. Dry specimens were used for testing with helium, and water saturated specimens were used when the permeability of the specimen was measured using water.
- 3) After the permeability test, the specimen was saturated with water and the volume of water in the specimen at saturation was measured. Effective porosity of the specimen was thus calculated using the bulk volume, dry weight, and the water content of the specimen at saturation.
- 4) The specimen was then immersed in a beaker containing the leach solution or lixiviant obtained from Cyprus Casa Grande Mine. The specimen was leached for varying intervals of time.
- 5) At the end of the leaching period, the copper content of the lixiviant was measured to estimate the rate of copper recovery from the specimen.
- 6) After the leaching process, the specimen was dried, weighed and the permeability of the specimen was measured again using either helium or distilled water. The specimen was then saturated with water to estimate the pore volume in the specimen and its porosity was calculated.

This sequence of experiments was repeated at various intervals of time during the leaching process.

3.5 Measurement of Effective Porosity

The effective porosity of the specimen was estimated by measuring the bulk volume of the specimen and the effective pore space within the specimen. The water saturation method was used to measure the effective pore space within the specimen. In this method, the specimen was dried at 105 °C and its weight was monitored every 12-24 hours until its weight stabilized. This is the weight of the dry specimen. After the drying process, the specimen was allowed to cool down to room temperature. It was then water saturated by placing it in a beaker containing distilled water. The specimen was weighed at regular intervals of time and the saturation curve, that is, the weight of the specimen versus time, was drawn for each specimen. It was assumed that specimen reaches saturation when there is essentially no change in the weight of the specimen with time during the saturation process. The volume of water within the specimen, which is the effective pore space, was calculated using the density of water as 1 g/ml. The bulk volume of the specimen was calculated by measuring the dimensions of the specimen. The effective porosity of the specimen was, therefore, calculated using the standard expression:

$$\text{Eff. Porosity} = \frac{(\text{Wt. of Sat. specimen} - \text{Wt of Dry Specimen}) \text{ in grams}}{(\text{Volume of the specimen}) \text{ in cm}^3} \quad (3.1)$$

3.6 Permeability Measurement

The primary objective of this investigation was to study the variation in permeability of the specimen with time during the leaching operation. The initial permeability of the rock specimens before leaching was very small - in the order of 10^{-16} m^2 (0.1 md). Due to the low permeabilities of the rock specimens, it was difficult to estimate the permeability using water. Therefore, a recourse had to be taken to measure the intrinsic or equivalent liquid permeability of the specimens using a gas. However, with continued leaching, the

permeability of the specimens increased considerably, and it was possible to measure the permeability using water after few days of leaching. The initial permeability of the specimen was, therefore, measured using a gas. However, after a few days of leaching, the permeability of the specimens was determined using water. The technique of using a gas to estimate the intrinsic permeability of rock is discussed in section 3.6.2.

3.6.1 Permeability to Water

The permeability of the specimen was measured using water by conducting a steady-state flow test on the specimen. A constant pressure gradient was applied across the two ends of the specimen and the volumetric flowrate through the specimen was measured after ensuring that steady state flow conditions were attained. Darcy's law for steady state flow of an incompressible fluid through a porous media was used to estimate permeability. This is given as (Carman, 1956):

$$Q = \frac{k A}{\mu} \frac{\Delta P}{\Delta L}$$

or, $k = \frac{Q \mu}{A} \frac{\Delta L}{\Delta P}$ (3.2)

where, k is the permeability of the media (m^2), A is the area of cross section of the specimen (m^2), μ is the viscosity of the fluid (Ns/m^2), $\Delta P/\Delta L$ is the pressure gradient (N/m^2-m), and Q is the volumetric flowrate at the outlet end of the specimen (m^3/s). Using this equation, the permeability of the specimen was calculated for steady state volumetric flow through the specimen.

3.6.2 Gas Permeability

When a compressible fluid (i.e., a gas) is used to measure the permeability of a rock specimen, Darcy's law governing the flow of a liquid through a porous medium is modified. In the case of an incompressible liquid, the volume of liquid flowing through a porous specimen is constant under steady state conditions. But when a gas is used to measure the permeability, the volume of gas flowing through the specimen under steady state conditions is dependent upon the pressure at the outlet end of the specimen. However, since the mass flowrate remains constant throughout the specimen, mass flow rather than the volumetric flowrate is considered. Darcy's equation for flow of a compressible medium, therefore, takes a slightly different form. The complete derivation is given in Amyx et al., (1960). The final expression for permeability is given as:

$$k = \frac{Q \mu \Delta L}{A \Delta P} \frac{P_o}{P_m} \quad (3.3)$$

where, Q is the volumetric flowrate at the outlet end of the specimen (m^3/s), P_o is the pressure at the outlet end (N/m^2), P_i is the pressure at the inlet end (N/m^2), P_m is the mean gas pressure (N/m^2), and is equal to average of the pressures at the inlet and outlet ends of the specimen. The other variables are same as defined earlier.

It was further shown by Klinkenberg (1941) that the permeability of the specimen determined using a gas is not the same as the permeability of the specimen to a liquid, or the intrinsic permeability of the medium. Permeability of a porous medium to a gas is a function of the mean free path of the gas molecules, and thus depends on the factors which influence this. These factors are the pressure, temperature, and the nature of the gas. Figure 3.5 shows a plot of the observed permeability of a rock specimen as determined at various mean gas pressures and using three different gases - hydrogen, nitrogen, and

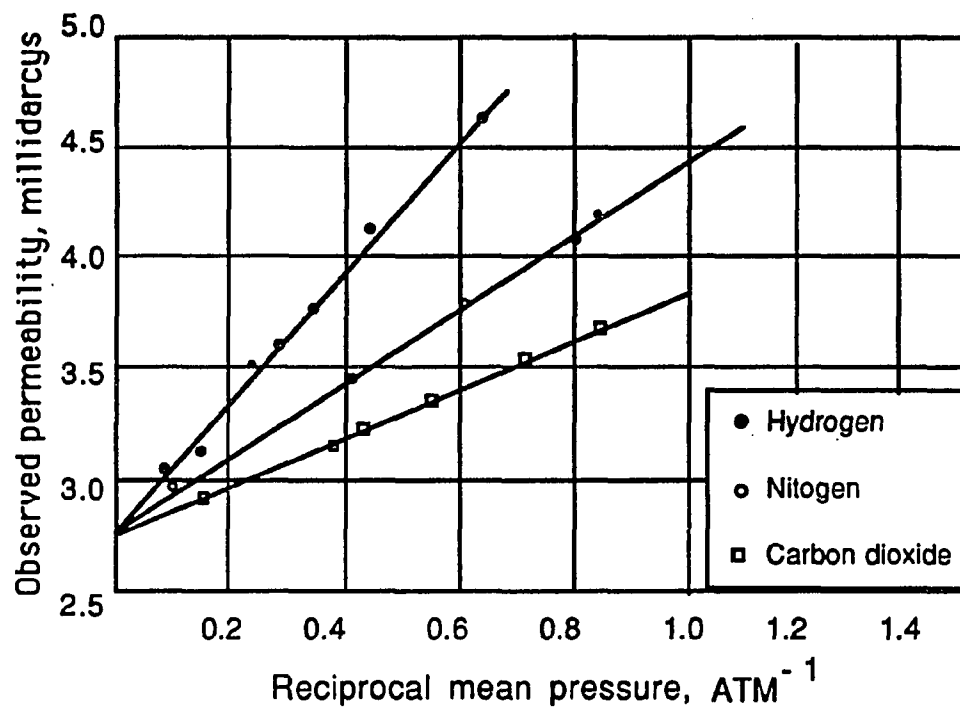


Figure 3.5. Permeability of a core sample to hydrogen, nitrogen, and carbon dioxide at different pressures (From klinkenberg, 1941).

carbon dioxide. As seen from the plot, the observed permeability of the specimen depends upon the mean pressure, and on the nature of the gas used to measure the permeability. But this figure also shows that for any particular gas, there is a linear relationship between the observed permeability and the reciprocal of the mean pressure of the test. This relationship between the observed permeability and the reciprocal of mean pressure is expressed as:

$$k_o = k \left(1 + \frac{b}{P_m} \right) \quad (3.4)$$

$$\text{and, } k_o = k \text{ at } P_m \approx \infty$$

where, k_o is the observed permeability, k is the intrinsic permeability of the medium or the permeability of the medium to a single phase liquid, P_m is the mean gas pressure, and b is a constant depending upon the nature of the gas used. As seen from this equation, the relationship between the observed permeability and the reciprocal of mean pressure is linear, with a slope, b , and an intercept equal to the intrinsic permeability of the medium. It is, therefore, possible to determine the intrinsic permeability of a medium using gas, by measuring the gas permeability of the medium at different mean pressures, and then extrapolating the linear relation between the observed permeability and reciprocal of mean pressure to infinite mean pressure or zero reciprocal mean pressure ($1/P_m = 0$). This method of estimating the permeability of rock specimens with low permeability has been found to be accurate (Stormont, 1990), and is commonly used in the oil and gas industry. The only precaution needed to use this method of approximation is that the inlet gas pressures should not exceed approximately 300 psi.

