Characterization of Grouts for Decommissioning of Abandoned Oil Pipelines

A Thesis

Presented to

the Faculty of the Department of Civil and Environmental Engineering

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in Civil Engineering

by

Navid Salehi Najafabadi

May 2013

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ABSTRACT

Due to higher demand for oil there has been increasing interest in offshore oil production. After the end of service life of oil wells based on the local, national and international rules and regulations, the entire infrastructure must be decommissioned. Generally in the offshore operations the time allocated for decommissioning has restrictions. In this study the objective was to develop a rapid method for the decommissioning of pipelines by using available grouting technology. Hence, a test protocol was developed to evaluate various types of grouts to rapidly fill and seal the pipes. Performances of the hydrophilic and hydrophobic expansive grouts were studied under simulated contamination, including the effect of salt water and oil on the curing and expansive characteristics of the polymer grouts in the abandoned pipes. Also, since the old oil pipelines will be coated with wax, plastic pipes with various sizes up to 3 in (75mm) diameter were used for the initial screening studies. The grout filled pipes were tested for leak under 100 psi (700 kpa) with air and water pressure. Based on the performance of the grouts, two grouts were selected for testing abandoned steel pipes (10 feet long 3 inch diameter) with different methods of grout injection. The performances of the grouted pipes were tested up to 100 psi (700 kpa) water and air pressure. Also the expansion of the grout in the confined pipe space was modeled using concepts such as gas production and strength development in the grout during the curing process.

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CHAPTER 1

INTRODUCTION

Because of the high demand for oil with limited resources of oil on-shore, it is obtained from offshore reservoirs. Today, over 7000 off-shore platforms are in operation and with over 60% located in the Gulf of Mexico. Due to state, federal and environmental regulations these offshore infrastructures have to be decommissioned within two years after the system shut-down. One major component of the decommissioning is the removal of pipelines that were used to deliver the oil.

1.1) Problem Statement

In the abandoned oil pipeline removal, the stage of decommissioning operation has different parameters that influence the decision making regarding the choosing the options. One of the key parameter that can make the decommissioning option superior to abandonment is the faster removal operation. However, the distance of the project from the off-shore shipping activities is another determining parameter. However, the shipping distance is not a parameter that could be easily controlled and hence, the parameter that could be dealt with is the duration of the operation. In this research it was decided to focus on stage grouting and plugging of the pipe operation so that it could be cut and removed without any residual oil leaking into the ocean. This oil spill should be prevented so that the entire operation is in compliance with the environmental regulations.

1.2) Objective

The overall goal in this study was to develop a methodology to fill the pipe with grout that is fast enough so that it can save time and provide complete sealing under operating conditions. The specific objectives of this study are as follows:

a) Develop a test protocol to evaluate the performance of various grouts.

b) Evaluate the performance of various grouts under different environmental conditions

c) Demonstrate the grout sealing concept in actual abandoned oil pipes

d) Model the performance of grouts in pressure development

1.3) Organization

In chapter one the need for the study with the objectives are included. In chapter two, background information available in the literature were reviewed. Besides, some of the technologies and methods that are used for decommissioning are reviewed. In chapter three, test protocols and standards that are used to characterize and investigate different parameters of the grouts and sealing capability are developed with justification. The test results and methodology for grout injections is explained in Chapter four. Also, in this chapter test results on different types of pipes with different diameter and lengths are presented. Basically, most of the study is concentrated on the water leak test on the grouted PVC and steel pipes. The steel pipes studied here are real 20 year old abandoned oil pipes that were decommissioned from Gulf of Mexico and shipped to the CIGMAT lab for testing. Chapter five discusses the modeling of the uniaxial stress development during the expansion of polyurethane grout during gelling.

CHAPTER 2

BACKGROUND

The term “Decommissioning” was mostly used since the Brent Spar Controversy (1995 – 98). Decommissioning defines the dismantling of existing installations which are either non operative or non productive followed by immediate site cleaning and rehabilitation. It is notable that there are over 7500 offshore petroleum installations located at around the world out of which 4500 are placed in the Gulf of Mexico (Parente et al., 2005) and 600 of them are located in North Sea (O’Donnell, 2012). It is also to be noted that there are approximately 40000 miles of pipeline along the shore of United States of America (Smith, 2002). On the Outer Continental Shelf (OCS) an average of 5.37 miles of pipeline are being reused and 268.67 miles are being decommissioned annually (Smith, 2002). With over 50% of the offshore structures located in the Gulf of Mexico, it is a real challenge to make an effective reuse of the abandoned structures by decommissioning them.

2.1) Offshore Decommissioning

According to Department of Interior (DOI), an offshore pipeline can be decommissioned in place only if it does not cause a hazard to navigation, commercial fishing operations or interfere with the other uses in the Outer Continental Shelf (OCS). Therefore, it is very essential that the pipelines are effectively plugged and sealed in order to not let the crude oil and petroleum products exfilterate and interfere with the aquatic environment after decommissioning. It must to be noted that if the pipeline is out of service for more than 60 months, it is to be decommissioned (Smith, 2002). Since, this gives an allowance for the pipeline to be non-operative yet situated in the place for 5 years, it is susceptible to various possible ways of deterioration with corrosion being the most prevailing one. Therefore, it is critical to identify and address the corrosion issue of nonoperative pipelines as soon as possible.

2.1.1) Decommissioning Options

For decommissioning the offshore structures there are three options briefly explained in following sections (Bureau Veritas UK, 2011). These are as follows

(a) Option 1: Complete decommission

Complete decommissioning solution is a requirement for all the platforms installed after 9th February 1999. For platforms installed before 9th February 1999, UK law enforces the operators to gradually plan to fully decommission the partially existing platform.

(b) Option 2: Leaving the platform partly in place

Under certain circumstances, for reasons of safety or technical complexity, it is more practicable for parts of the platform to remain in situ. For example, this might happen in the case of some concrete installations and footings of steel structures. In addition to these primary options for platform decommissioning, a third option is applicable to the decommissioning of pipelines.

(c) Option Three: Leaving the entire pipelines in place

As with Option 2 above, the most suitable option may be to leave the entire pipeline in place. It is important to note that pipeline decommissioning cannot be granted derogation under Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) Decision 98/3, although the process is subject to comparative assessments and depending on the proposals submitted. In the cases where the owners of platforms and pipelines are separate parties, the decommissioning work scopes should be produced as individual projects. Timescales must be defined for both pipeline and installation decommissioning projects. Apart from the mentioned three optiones, based on the regulations in USA three more options are available (Adedayo, 2011).

(d) Option 4: Toppling

The structure is removed by severing its legs above the mud line, after which it falls over onto the seabed. The installation simply remains on its side at the site. This process is suitable for steel but not for concrete structures.

(e) Option 5: Leave in situ

The structure is left in place at the end of production. The equipment and modules on the deck are completely or partially removed to leave the support structure standing.