3.7 Experimental Setup

3.7.1 Water Permeability

It was decided to perform all permeability experiments with the specimens stressed triaxially in order to simulate the *in situ* conditions in the field. An experimental setup which permitted simultaneous control of applied stresses, applied fluid pressure, and measurement of flowrate through the specimen was designed. Figure 3.6 shows the experimental setup used to perform the permeability experiments. The setup consists of a positive displacement pump, pressure gauges to measure the pressures at the upper and lower ends of the specimen and control valves to apply the pressures. A triaxial cell connected to a hydraulic pump provided the confining stress. The axial stress was applied by placing the cell in a load frame of capacity 1 MN (Cobb and Daemen, 1982). A series of pressure gauges monitored the applied stresses and fluid pressure.

A triaxial cell, originally designed by Hoek and Franklin, was slightly modified for permeability testing (Hoek and Franklin, 1964). Figure 3.7 shows a cross section of the triaxial cell. The synthetic rubber sleeve in the cell sealed off the cylindrical surface of the specimen from an annulus of oil which was pressurized with a hand operated hydraulic pump. A pressure gauge attached at the oil inlet of the triaxial cell measured the confining pressure. To measure the permeability, the cell was modified to provide inlet and exit ports through the upper and lower platens. Figure 3.8 shows the triaxial cell, holding a 1.5 inch diameter specimen, placed in a loading frame. The axial and confining stresses on the specimen were applied using hand operated pressure pumps. Figure 3.9 shows the schematic of the experimental setup used to measure the permeability of the specimen using water. The specimen to be tested was inserted into the cell and upper and lower platens were then inserted into the ends of the cell. To collect the fluid uniformly from the entire surface of the specimen, two 1/4 inch thick stainless steel discs with 0.125 inch diameter

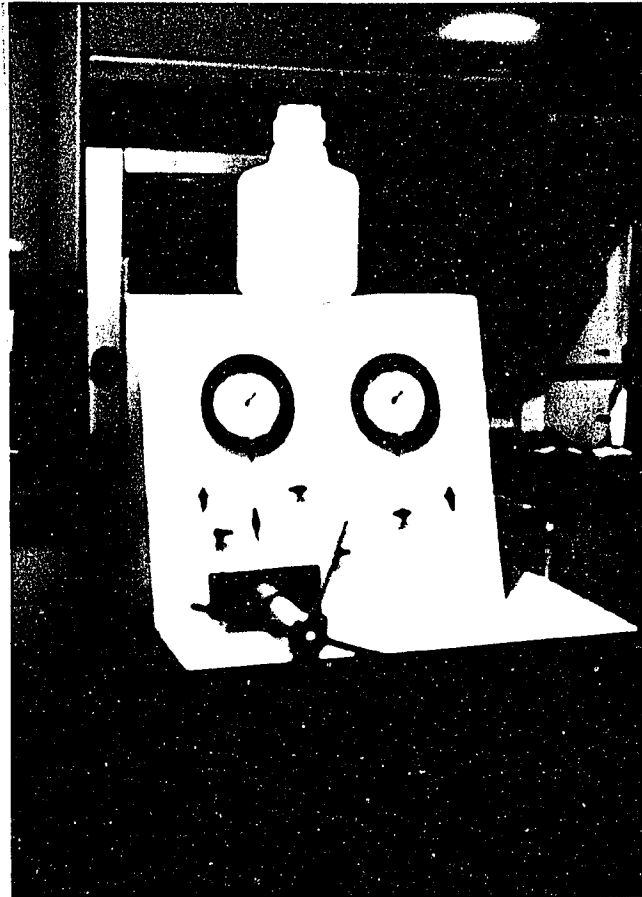


Figure 3.6. Experimental panel that was constructed to perform the permeability experiments.

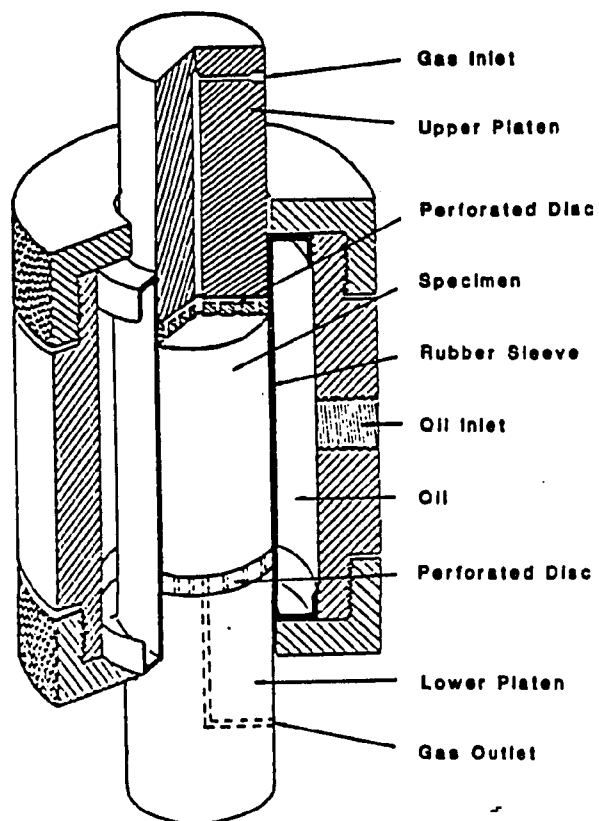


Figure 3.7. Cross section of a triaxial cell.

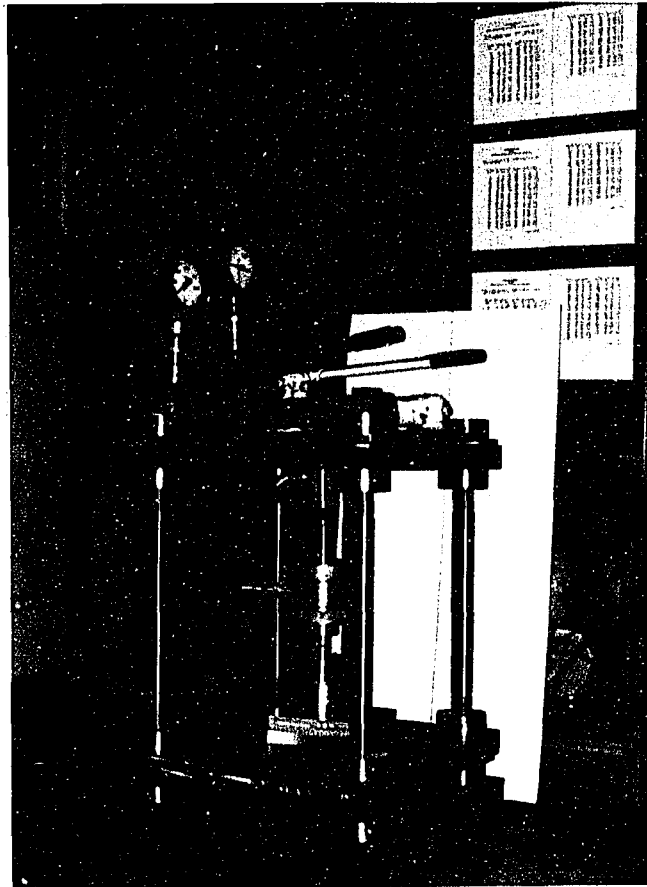


Figure 3.8. A triaxial cell holding an 1.5 inch diameter specimen, placed in a loading frame.