(f) Option 6: Platform Reuse

The structure or part of it may be refurbished and relocated to another oil and gas production site. It is possible to use the infrastructure as a logistics base for helicopters or boats if sufficiently near other oil fields.

2.1.2) Offshore Decommissioning operation Procedures

Projects are reported in Twatchman, Synder, and Byrd, Inc. (TSB) databases in terms of eleven service categories. These eleven categories were reduced to six to represent the main stages of decommissioning and to minimize the amount of overlap between the reported service activities (Kaiser et al, 2003). The six categories for decommissioning operations are as follows:

1. Plugging and abandonment,

2. Structure preparation,

3. Pipeline abandonment,

4. Structure removal,

5. Site clearance and verification

6. Diving services.

One of the key parameter during the decommissioning operations is the environmental concerns. Basically this operation can have environmental impacts in different ways such as the vibrations generated during cuttings and movements of vessels (Kaiser, 2006). However, the vibration occurs only during operation and other impact like hydrocarbon spill will have longer effects and last even after the completion of the project. Hydrocarbon spill can occur due to either form the vessel fuels or form the wells. However, the probability of a spill as a result of a loss of well control is extremely low and it should be noted that the wells are being abandoned as they no longer produce economically viable amounts of oil (HESS Co, 2013).

Regarding the stage of pipeline abandonment it could be done according to MMS regulations, a pipeline may be abandoned in place if it does not constitute a hazard to navigation or commercial fishing operations and does not unduly interfere with other uses in the OCS. Pipelines abandoned in place need to be flushed, filled with seawater, cut, and plugged with the ends buried at least 1 m below the mud line. Most pipelines in the GOM are abandoned in place, and very few complete removals have been performed (Pulsipher 1996).

Pipeline abandonment cost is determined by the water depth involved, the length and type of the pipeline, the number of endpoint connections, and whether the pipelines terminate at a subsea tie-in or another platform. Pipelines need to be purged and cleaned and one factor influencing pipeline decommissioning cost is the volume of fluids used to clean the line, which can be estimated by the diameter of the pipe multiplied by the length of the line. Water depth is another factor involved in estimating the cost of pipeline abandonment operations; because water depth places a physical restriction on the amount of time divers can safely work (Kaiser et al, 2003). Average pipeline abandonment cost as a function of water depth is shown in Fig.2.1. The pipeline abandonment cost of a decommissioning project holds 9.1-12.4 % of the whole project cost (Kaiser et al, 2003). However an important question arises here that in the presented chart and suggested model for pipeline abandonment cost function in reference (Kaiser et al, 2003) the parameter of the length of the pipeline is neither mentioned nor considered. Therefore, the presented data in Fig.2.1 may vary too much based on the length of the pipeline.

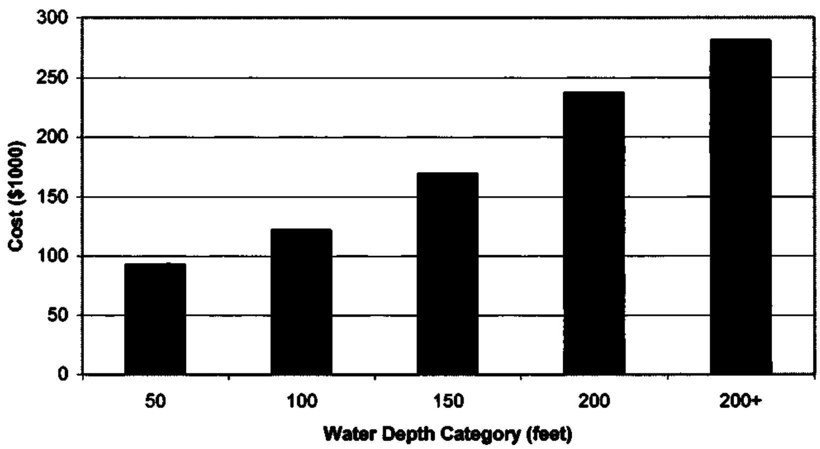


Figure 2.1 Pipeline abandonment cost based on water depth (Kaiser et al, 2003)

2.1.3) Summary

Based on what has been understood from the previous projects and existing literature, it could be concluded that; decommissioning the pipelines is a competitive option versus the pipeline abandonment in situ. Because, as it was mentioned in situ abandonment of the pipes is a function of various parameters that each of them can effectively increase the cost of the operation. On the other hand, the cost of decommissioning operation could be considered only as function of depth of the sea and diameter of the pipe which indicates the cost of pipe plugging. If this function is compared with in situ pipe abandonment, it is could be concluded that this operation has less complexity in cost analysis and it is worth to do a cost analysis for pipeline decommissioning and be compared with total cost of other option (in situ abandonment) and then the final decision be made. Another advantage of the Decommissioning in comparison with in Situ abandonment is the freedom of any state or federal regulations regarding the abandonment regulation. Furthermore, time is also saved, since approval for the regulation compliance is not needed. On the other hand the duration of the entire operation is much shorter because the operation could be summarized in following three stages:

Stage 1) Pipe filling

Stage 2) Cutting and loading on barge

Stage 3) Shipping to on-shore disposal sites

As it is seen remarkable time saving could be achieved by choosing decommissioning rather than In-situ abandonment. Basically, the total cost of off-shore projects are comprised of the equipment and barge rentals. Therefore, in order to minimize the total cost of the operation, Time-saving also plays the most important role in the overall cost. Furthermore, in order to reduce the operation time more, it could be focused on the faster cutting technologies and also on the faster filling methods of the pipes. Based on the collected data, in recent years significant advances in the field cutting technologies and methods have been developed and obtained. With the advancement of technologies prospect for further studies on the method of filling is more promising and it is a factor that less attention is paid to. Therefore, in this study it was aimed to develop a rapid method for filling the pipes that enables us to minimize the interval between the Stage-1 and Stage-2 of the operation. Based all what have mentioned, the first step is to find an appropriate method for filling the pipe is a short time and also it should have been already used for other purposes and its advantages and disadvantages are documented in the literature.

In the following the summary and the concentration of the previous studies and researches on decommissioning projects are presented in Table 2.1. These references mostly focused on the cost functions and environmental issues related to the operation and also post operation. Also it is observed that in none of these researches any type of technology or special method for pipeline decommissioning is offered or developed.