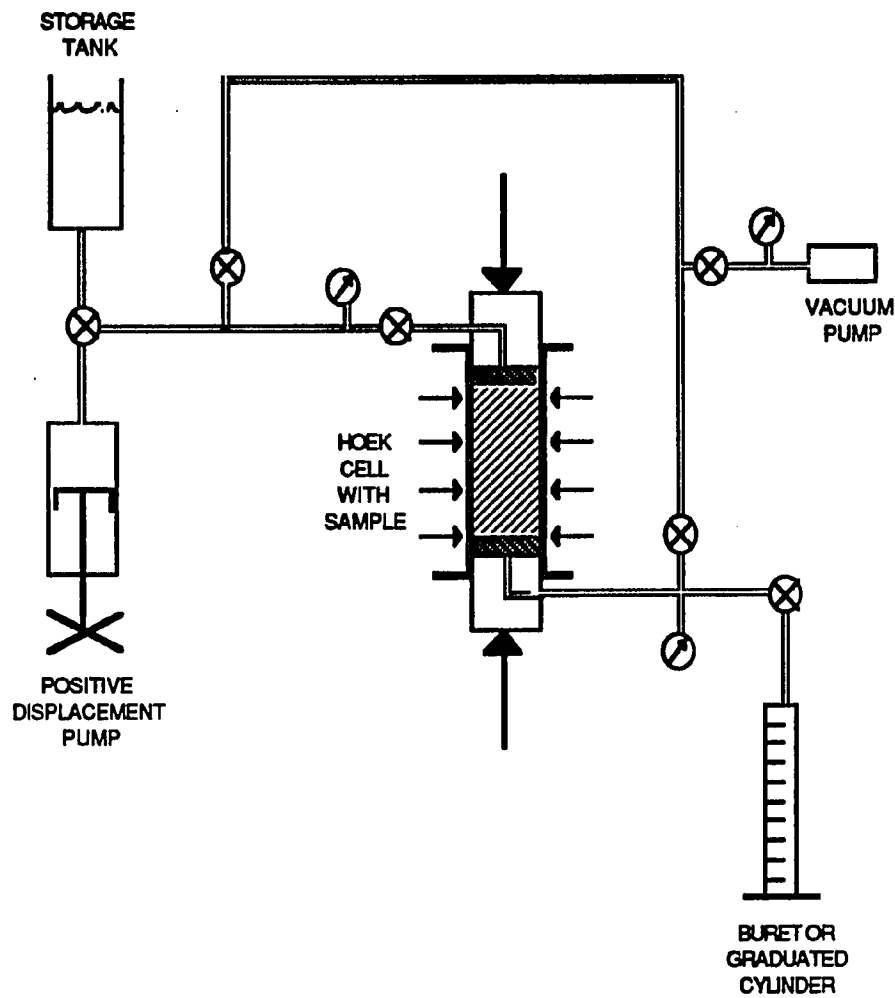


Figure 3.9. Schematic of the experimental setup used to measure the permeability of a specimen using water.

holes were placed between the specimen and the platens. Water from the reservoir was applied at a certain pressure at the upper end of the specimen using a positive displacement pump. The flowrate through the specimen was measured using a measuring flask.

3.7.2 Gas Permeability

The experimental setup as designed to measure the permeability of the specimen using water was modified slightly when using a gas. Figure 3.10 shows the modified experimental setup for permeability measurement using a gas. The gas flowrate through the specimen was measured using a soap bubble flow meter. Figure 3.11 shows the schematic of the experimental setup used to measure the permeability of the rock specimen using a gas. In this setup, the method of applying the axial and confining stresses is the same as described earlier. Helium was supplied at a certain pressure at the upper end of the specimen, and the flowrate through the specimen was measured at the downstream end using a soap bubble flow meter. The bubble meter is capable of measuring gas flowrate at standard pressure and temperature with errors of less than 1% for flows ranging from 0.1 to 1000 ml/min (Levy, 1964). When laboratory conditions are different from the standard pressure and temperature, the measured flow rates are usually adjusted to take into account this discrepancy. A standard bubble meter is shown in figure 3.12. A vacuum pump was sometimes used to dry any water vapor present in the system before performing the permeability experiments. Figure 3.13 shows the complete experimental setup that was used to measure the permeability of the specimen using a gas.

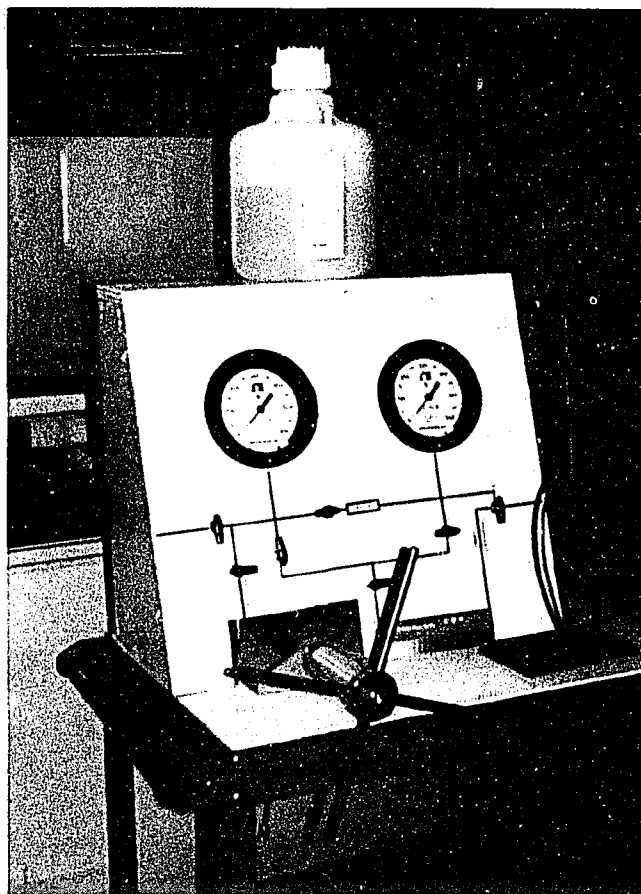


Figure 3.10. Experimental panel modified to be used in permeability measurement experiments using a gas.

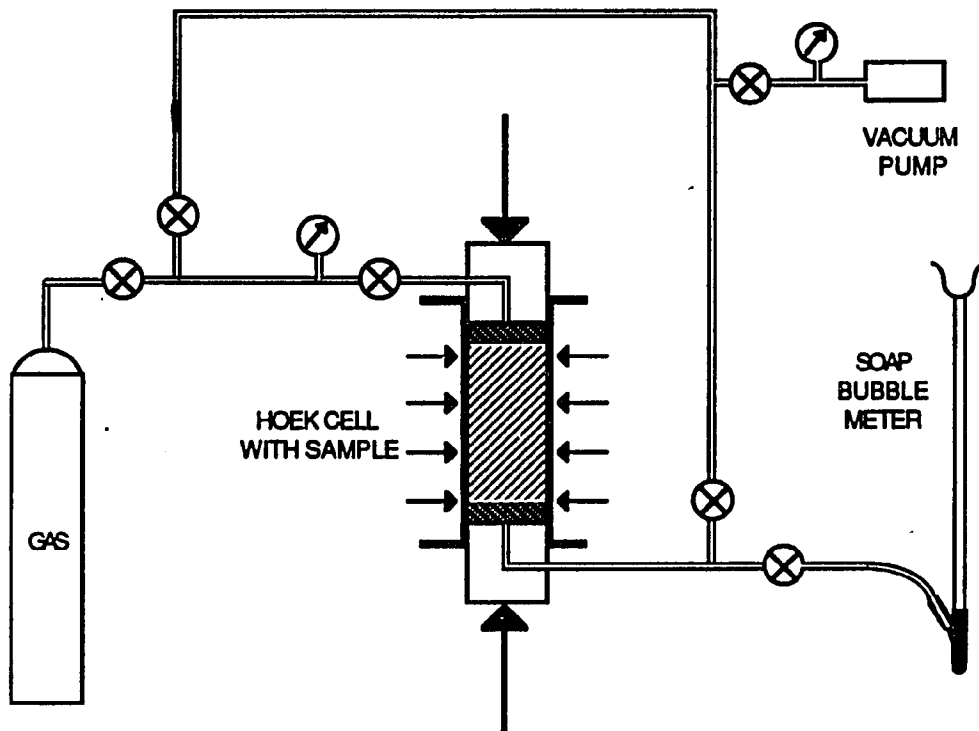


Figure 3.11. Schematic of the experimental setup used to measure the permeability of a specimen using a gas.

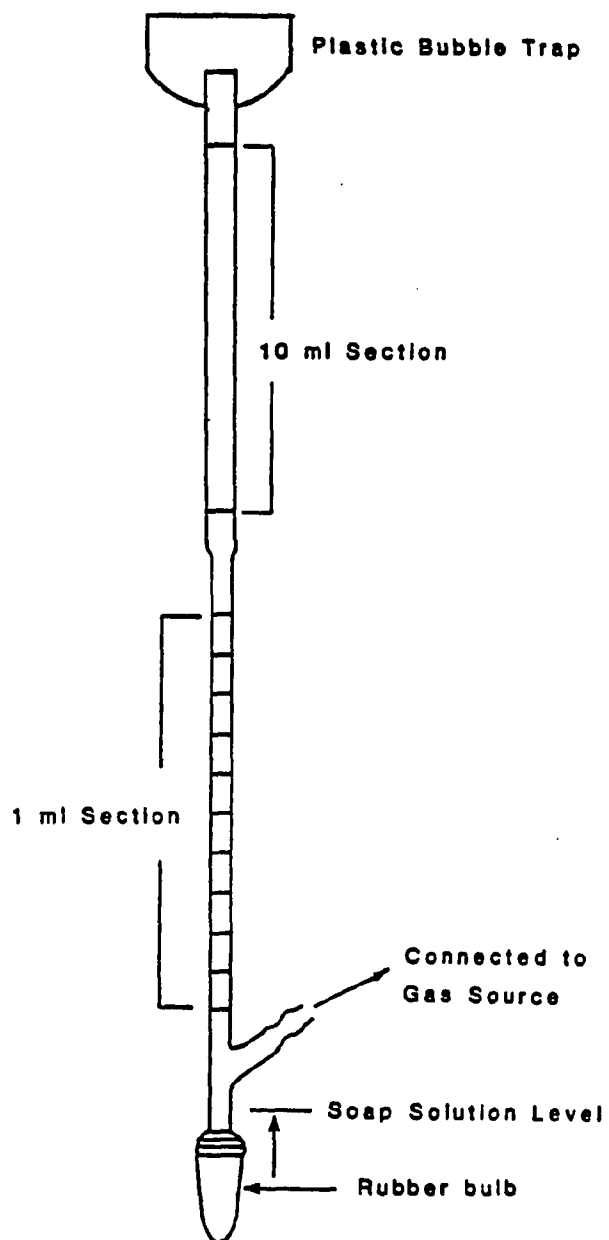


Figure 3.12. Soap bubble flow meter.

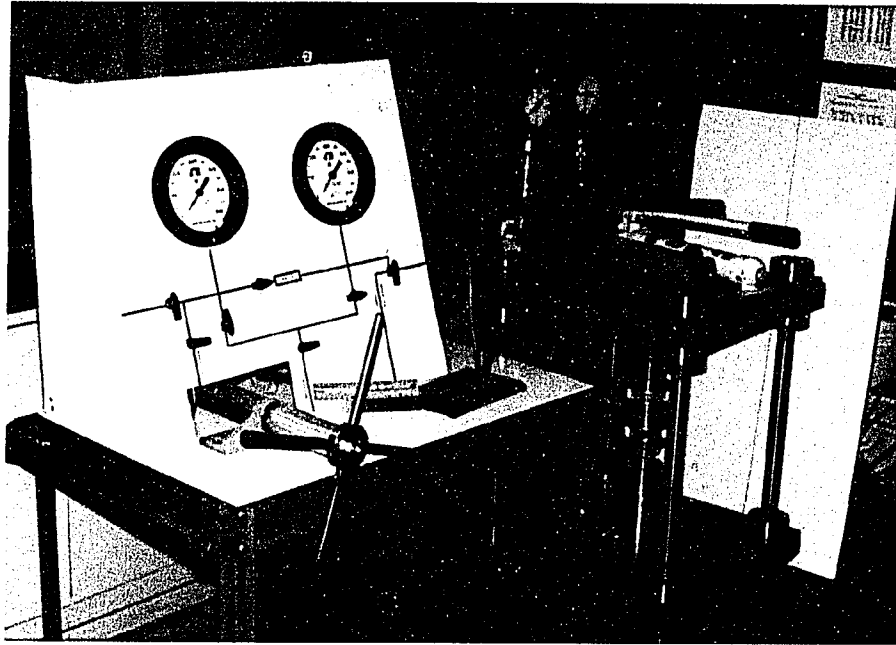


Figure 3.13. Complete experimental setup that was used to measure the permeability of the specimen using a gas.

3.8 Experimental Procedure

For permeability tests using water, the specimen to be tested was saturated with water prior to the experiment. The specimen was then inserted into the hoek cell. Two steel perforated discs were fitted, one on either side of the specimen. Next, the two platens were inserted into the ends of the cell. The triaxial cell was placed in the load frame to apply the axial load on the specimen. Confining stress was applied using a hand operated hydraulic pump attached to the hoek cell. The upper platen was connected to the positive displacement pump. The flowrate through the specimen was measured using a measuring flask and a stop watch. The flowrate through the specimen was measured at 30 minute intervals until three consecutive measurements were similar to ensure that steady state flow conditions were attained within the specimen being tested.

For measurement of permeability using a helium, a dry specimen was used. The experimental specimen was inserted into the hoek cell. Two steel perforated discs were then fitted, one on either end of the specimen. Next, the two platens were inserted into the ends of the cell. The upper platen was connected to the gas cylinder, and the lower platen to a soap bubble meter. The hoek cell was placed in the load frame to apply the axial load on the specimen. Confining and axial stresses were applied to the specimen. The two were kept equal, that is, hydrostatic stress conditions were maintained.

Helium was used for these permeability tests since it does not get adsorbed on to the surface of the rock, and also the small molecular diameter and light weight of helium molecules ensure maximum penetration and flow through the microfractures present in the specimen. A pressure of 50 psi was applied at the upper end of the specimen using a regulator, and the flowrate at the lower end was measured at 30 minute intervals until three consecutive flow measurements were similar to ensure that steady state flow conditions.

Once this occurred, the gas pressure at the upper end of the specimen was increased in increments of 50 psi up to 300 psi, and the procedure was repeated.

3.9 Estimation of Copper Recovery Rate

The rate of copper recovery from the specimen during leaching was estimated by measuring the copper content of the solution used to leach the specimen. The specimens were leached by placing them in beakers containing the lixiviant. At the end of each leaching cycle, the copper content of the lixiviant was estimated using an atomic absorption spectrometer. The atomic absorption spectrometer measures accurately up to 7 mg/l of copper in the solution. The pregnant leach solutions with dissolved copper, therefore, had to be diluted in order to measure the copper content. Using this measured concentration of copper and the quantity of the lixiviant used to leach the specimen, the amount of copper recovered from the specimen during each leaching cycle was determined. Evaporation of the leachant during leaching was minimized by covering the beakers containing the specimen and the leachant with aluminum foil.

After the specimens were leached for about 75-90 days (ie, after 6-8 leaching cycles) most specimens cracked along the fractures and it was not possible to continue permeability and porosity measurements of the specimens. The specimens were, therefore, crushed into small pieces using a hand held hammer and leached in the lixiviant for about 10 to 15 days. The copper content of this solution was estimated in order to determine the amount of copper left in the specimen. The sum of the copper recovered from the specimen during the leaching cycles, and the copper recovered from the crushed specimen at the end of the leaching cycles, gave the total leachable copper content of the specimen, assuming that solution access to the entire leachable portion of the rock is possible.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Variation in Porosity

The changes in the flow characteristics during leaching, that is, the variation in porosity and permeability of both the 1.5 inch and 4.0 inch diameter specimens were monitored. Four 1.5 inch diameter specimens and two 4.0 inch diameter specimens were used in the experiments.

The saturation curve for each specimen was drawn for a period of 400 hours. Figure 4.1 shows the saturation curve for one specimen. The plot clearly indicates that there is very little increase in the volume of water absorbed by the specimen after 72 hours. The effective porosity of the specimen after each leaching cycle was, therefore estimated by measuring the amount of water absorbed by the dry specimen during a period of 72 hours. The initial porosity of the specimens varied from 9% to 18%. Also, the porosity of the large 4.0 inch diameter specimens was in the same range as the 1.5 inch diameter specimens. However, the effective porosity of the specimen always increased with the amount of leaching. The variation in the observed porosity of the specimen, measured as a ratio of the initial porosity, is shown in Figure 4.2. The results indicate that the initial rate of increase in the porosity of the specimen was slow. But after about 15 days of leaching, the porosity increased more rapidly. This rapid rate of increase in porosity continued for 60 days of leaching, after which the rate of increase in porosity gradually decreased as the soluble material available within the specimen was depleted. Over an 80 day period, the effective porosity increased by over 50% of the initial porosity. This suggests formation of

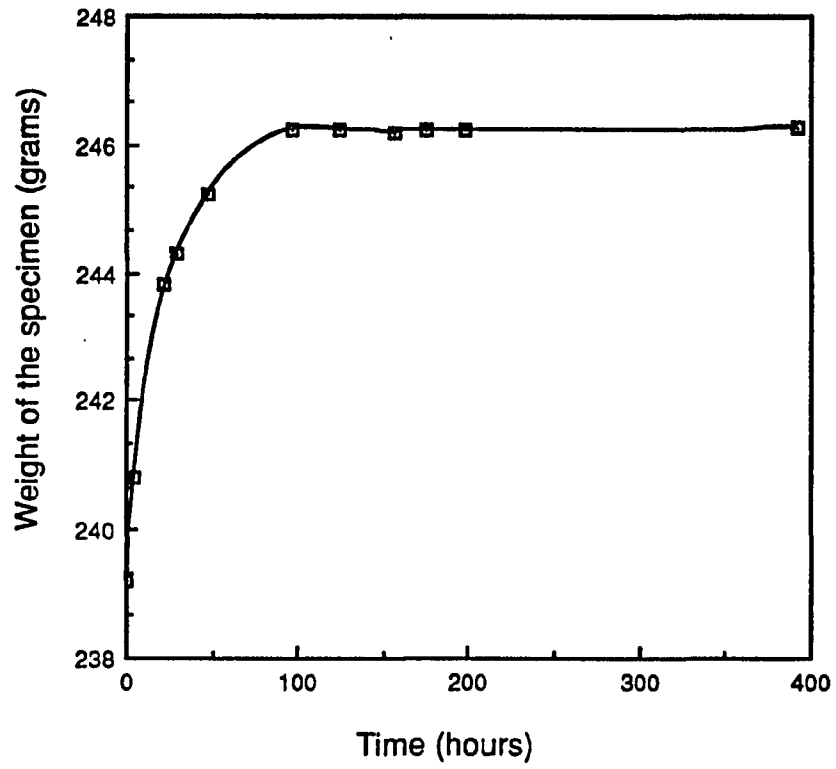


Figure 4.1. Saturation curve of the specimen.