Table 2.1 Summary of the off-shore decommissioning projects and studies

Reference	Project Location	Water depth (ft)	Technology& Techniques	Regulations & Standards	Analysis and Modeling	Remarks
Breidablikk (2010)	North Sea	N.A	Cutting techniques, Vessel types and heavy lifting methods	N.A	N.A	Cutting technologies, Vessel types and introduction and heavy lifting methods were presented
Lakhal, Khan and Rafiqul Islam (2009)	Gulf of Mexico	All water depths	N.A	On-shore waste management, Reuse of drilling wastes and waste disposal	Total Waste function for drilling operation and life cycle analysis	Waste management and drilling waste reuse were reviewed. Also a total waste function for drilling operation is developed
Kaiser (2006)	Gulf of Mexico	0-600	Rig vs Rigless operation	Summary on operation Regulatory Requirements	A total cost function based on the structure complexity is developed	A cost function based on the structural complexity is developed and a summary on the regulations were presented
Kaiser, Pulsipher and Byrd (2005)	Gulf of Mexico	0-350	Abrasive cutting	N.A	The cost function for entire cutting job is modeled	The cost function for cutting job of the operation is studied and a description of the cutting technologies are presented
Kaiser and Pulsipher (2004)	Gulf of Mexico	$0\text{-}200^{+}$	Explosive method for removal	Environmental Impact of operation on the turtles and marine mammals	N.A	Environmental issues and involved operational methods are reviewed

Table 2.1 Summary of the off-shore decommissioning projects and studies (Continued)

Schroeder and Love (2004)	Southern California Bight	0-350	Decommissioning options	Comprehensive Environmental Regulations	N.A	The option for platform decommissioning and environmental regulation were discussed
Kaiser, Pulsipher and Byrd (2003)	Gulf of Mexico	0-350	N.A	N.A	A total cost function for the structure removal is developed	A cost function based on the structure size for the entire removal operation is offered
Hamzeh (2003)	Worldwide	N.A	Decommissioning techniques	International Rules	N.A	Decommissioning options and international regulations were reviewed
Osmundsen and Tveteras (2002)	North sea	All water depth	Decommissioning options	Fisheries and environmental issues	Comparison of total cost of decommissioning options	Financial comparison of decommissioning projects and also the environmental issues were studied
Kasoulides (1989)	North Sea and Gulf of Mexico	N.A	Decommissioning techniques	International standards	N.A	Decommissioning options and international standards and regulations were reviewed
Side, Baine and Hayes (1993)	North Sea	All water depths	Material and structure disposal techniques and limitations	Geneva and LOS Convention and IMO Guidelines	N.A	Material and structure disposal techniques were explained and also international regulations were presented
Remarks	Mostly in North Sea and Gulf of Mexico	No specific depth was considered	No specific technology for pipeline removal was offered or reviewed	The regulations were concentrated on environmental issues	All of the models were cost functions and just one was total waste function	**Available literature mostly focuses on the Cost functions and environmental issues and offers no specific technology for pipeline decommissioning**

2.2) Pipeline Sealing Methods

Current grouting technologies in sealing the pipes are mainly used for joint sealing or pipe leak sealing. The existing methods could be modified and adopted for the purpose of this project. The existing methods mostly use different types of grouts for most of the pipe sealing purposes. For example for joint sealing epoxy resins or mortars could be used to seal the sewer from inside seal the cracks and leaks and, grouts have a variety of chemical formulas that are matched to be compatible with local soil conditions and pipe materials (ISTT, 2013).

There are various options for pipe casing grouting that should be structurally strong and also provide sealing. For this purpose also ready-mix sanded grouts, cement – bentonite grouts and cellular grouts (White, 2010). Also for other purposes like manhole rehabilitation different types of chemical grouts like acrylamide, acrylate, acrylic, polyurethane could be used (Snyder, 2003). Among the mentioned chemical grouts the polyurethane grouts due to their different properties and high expansion rate (29 times) have the good potential for our aimed application (Kelly, 2009).

The rapidness of the sealing method was a concern in this study. (Seiler et al. 2005) also worked on the rapid closing of the damaged or exploded pipes. The idea in their study was the deployment of the airbag. The advantage of air bag deployment is its very fast performance and after initial preparation it can block the pipe in less than few second. However, this method has its own limitations and cost considerations and since the current project is in subsea condition further parameters should be taken into account that challenges the idea of airbag deployment method. On the hand, since the Polyurethane grouts generally complete their reaction in few minutes they could be considered as a potential option (Kelly, 2009). Besides, the testing and experimentation with Polyurethane grout is pretty familiar to CIGMAT research center and enough equipment and background experience is available to perform further studies. Based on all the mentioned facts polyurethane grouts are chosen as the material for filling and sealing the pipe at certain pressures that enables us to completely plug and seal the pipe section under subsea conditions.

2.3) Polyurethane grouts

2.3.1) History of Polyurethane Grout

Primary studies on polyurethane polymers were performed by Otto Bayer in 1937 in Germany (German Patent, 1937). On the other hand the first flexible polyurethane was developed by Hochtlen in 1952 (Wirpsza, 1993). Besides, the first commercially available polyether polyol was introduced by DuPont in 1956. Furthermore, less expensive glycols were introduced in 1957. Also in other countries such as Japan adopted a grout and used it in tunnel and sewer systems by the end of 1960`s (Ohama,1997).

In the 1960`s the production rate of polyurethane has increased remarkably, initially at a rate of 18% annually, to 2 x 10^6 (tones) in 1973 and 3 x 10^6 t in 1980 which was 6% of total plastic production. The production has increased 4-5% per year to 5 x 10^6 t in 1990 (Wirpsza, 1993). Moreover, private companies promoted grouts to prevent seepage and consolidation in Europe in the middle of 1970`s. Water-blown microcellular foams were introduced in the early 1980s and used in the automotive industry. In the 1980`s, polyurethane grouts were used in restoration of a dam in North America. The wide variety of uses of polyurethanes is due to the structure of polyurethanes can be controlled by adjusting their segmental and domain structure over a considerable range.

2.3.2) Polyurethane Applications

Polyurethane grouts are being used in tunnel constructions, stabilizing ground, controlling leaks in water and wastewater systems during construction and maintenance, lifting pavement and slabs, and treating cracked concrete walls. Due to the wide range of applications, there is an increased interest in characterizing the behavior of both hydrophilic and hydrophobic polyurethane grouts.

The ideal grout for these applications should have low viscosity to minimize pumping pressure, good gelling time and the ability to make the soil at the leaking area impermeable (Karol, 2003). Several hydrophilic grouts like Acrylamide, acrylics, Acrylate, urethane gel, and urethane foam are available for leak control. Polyurethane is one of the popular types of grout that is used for leak control (Vipulanandan, 1999). Hydrophilic and hydrophobic polyurethane grouts will expand when mixed with water or other components and seal the leaks. But the grouting behavior of polyurethane is not well understood. It should be noted that there is no ASTM standard methods for testing the polyurethane grouts and there is not enough data in the literature. Lack of testing procedures for polyurethane grouts makes it difficult to select this material for different and appropriate applications.