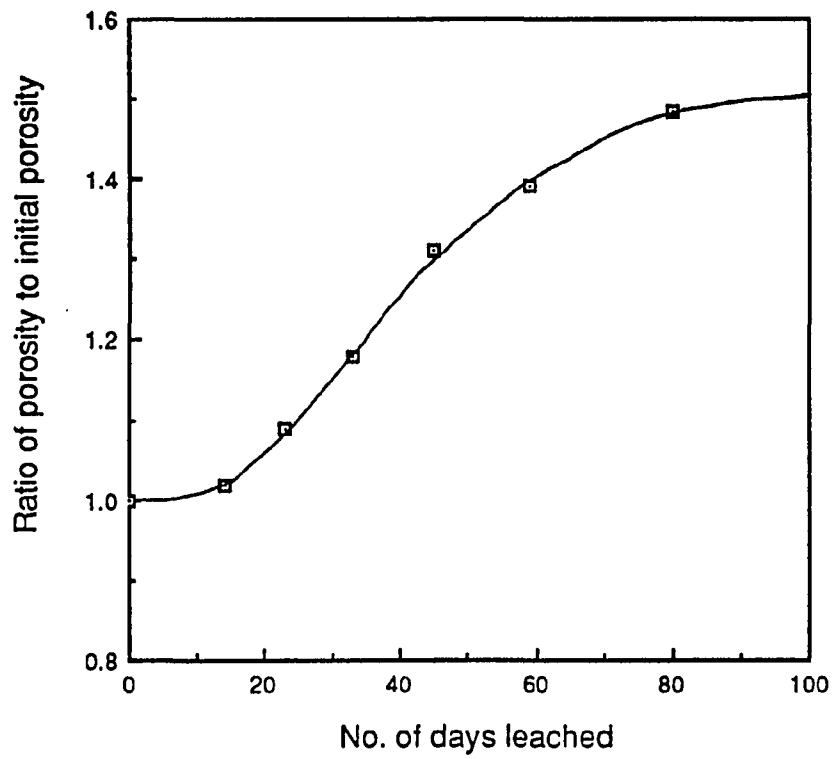


Figure 4.2. Variation in porosity with time as leaching progresses.

new void space within the specimen as soluble material dissolves in the acid, and is removed.

4.2 Variation in Permeability

The permeability of the unleached rock specimens was very low and was extremely difficult to estimate using water. Helium was, therefore, used to estimate the initial intrinsic or equivalent liquid permeability of the specimens. But as the specimens were leached, their permeability increased considerably, and it was possible to measure the permeability of the specimen using water after few days of leaching.

As explained in section 3.8, the specimen was subjected to different pressure gradients and the permeability of the specimen to helium was determined. Figure 4.3 shows the observed permeability of the specimen to helium measured at each pressure gradient, plotted as a function of the reciprocal mean pressure applied during the test. The linear relationship between the observed permeability and the reciprocal mean pressure applied during the test suggests a definite Klinkenberg effect. A sample calculation, along with the Klinkenberg plot, is presented in Appendix A. The equivalent liquid permeability of the sample was estimated by extrapolating this linear relationship to infinite mean pressure (reciprocal of mean pressure = 0). This exercise was repeated after each permeability test. But when water was used to measure the permeability, a pressure gradient was applied across the two ends of the specimen and the flowrate through the specimen was measured to estimate the permeability.

The variation in the intrinsic or equivalent liquid permeability of the specimen as leaching progresses is shown in Figure 4.4. The percentage increase in permeability from one leaching cycle to the next is high initially. This rate of increase in permeability gradually decreases as leaching progresses indicating that after a certain period of leaching,

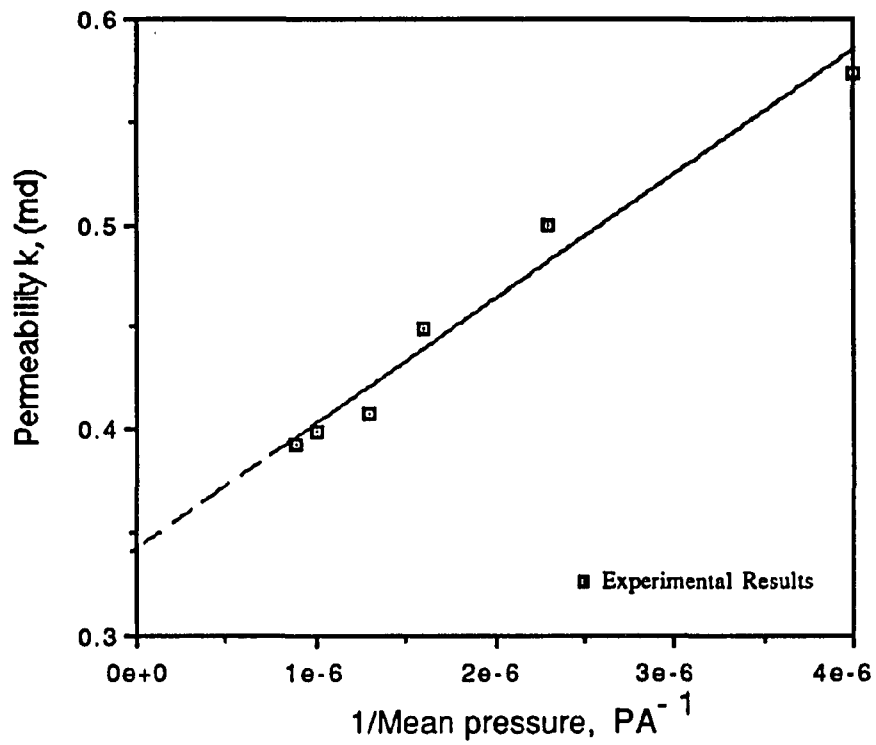


Figure 4.3. Permeability at various pressure gradients as a function of reciprocal of mean pressure.

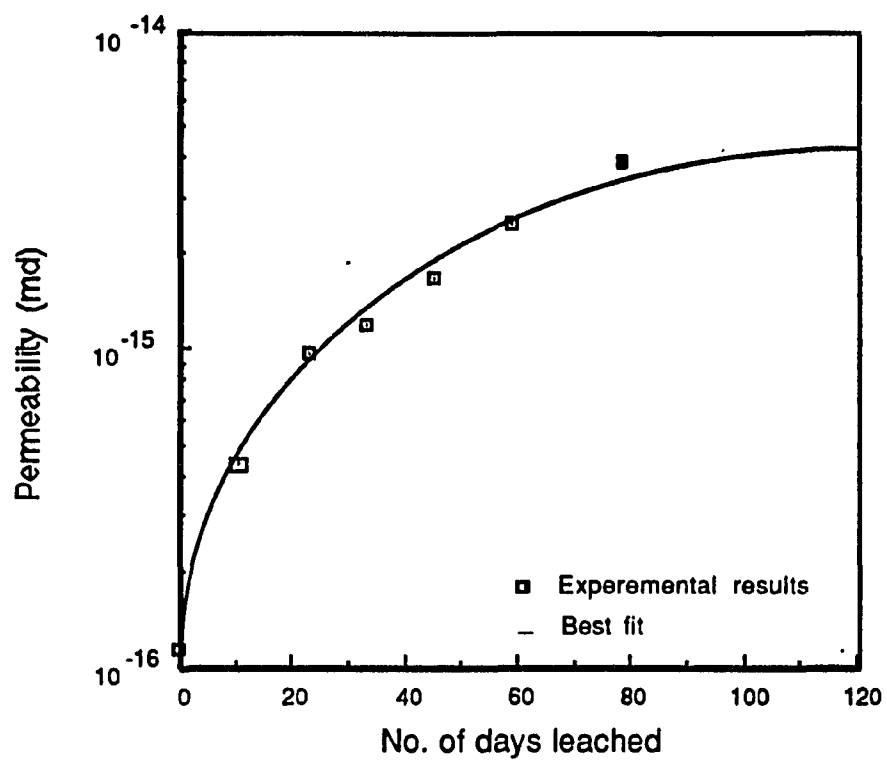


Figure 4.4. Variation of permeability of the specimen during leaching.

the specimen will reach a condition when there is no increase in its permeability with further leaching. This stage probably corresponds to the physical condition when all the soluble material within the specimen is dissolved. Unfortunately, the specimens in the laboratory could not be leached long enough to attain this condition of constant permeability, as most of them cracked along the existing fractures with continued leaching. Figure 4.5 shows a broken 1.5 inch diameter specimen and figure 4.6 shows a 4.0 inch diameter specimen which cracked into a number of pieces. In fact, most specimens disintegrated into several small pieces once the minerals present along the fractures were leached, making any further measurements impossible.

4.3 Validity of Darcy's Law

Darcy's equation for flow of liquids through a porous medium, or Darcy's equation modified for flow of compressible fluids, was used for all permeability calculations. The results were examined to determine whether Darcy's law was, in fact, valid for the flow regimes encountered in the experiments, since it is valid only for laminar flow. Scheidegger, (1974) observed that for flow of gases through a porous media, the value of Reynolds (Re) number above which Darcy's law is no longer valid ranged between 0.1 and 75. This uncertainty of a factor of 750 in the 'critical' Re number is due to differences in the pore structure of different types of rocks.

For this investigation, the pore size distribution of the specimens could not be determined. However, to be well within the laminar regime, Re number of 0.1 was considered to be acceptable. The Reynolds number equation for flow through a porous media is given as (Freeze and Cherry, 1979):

$$Re = \frac{D v r}{\mu}$$

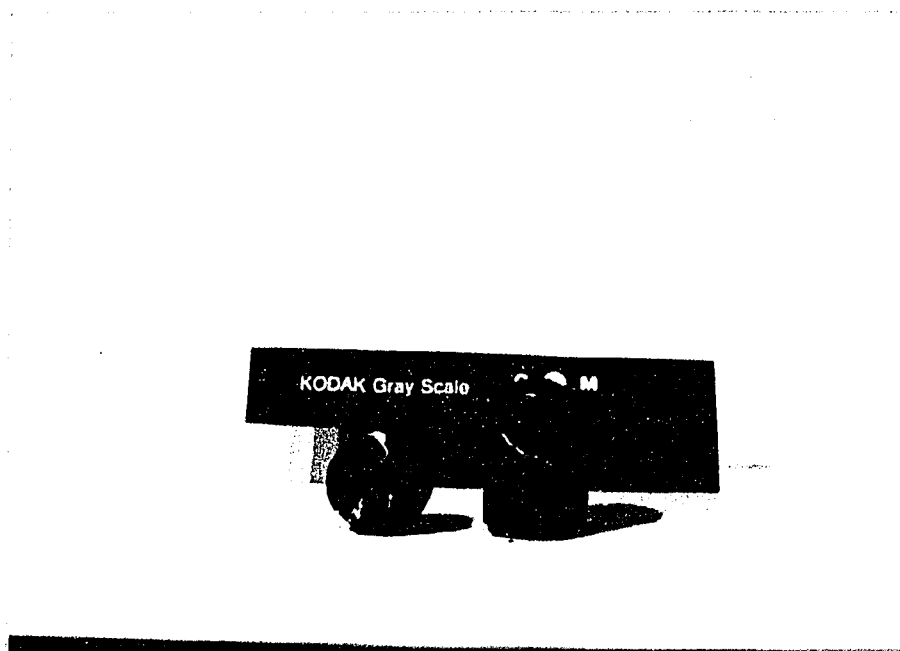


Figure 4.5. A 1.5 inch diameter specimen that broke into two pieces after 80 days of leaching.

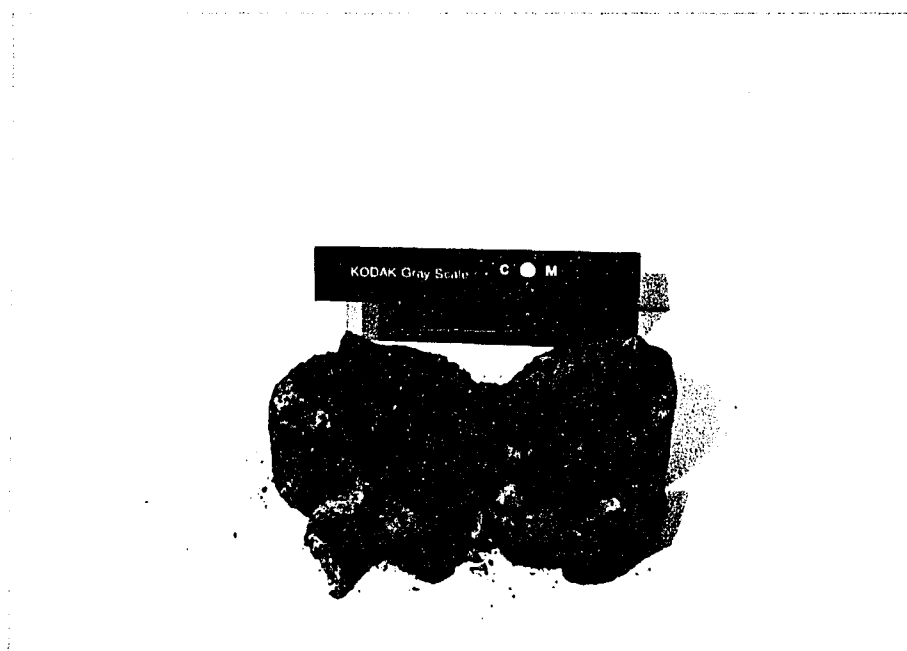


Figure 4.6. A 4.0 inch diameter specimen that broke into a number of small pieces after 67 days of leaching.

where, Re is the Reynolds number, v is the average velocity of flow, ρ is the fluid density, μ is the fluid viscosity, and D is the grain diameter.

The highest flowrate observed during the investigation was 24.39 ml/s. Area of cross-section of the sample was 10.87 cm². Therefore, average velocity, $v = 2.24$ cm/s. Density of helium at 24 °C is 0.1785 kg/m³ and viscosity is 1.941×10^{-5} Ns/m². Re can thus be calculated:

$$Re = \frac{D \times 0.0224 \times 0.1785}{1.941 \times 10^{-5}}$$

$$Re = 206 D$$

$$\text{for } Re = 0.1, D = \frac{0.1}{206} = 4.85 \times 10^{-4} \text{ m}$$

$$D = 0.485 \text{ mm}$$

Visual observation of the specimen showed that the grain diameter was less than 0.4 mm, and therefore, the flow regime is laminar for all flowrates.

For flow of water through a porous media, it was shown that Darcy's law is valid for $Re < 1$ and does not depart seriously upto $Re = 10$ (Ahmed and Sunada, 1969). This represents an upper limit to the validity of Darcy's law. However, to be well within the laminar regime, Re number of 1 was considered acceptable.

The highest flowrate observed during the permeability measurement experiments using water was 0.048 ml/s. Area of cross-section of the sample was 10.87 cm². Therefore, the average velocity of flow is 0.0044 cm/s. Density of water at 24 °C is

997.07 kg/m³ and viscosity is 0.9325 x 10⁻³ Ns/m². Re can thus be calculated as shown below:

$$Re = \frac{D \times 0.000044 \times 997.07}{0.9325 \times 10^{-3}}$$

$$Re = 47 D$$

$$\text{for } Re = 1, D = \frac{1}{47} = 2.13 \times 10^{-2} \text{ m}$$

$$D = 2.13 \text{ cm}$$

Visual observation of the specimen showed that the grain diameter was less than 2.13 cm, and therefore, the flow regime is laminar for all flowrates.