2.3.3) Mechanism of foam formation and foaming process

Polyurethane grouts are divided in to three major categories, hydrophobic, hydrophilic and elastomeric grouts based on their reaction with water and their elongation. Hydrophilic grouts can incorporate large amounts of water into their chemical structure, thereby creating a gel with variable water content, and hence the volume increases several times its original volume. Polyurethane grout shows various characteristics under different allowed volume changes and water-to-grout ratios. Maximum temperature and pressure during curing varied notably with the water-to-grout ratio (Joyce, 1992). Water-to-grout (W/G) ratio is the most important variable for hydrophilic PU grout to achieve the desired characteristics for different applications.

Some of the polyurethane grout characteristics depend on W/G ratio, volume expansion, density, setting time and temperature change of PU grout during curing (Yenny, 2001). Polyurethane grouts are formed by reaction of one or more polyhydroxyl compounds with a stoichiometric quantity of a dysfunctional isocyanate (-N=C=O) such as MDI (methane di-isocyanate) or TDI (toluene di-isocyanate). It is possible to prepare a range of solid polyurethane materials from a soft elastomer to a rigid solid by adjusting the molecular weight and composition of the hydroxyl components. Urea and carbon dioxide are produced when an isocyanate (-N=C=O) reacts with water Figure 2.2. Polyurethane foam is the combination of isocyanate, urea and carbon dioxide. There is an upper limit to the amount of foam expansion that can be generated by carbon dioxide since the reaction is exothermic.

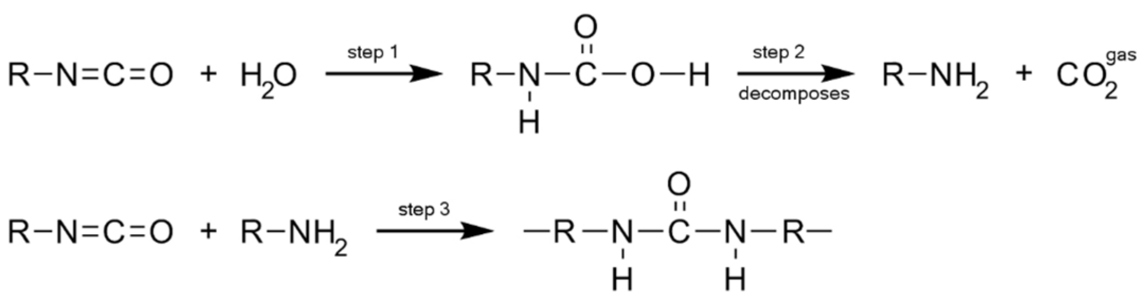


Figure 2.2 Hydrophilic polyurethane grout curing reactions

The main difference between hydrophobic and hydrophobic grouts is their reaction with water. Hydrophobic grouts use water as a reacting agent and absorbing very little additional water. Hydrophilic grouts can incorporate large amounts of water into their chemical structure so that a gel with varying water content is created. The undesired capacity of shrinking and swelling capacity of hydrophilic grouts may decrease with time but ultimately leaves those grouts vulnerable to physical and chemical attacks. Limited information is available about polyurethane grout performance in infrastructure, repair and maintenance applications. An ideal chemical grout should be inexpensive, abundant powder; readily soluble in water (eliminates the expense of transporting a solvent). It should also be non-toxic, non-corrosive, and non-explosive, as should be the grout solution and the hardened grout. It should be stable under normal temperatures, insensitive to salts in the groundwater, and readily controlled for varying gelling times. The hardened grout should be a permanent gel with a high strength. (Bikard et al. 2007) studied the polymerization reaction of a two component polyurethane chemical. They investigated the expansion during the polymerization reaction (gelling) and also during curing (strengthening). A phenomenological model developed mainly depended on the evolution of gas phase during the chemical reaction. The model was mainly based on the diphasic compressible fluid (liquid/gas phase). It is to be noted that, as shown in Figure.2.3, the evolution or the production of carbon dioxide takes place at an exponential rate eventually the curve follows the path of exponential decay.

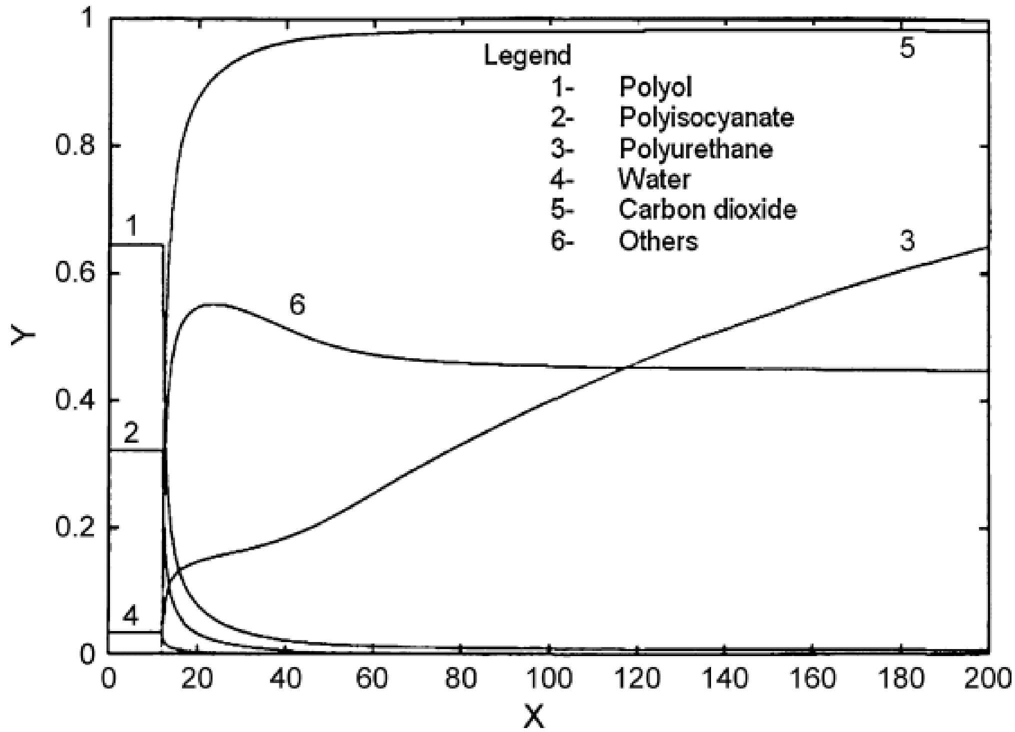


Figure 2.3 The evolution of Carbon dioxide by time (Lefebre, 1993)

2.3.4) Summary of Polyurethane grouts and Applications

A short summary on the previous researches on the Polyurethane grouts and their applications are presented in Table 2.2. The researchers are reviewed based on the type of grout, Testing method, Grout Property and the application of the grout.

Table 2.2 Summary of studies on Polyurethane grouts

References	Grout	Tests	Properties	Applications	Remarks
M.C.Saha, Md.E.Kabir and S.Jeelani (2008)	2-part Polyurethane Foam	SEM,IR,TGA, Tension, Compression and Flexural Testing	Density (liquid) = 15 Pcf Tensile Strength = 580 psi Tension Modulus = 19870 psi Comp. Strength = 2900 psi at 70% strain Comp. Modulus = 18855 psi	Sandwich Structures	A consistent enhancement in thermal and mechanical Properties observed with infusion of Nano particles.
M. Thirumal, D. Khastgir, N.K. Singha, B.S. Manjunath and Y.P. Naik (2008)	Water blown rigid polyurethane foam	Density, Compression Testing, Energy Absorption, Hardness, Water absorption, Thermal Conductivity, Morphology	Density = 2.6 - 7.2 Pcf Comp. Strength = 29 - 145 psi at 10% strain Comp. Modulus = 464 - 3133 psi Water Absorption = 0.6 - 6.8%	General	Mechanical properties change with the density of polyurethane foam. Higher density results in higher compressive strength with low water absorption.
Y.Mattey and C.Vipulanandan (2001)	Hydrophilic polyurethane grout	Unit weight, Compressive Strength, Swelling shrinking behavior, P-T-t relationship	Density = 22-61 Pcf Average bonding strength to concrete = 10-24 psi at 20 days Compressive strength = 50-240 psi At 60% strain Max. Pressure = 174 Psi and Max. Temp. rise = 38.8 °C	Water leak control in concrete structures	Water to Grout ratio was between 0.5 to 6 and allowed volume expansion was between 0 to free expansion.

Table 2.2 Summary of studies on polyurethane grouts (Continued)

References	Grout	Tests	Properties	Applications	Remarks
Snuparek and Saucek (2000)	Polyurethane 2 component	Viscosity, Compression, Tension	Difference in viscosity- decreases exponentially with increase in temperature. Compressive Strength Decreases as foaming factor increases	Multi Purpose	strain hardening behavior, bulging, large scale model for fissure grouting
S.H. Goods, C.L. Neuschwanger, L.L.Whinnery and W.D.Nix (1999)	Hydrophilic polyurethane grout	Thermal Conductivity, Glass Transition And decomposition temp and mechanical strengths	Density = 6.9 Pcf Tensile Strength = 203 psi Tension Modulus = 5220 psi Compressive Strength = 174 psi	Insulation Material	Compressive, tensile strength and modulus increased with addition of glass fiber.
Remarks	No Study on Hydrophilic Grouts	All tests are mechanical and no test on permeability and sealing properties of PU grouts	Density =2.6- 61 Pcf Tensile Strength = 203-508 psi Compressive Strength = 50-2900 psi	There is sealing application but not for subsea or oil related purposes	A great lack in studies on permeability and sealing properties is noticed, so, current study is suggested to be more on these properties

2.4) Summary

Based on the literature review following observations are advanced:

1) One part of the decommissioning project is pipeline decommissioning. As it was reviewed in the literature the cost of pipeline decommissioning is highly dependent on the speed of operation since the total cost is mostly comprised of the equipment rentals in order to minimize the total cost the speed of operation should be maximized.

2) Among the options for sealing and filling the pipes, the Polyurethane grouts are found to be the best options since they have high expansive properties and also they cure so fast and just within couple of minutes after the grouting the pipes could be cut.

3) Polyurethane grouts have different types such as Hydrophobic, Hydrophilic and multi component. Generally hydrophobic types have stronger structure and also they have less shrinkage compared to the others.

4) In this study two types of Hydrophobic and multi component polyurethane grouts are chosen for further study and various types of experimentations are done on them to screen them and find the best options and type for the aimed project and purpose.

CHAPTER 3

MATERIALS AND METHODS

3.1 Materials and Equipments used for Grout characterizing

The testing involved characterization of grout material and grouted pipe performance. In addition, model tests were performed to determine the effectiveness of grouting in controlling the leak at the horizontal direction. The following is a summary of the methods and test procedures used in this study.

Properties of the grout specimen samples tested were grouped as follows:

1) Working properties;

2) Physical and mechanical properties;

3) Sealing properties

Since there were no American Society of Testing and Materials (ASTM) test procedures existed to determine the grout properties, CIGMAT had developed their own testing protocols and these protocols were used.

3.1.1 Grouts

In this study five grouts were selected. They are named as Grout-1 to Grout-5. Among these grouts, Grout-1, 2, 3 and 5 were hydrophobic and Grout-4 was hydrophilic. These grouts have been developed for different applications. In this study it is planned to study some general parameters of grouts that are critical for the intended application. The descriptions of all grouts are summarized in Table 3.1.

Table 3.1 Chemical composition of grouts

Grout		Ingredient Name / CAS Number	Exposure Limits	Concentration
1		4.4'- Diphenylmethane Diisocyanate CAS #101-68-8	OSHA PEL: 0.2 ppm ACGIH TWA: 0.05 ppm	Trade Secret
		Polymethylene Polyphenyl Isocyanate CAS #9016-87-9	OSHA: Not established ACGIH: Not established	Trade Secret
2		4,4'-Diphenylmethane Diisocyanate (MDI) CAS number 101-68-8	OSHA: 02 ppm ceiling - .20mg/m3 ceiling ACGIH: 005 ppm TWA- .951mg/m3 TWA	Trade Secret
3		4,4' – Diphenylmethane Diisocyanate (MDI) CAS #101-68-8	OSHA: .02 ppm - .20 mg/m3 ceiling ACGIH: .005 ppm - .951 mg/m3 TWA	Trade Secret
		Dibutyl Maleate CAS #105-76-0	OSHA PEL: Not established ACGIH TLV: Not established	Trade Secret
		Polyoxyalkylene Polyol CAS #9082-00-2	OSHA PEL: Not established ACGIH TLV: Not established	Trade Secret
4		2-(2-ethoxy)ethyl Acetate CAS #112-15-2	OSHA: Not established ACGIH: Not established	Trade Secret
		Poly (ethylene oxide) – TDI Trimethylpropane Polymer CAS #53426-99-6	OSHA: Not Established ACGIH: Not established	Trade Secret
		2,4 Toluene Diisocyanate CAS #584-84-9	OSHA PEL: 0.005 ppm ACGIH TWA: 0.005 ppm	Trade Secret
		2,6 Toluene Diisocyanate CAS #91-08-7	OSHA PEL: 0.005 ppm ACGIH TWA: 0.005 ppm	Trade Secret
5	Part A	Diphenylmethane diisocyanate (MDI) CAS #101-68-8	OSHA PEL: 0.02 ppm (ceiling) ACGIH TWA: Not established	Trade Secret
	Part B	1,1,1,2,2-pentafluoropropane (CF3, CH2CHF2 or HFC-245fa) CAS #460-73-1	OSHA PEL: Not established ACGIH TWA: 300 ppm	Trade Secret

3.1.2 Contaminations

Based on the possible occurrences of contamination in the field it was found necessary to include some contaminations that are most likely to be present in the field. Therefore, used car oil and also the Galveston seawater were chosen to be as the contaminations during this study.