4.4 Variation in Copper Recovery Rate

The rate of copper recovery and the percentage of total copper in the specimen that can be recovered through leaching, are two important factors in the evaluation of economic feasibility of an *in situ* leaching project. The total amount of copper recovered, as a percentage of the total copper in the specimen that can be recovered through leaching, is shown in Figure 4.7. In general it was found that after about 70 to 80 days and 6 cycles of leaching, about 70 to 85% of total copper in the specimen was recovered. The flattening of this curve indicates that after an initial high rate of copper recovery, it gradually decreases as the copper in the specimen is depleted. The decrease in the rate of copper recovery can be seen more prominently in Figure 4.8 which shows the variation in the amount of copper recovered per day of leaching. This figure shows that there is an initial increase in the amount of copper recovered per day of leaching. However, soon after reaching a

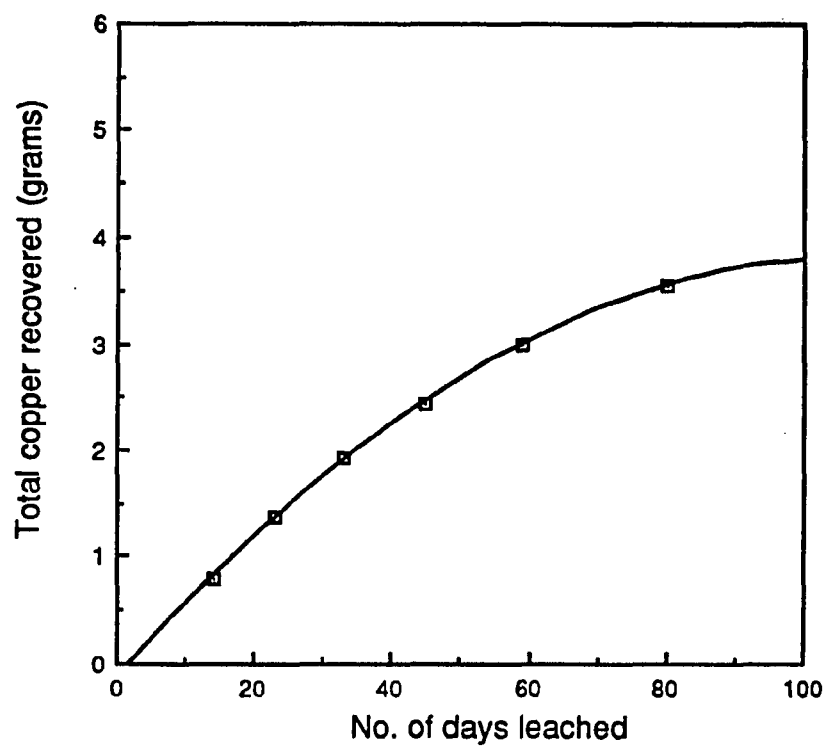


Figure 4.7. Total copper recovered from the specimen as leaching progresses

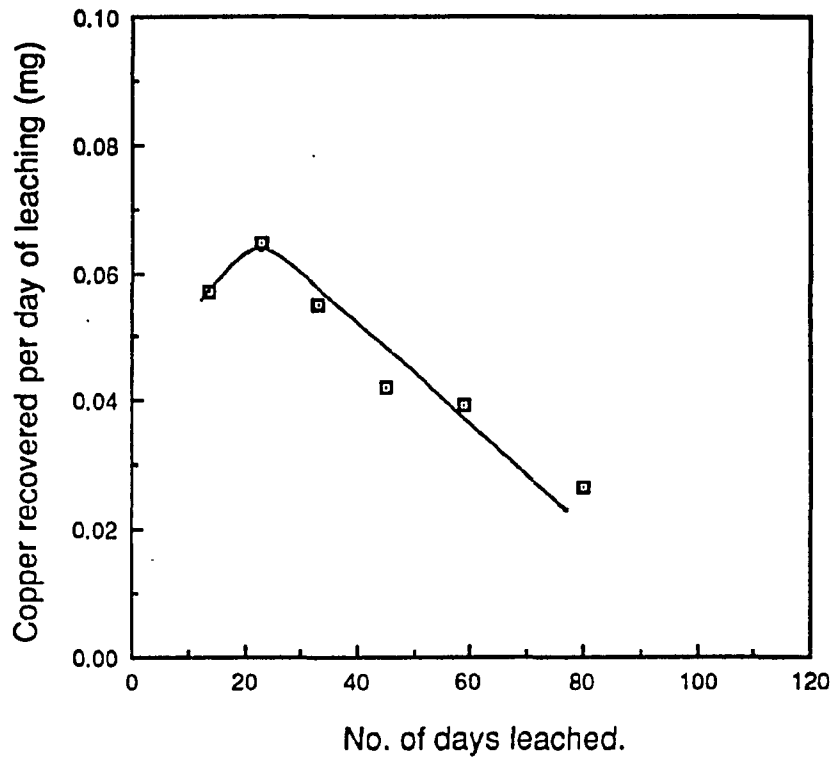


Figure 4.8. Amount of copper recovered per day of leaching.

maximum, the rate starts decreasing as leaching progresses. This suggests that the amount of copper recovered per day of leaching decreases as the copper available within the specimen is depleted, except for the initial hump. This trend in the amount of copper leached was observed in each specimen tested.

Figure 4.9 shows the loss in the weight of the dry specimen and the total copper recovered from the specimen. Initially, 70% of the material dissolved by the leach solution is copper. This is perhaps due to the fact that copper oxide, which is mostly present along the fractures of the specimen, is more easily accessible to the leach solution. But once this is depleted, more of the other minerals present in the rock specimen dissolve in the acid. At the end of 80 days of leaching, copper forms only 32% of the total material dissolved from the specimen, although there is an increase in the overall material dissolved by the raffinate.

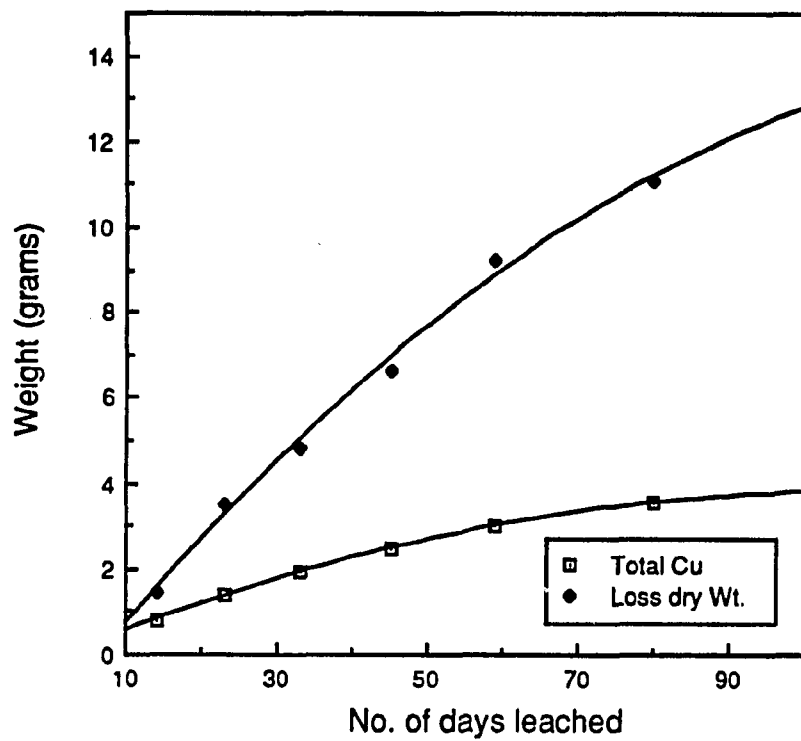


Figure 4.9. Loss in weight of dry specimen and the total copper recovered from the specimen.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions and Implications

Permeability testing of the tactite core specimens showed that there is a definite increase in the permeability as leaching progresses. The rate of increase in permeability is high initially even though the corresponding increase in the porosity of the specimen for the same leaching period is comparatively low. This rapid increase in the permeability of the specimen during the initial period of leaching might, therefore, be due to the dissolution of copper mineral(s) present along the fractures, thus opening new fractures and widening the existing fractures. A part of the increase in permeability might also be due to dissolution of the matrix material. However, it was felt that this would not be significant as the flow of the lixiviant through the matrix is much slower. Most specimens broke along the fractures after leaching for a period of 60 to 80 days confirming the dissolution of copper mineral(s) present along the fractures. Also, the topographic imaging of the specimens during the leaching process has shown that there is a considerable increase in the number of fractures present in a specimen during the first few days of leaching (Harpalani et al., 1991). These new fractures are formed when the copper mineralization present within is dissolved by the lixiviant.

The rate of increase or the percentage increase in permeability from one leaching cycle to the next decreases with leaching. This indicates that after a certain period of leaching, the specimen will reach a condition when there is no increase in its permeability with further leaching. This stage probably corresponds to the physical condition when all the soluble material within the specimen is dissolved. The specimens in the laboratory

could not be leached long enough to attain this condition of constant permeability, as most of them cracked along the existing fractures with continued leaching. The permeability of the specimens increased by 1 to 2 orders of magnitude after about 60 days of leaching. Also, no significant difference in the variation of flow characteristics of 1.5 inch and 4.0 inch diameter specimens was observed.

The effective porosity of the specimens increases with leaching. The rate of increase in porosity is slow initially, followed by a relatively rapid rate. This is, once again, due to the dissolution of soluble material in the specimen. The initial slow increase in porosity might be due to dissolution of mostly copper minerals(s) present along the fractures, during the first few days of leaching. But as leaching progresses, matrix flow increases leading to dissolution of soluble rock material as well. This causes a more rapid increase in porosity as seen from the porosity measurements. After about 60 days of leaching, the rate of increase in porosity decreases gradually as the soluble material available within the specimen is depleted. On an average, the porosity of the specimens increased by over 50% of the initial porosity when the specimens were leached for 60 to 80 days.