3.1.3 Measurement equipments

Load Cell: A load cell with a capacity of 2000 lbs was used to measure the total load generated during polyurethane curing. The accuracy was 2 lb.

Thermocouple: Temperature changes during curing were monitored by using a thermocouple. Thermocouple had an accuracy of 0.1°C.

Analytical balance: All of the mixing proportions and cured specimens were weighted with a digital balance with an accuracy of 0.1 g.

Vernier Caliper: Diameters and heights of cured specimens were measured using a vernier caliper with a least count of 0.01 mm of accuracy.

3.2 Grout specimen preparation

Molds: The mold that was utilized to make the polyurethane grout test specimens are shown in Figure 3.. The Teflon mold was encased with a steel cylinder to increase strength of mold since polyurethane grout produces carbon dioxide gas which increases pressure inside the mold. Top and bottom of the mold was strengthened with steel plates connected with threaded rods. Molds had a volume of 100 mL. The Teflon mold eliminated any reaction with the polyurethane grout and grout did not stick to the mold which gave ease of taking the specimen out of the mold. The Teflon mold allowed the polyurethane to cure uniaxially. The molds were sealed tight so that there was no leakage during the curing period. The mold that was utilized to make epoxy grout specimens were shown in Figure 3.. Molds were made out of Teflon (polytetrafluoroethylene**)** which did not stick to the grouts. Bottom of the mold was sealed with a rubber stopper, it was necessary to seal upper side of the mold also, because the polyurethane grout is highly expansive. Since the temperature rise was more high the molds are made out of Teflon, temperature increase did not affect the molds.

Stirring rods: Glass rods were used to mix water and polyurethane resin in the mold. In the case that we have the hydrophilic grout we could use a electrical mixer for blending.

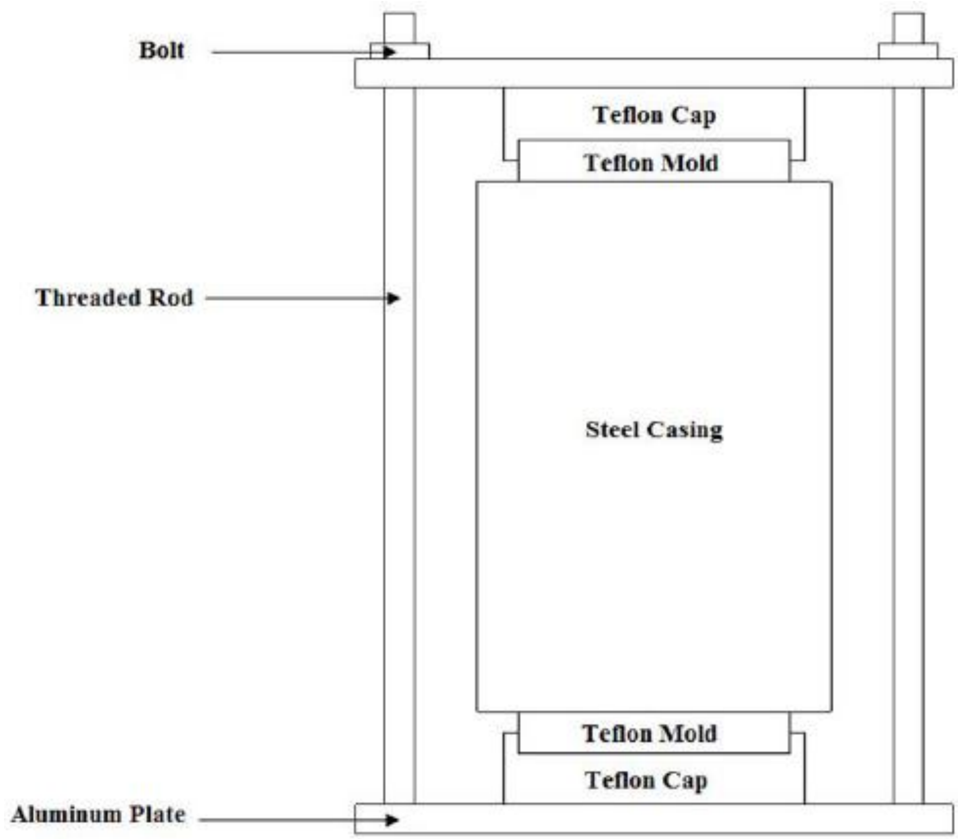


Figure 3.1 Confined condition mold for making grout samples

After solidification, specimens were removed from the mold and stored in labeled, sealed plastic bags for identification, protection, and to prevent moisture loss. The specimens were stored in a temperature- and humidity-controlled room at 23 ± 2°C (Room temperature) and 50% ± 5% humidity. Polyurethane specimens were prepared under controlled volume change. The amount of resin and water to be added were determined by the allowable volume change.

A volume expansion of 100% was selected with various water-to-grout ratio. 50 mL of the mold was filled with grout mix. Specific amounts of grout were mixed with an allowable volume change of 50 mL which is 100%. Resin and initiator were mixed at room temperature (23±2 °C) and at relative humidity (50±5%). Although the grout reacted with water immediately, the reaction did not start until the grout was stirred with a glass stick. The thermocouple was placed inside the mold and the load cell was placed on top of the upper cap of the mold. So that the temperature and pressure changes during curing were determined. These measurements were taken until temperature returned to its initial temperature.

3.2.1 Grout curing monitoring

For this test there is no standard test protocol. However, simply the Temperature and Pressure development during the curing of the grout could be recorded. Therefore, A Thermocouple is located at the bottom of the mold as shown in Figure 3. to measure the Temperature changes. Besides, a load cell is put on top lid of the mold and when the pressure starts to increase and the gas is being produced in the mold it presses the load cell against the top tightening plate. By this mean we can record the changes in pressure. Since for all the grouts the reaction is mostly completed within first 5 minutes, the recording times are planned to be as summarized in Table 3.2.

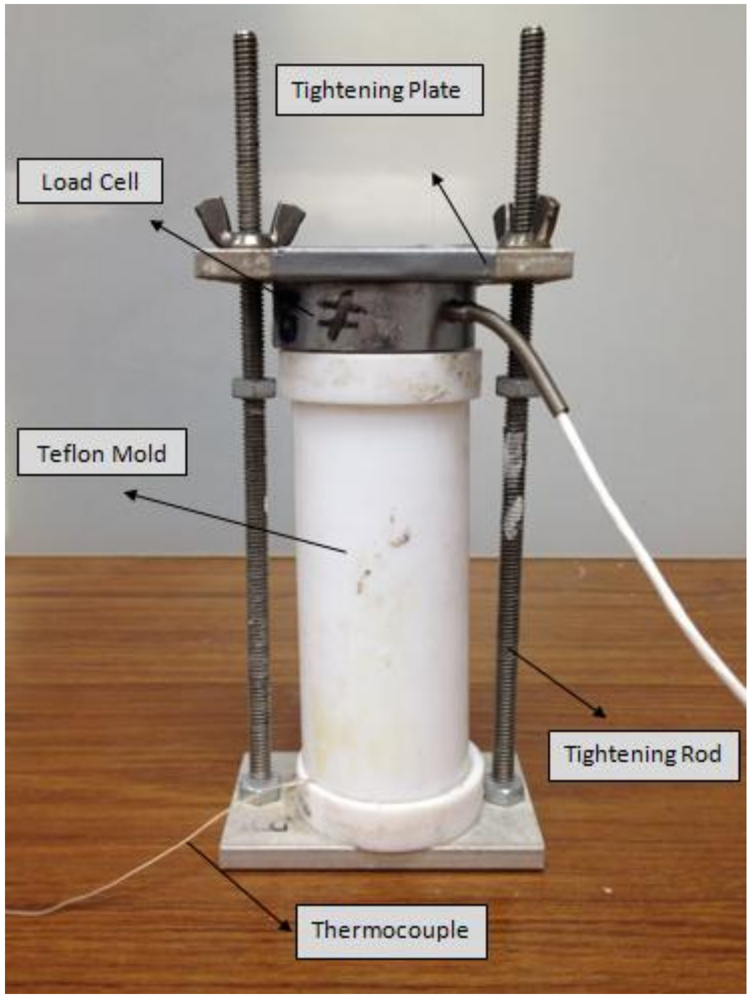


Figure 3.2 Typical configuration of the curing monitoring Setup

Table 3.2 Recording time schedule for grout curing

Time span	0-1 min	1-2 min	2-3 min	3-5 min	5-15 min	15-30 min
Record Interval	10 seconds	15 seconds	20 seconds	30 seconds	2 minutes	5 minutes

3.3 Grout Tests

In this chapter the initial tests that were performed to characterize the grouts are illustrated and explained briefly.

3.3.1 Setting (Gel) time

Gelling time of the grout is defined as the time during which the grout transforms from a liquid to solid. In other words, gelling time is defined as the time when the flow ability of the grout is completely void. Initially, in the industry, the gelling time was obtained by a fairly simple methodology. The grout mix was placed in a cup and the cup was tilted to 45º. And during this motion between horizontal to a 45º tilt of the cup, the movement of the grout mix was visually observed and when this movement is null, the corresponding time was accounted to be the gelling time of the grout.

To add more science to this, the new CIGMAT standard was developed to evaluate the gelling time of the grout. The CIGMAT 8-09 gives the detailed procedure to evaluate the gelling time of the grout and is attached in appendix A. The basic principle behind the development of gelling time test method is that, the phase transformation occurring due to polymerization is an exothermic chemical reaction. By measuring the rise in temperature of the sample, it is to be noted that, the temperature increases once the polymerization begins (when the liquid has become a solid) and then rises to a peak value (solid strengthening phase) and finally reaches the room temperature indicating the completion of the chemical reaction or in other words, all the chemicals involved in the chemical reaction for grout formation have been used up which leads to the termination of the polymerization. This phenomenon was measured using the thermocouple which was inserted into the grout immediately after the grout was mixed in a cylindrical cup and the other end of the thermocouple (probe) which was connected to the data acquisition system captured the rise in temperature with time. By relating the time with temperature, the gelling time was obtained by examining the curve. The time during which the slope of the curve began to increase rapidly from zero was taken to be the gelling time of the grout. Figure 3-10 shows the setup for the gelling time test.

In the case of polyurethane grouts, however, the gelling time was determined by visual observation. Setting time of the polyurethane grout is defined as the elapsed time from the grout preparation to the time when the grout no longer flows from a beaker inclined slowly to 45º. Approximately 20 mL of freshly prepared grout was used. Care was taken not to confuse the expansion of the grout to movement of the grout. At periodic intervals, based on the observed setting of grout, the container was slowly tipped to approximately 45º to determine if the grout exhibits liquid flow properties or if the grout sample had gelled and the specimen can no longer flow from the container.

3.3.2 Unit weight

Solidified grout specimens were used to determine the unit weight of the grout. The determination was completed per CIGMAT GR 1-04 for grout specimens. Unit weight was calculated using the weight and volume of the specimens. A minimum of three replicates were evaluated for unit weight. The length and width of specimens were measured using a vernier caliper. Results reported were the mean of a minimum three measurements. Unit weight was calculated as presented in eqn. 3.1.

$$Unit\ Weight = \frac{M}{V} = \frac{Weight\ of\ specimen\ (g)}{Volume\ of\ specimen\ (cm^3)}, \tag{3.1}$$

3.3.3 Free expansion rate

In order to evaluate this parameter, known amount of pure grout chemicals were poured in the mold and all other required additives were also mixed and let reaction to start and finish. After the completion of the reaction the final volume of the generated foam is measured and the Free Expansion Rate is calculated by the (3.2,

$$\Delta V = \left(\frac{V_1 - V_0}{V_0}\right) \times 100\ , \tag{3.2}$$

where V_0 = Initial volume of the specimen,

V_1 = Volume of the specimen after immersion into water and

ΔV = Percentage of volume change.

3.3.4 Unconfined compressive strength and stress/strain relationship

CIGMAT GR 2-04 was developed for testing grout specimens in compression under monotonically increasing load (load increasing linearly). Compression tests were performed using screw-type machines. The specimens were trimmed to ensure smooth and parallel surfaces. For foam type grouts like polyurethane the minimum height was 25.4 mm (1 in) and the maximum height was no greater than 75% of the diameter of specimen. Polyurethane specimens were not capped but both ends were cut with blade to create a horizontal surface. Several specimens were tested at 7 days following specimen preparation. The rate of crosshead movement was selected as 1%/min of the initial height of specimen or such that the specimen failed in 20 minutes. The reported data includes the compressive strength, modulus and failure strain. The modulus was determined from the initial slope of the stress/strain relationship and the failure strain was the maximum strain before the specimen failed. The compressive strength was defined as presented by (3.3,

$$Compressive\ Strength\ (\sigma_0) = \frac{Maximum\ Load\ (lbs)}{Cross\ sectional\ area\ (in^2)}\ , \tag{3.3}$$

Polyurethane grouts were tested using an automated load testing system designed specifically for geotechnical testing laboratories. The compression machine used for performing these tests has a capacity of 10 kips. Each machine contained their own software that enables data acquisition and mechanical control for compression testing.

Polyurethane grouts were tested up until a yield point was reached or until the specimen was compressed to 60% of strain since it was a foam type grout. Some cyclic load tests were done also. For some grouts, due to low modulus it was necessary to proceed the test up to higher strains so that some noticeable changes in the force be observed and acquired.