The rate of copper recovery from the specimen during the leaching process is high initially, but reduces as leaching progresses. This is due to exhaustion of the copper available in the specimen. Initially, copper forms a major part of the material dissolved from the specimen, but with continued leaching, there is a substantial amount of non-copper material being removed from the specimen. This is due to depletion of copper present along fractures and due to increased flow along the matrix, where soluble rock material is dissolved.

The variation in the flow characteristics actually occurring during *in situ* leaching might be quite different from that measured using core specimens. This is due to the

impact of large fractures and the preferential flow paths occurring in a deposit. However, correlation of laboratory data with the flow data from injection and recovery wells can be used in predicting the flowrates in these wells at a later time, by using the history matching techniques. Data on the rate of copper recovery and the percentage of total copper in the specimen that can be recovered through leaching can be used in assessing the optimum size of *in situ* leaching blocks, the expected rate of recovery and the total copper that can be recovered from a deposit through leaching. During the course of this study, and other studies being carried out in parallel, it was possible to compare the variation in permeability of core specimens during leaching with the permeability variation occurring during *in situ* operation at the Cyprus Casa Grande site. Data on permeability variation of *in situ* leaching blocks was obtained from work done by Kim et al. (1991). The trends in the variation of permeability during the first few days of leaching of core specimens and *in situ* leaching blocks appeared to be similar. But a slight decrease in the permeability of *in situ* leaching blocks was observed after leaching for a year or so. This was attributed partly due to intentional grouting of large fractures, and partly due to precipitation of iron sulfates in the deposit, thus decreasing the permeability. Decrease in the permeability of core specimens during the leaching process due to precipitation of iron sulfates was not observed.

5.2 Recommendations for Future Work

Future work in this area should be carried out on designing leaching systems to better simulate *in situ* leaching. In this investigation, core specimens were leached by placing them in beakers containing the lixiviant. Leaching experiments in which continuous flow of lixiviant occurs through the specimens under viscous conditions might yield more information. More work also needs to be performed to investigate the effect of size of the specimens on flow characteristics, and copper recovery. Experiments on different sizes of core specimens need to be performed for this purpose. Leaching of large

rock boulders, like 1 m size rocks, emplaced in an encasing material not affected by the lixiviant would provide more information about the variation in flow characteristics and copper recovery. These large boulders could be leached through holes drilled using a five-spot pattern. The corner wells in this pattern serve as recovery wells and the center well for the injection of the lixiviant into the rock. The initial hydrologic condition of the orebody would also have an impact on *in situ* leaching. In this investigation, leaching was carried out on water saturated specimens. Core leaching experiments using partly saturated and unsaturated specimens should also be investigated.

APPENDIX A**SAMPLE CALCULATIONS**

1. Porosity of the Specimen: f

Length of the specimen = 0.06805 m

Radius of the specimen = 0.0186 m

$$\begin{aligned} \text{Bulk volume of the specimen} &= \pi r^2 h \\ &= 3.142 \times (0.0186)^2 \times 0.06805 \\ &= 7.0 \times 10^{-6} \text{ m}^3 \end{aligned}$$

Porosity of the specimen, f :

$$\begin{aligned} &= \frac{\text{Pore volume of the specimen}}{\text{Bulk volume of the specimen}} \\ &= 9.46\% \end{aligned}$$

2. Permeability of the Specimen Using Helium:

Darcy's law modified for flow of compressible fluids:

$$k = \frac{Q \mu \Delta L P_o}{A \Delta P P_m}$$

$$\text{and, } P_m = \frac{P_m + P_o}{2}$$

where, k = Permeability of the media (m^2)

A = Area of cross section of the specimen (m^2)

$$= 1.087 \times 10^{-3} \text{ m}^2$$

μ = Viscosity of the fluid (Ns/m^2)

$$= 1.941 \text{ Ns/m}^2$$

$\Delta P/\Delta L$ = Pressure gradient ($\text{N/m}^2\text{-m}$)

Q = Volumetric flowrate at the outlet end of the specimen (m^3/s)

P_o = Pressure at the outlet end (N/m^2)

P_i = Pressure at the inlet end (N/m^2)

P_m = Mean gas pressure (N/m²)

Table A.1. Gas flow readings to measure permeability of a specimen using helium.

Inlet Pressure (KPa)	Outlet Pressure (KPa)	Flowrate (m ³ /s)	1/Mean Pressure (1/Pa)	Observed Permeability (m ²)
782.56	93.08	5.0E-7	2.3E-6	1.60E-16
1127.29	93.08	9.6E-7	1.6E-6	1.42E-16
1472.03	93.08	1.6E-6	1.3E-6	1.40E-16
1816.77	93.08	2.4E-6	1.0E-6	1.35E-16
2161.51	93.08	3.3E-6	8.9E-7	1.31E-16

Klinkenberg equation:

$$k_o = k \left(1 + \frac{b}{P_m} \right)$$

and, $k_o = k$ at $P_m \sim \infty$

where, k_o = Observed permeability (m²)

k = Intrinsic permeability of the medium (m²)

P_m = Mean gas pressure during the test

b is a constant

Observed permeability is a linear function of the reciprocal mean pressure ($1/P_m$).

When this linear relation between observed permeability and reciprocal mean pressure is extrapolated to infinite pressure ($1/P_m = 0$), we obtain the intrinsic permeability of the medium. Figure A.1 shows the plot between observed permeability and the

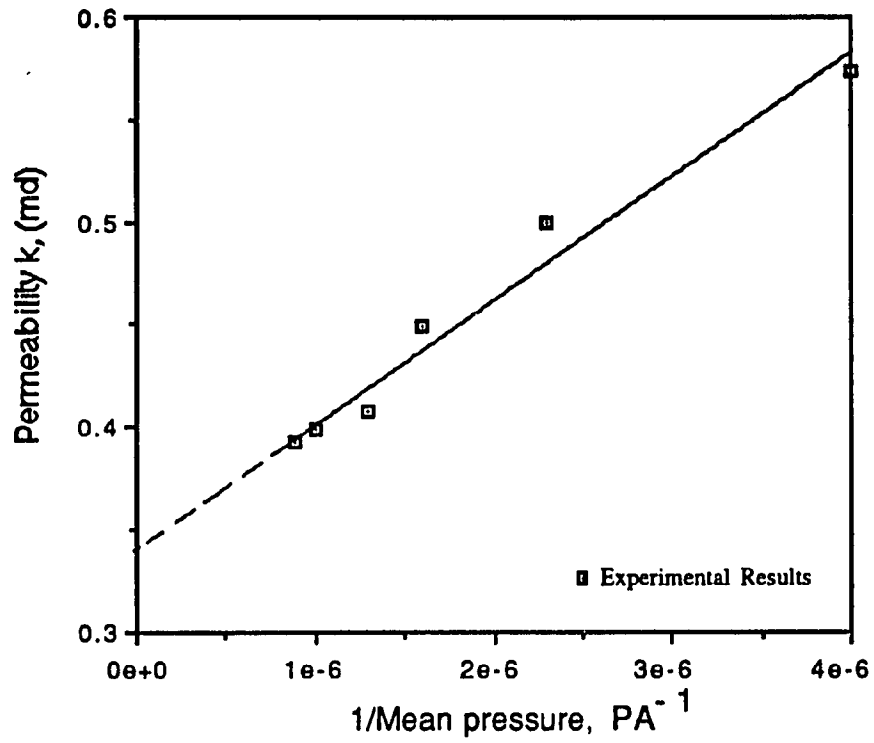


Figure A.1. Permeability at various pressure gradients as a function of reciprocal of mean pressure.

reciprocal mean pressure. As seen from this plot, the permeability of the specimen is $1.140 \text{ E-}16 \text{ m}^2$.

3. Permeability of the Specimen Using Water:

According to Darcy's law, steady state flow of a incompressible fluid through a porous media is given as:

$$Q = \frac{k \mu \Delta P}{A \Delta L}$$

$$\text{or, } k = \frac{Q \mu \Delta L}{A \Delta P}$$

where, k = Permeability of the media (m^2)

A = Area of cross section of the specimen (m^2)

μ = Viscosity of water (Ns/m^2)

$\Delta P/\Delta L$ = Pressure gradient ($\text{N/m}^2\text{-m}$)

Q = Volumetric flowrate at outlet end of the specimen (m^3/s)

using this equation and the measured flowrate, the permeability of the specimen was determined.

Table A.2. Water flow readings to measure permeability of a specimen using water.

Pressure Difference (KPa)	Volume of Flow (ml)	Time (sec)	Permeability (m^2)
689.48	35	1200	2.47E-15
689.48	30	1020	2.49E-15

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