3.3.5 Permeability

The purpose of this test was to measure the permeability of grouts. Solidified grout specimens were used to determine their permeability. Specimens were prepared in 1.5-in. diameter plexiglass cylinders and permeated with water under ambient hydraulic gradient, per CIGMAT GR 7-04. Testing was done at room temperature and humidity. Three replicate samples were tested. Permeameter was used to measure the permeability. The grouts were prepared with Teflon mold caps then those caps were removed and the specimen was placed into the permeameter as shown in Figure 3.. A 100 mL jar was used to measure the discharge to an accuracy of 0.2 mL. A constant head water tank was used to supply water without air in it and it maintained required pressure using a control valve during test. Permeability test setup layout is shown in Figure 3. and the setup configuration is shown in Figure 3..

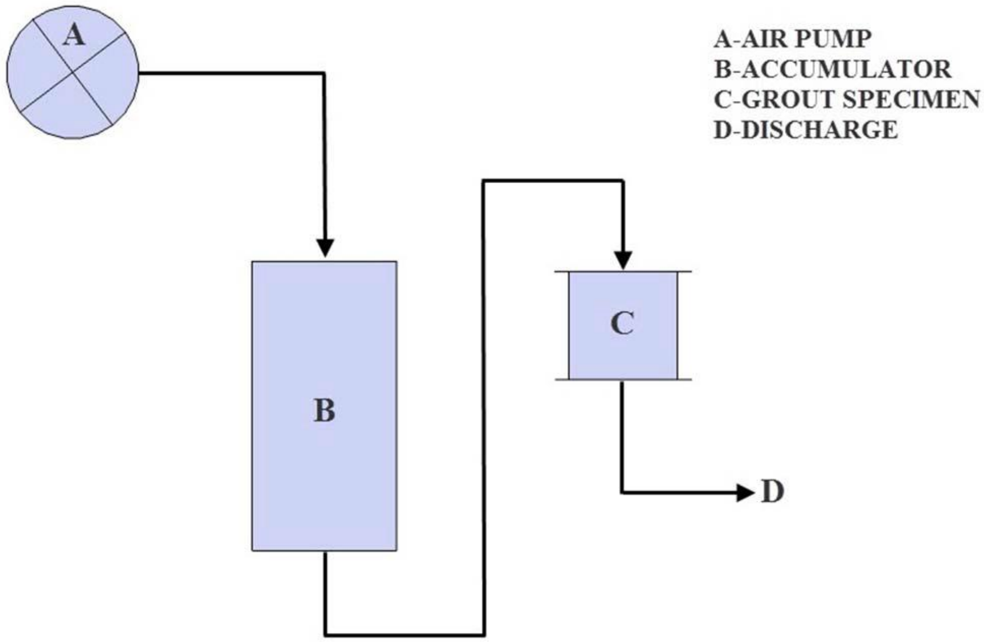


Figure 3.3 Permeability test setup layout

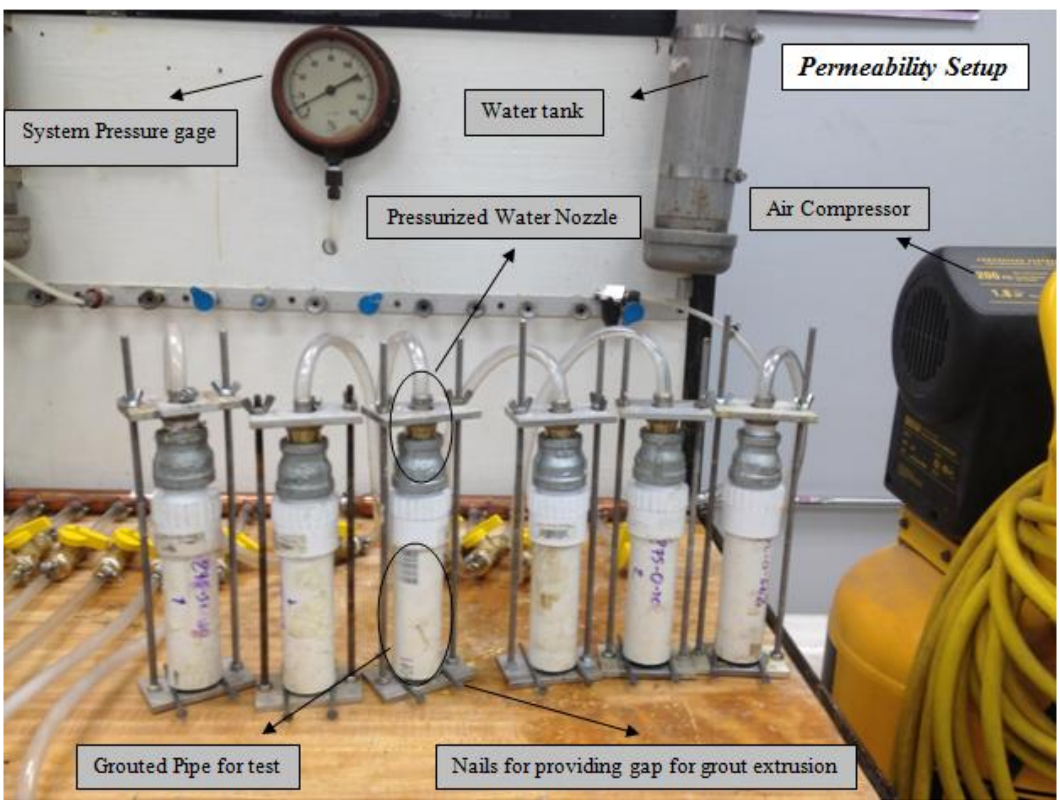


Figure 3.4 Permeability test setup configuration

3.3.6 Soaking/Water Absorption

Water absorption characteristics were evaluated for grout specimens as outlined in standard procedure CIGMAT GR 3-04. Three grout specimens were immersed in tap water (initial pH in the range of 7) and changes in weight and volume (determined by measuring specimen diameter and height) of the specimens were recorded a minimum of once every working day (Monday through Friday, excluding holidays) until the changes in weight and volume become negligible (less than 0.5 percent of the previous weight and volume), or for one week, whichever occurred first. The purpose of this test method is to provide a mean for water absorption of grouts. At least three specimens were tested. The water absorption as volume and weight percentages was calculated as

$$\Delta V = \left(\frac{V_1 - V_0}{V_0}\right) \times 100 \,, \tag{3.4}$$

where V_0 = Initial volume of the specimen,

V_1 = Volume of the specimen after immersion into water and

ΔV = Percentage of volume change.

To obtain initial characterization information on the grout, all specimens were weighed to 0.1 g using a calibrated digital balance and measured (diameter and height) using a vernier caliper with a least count of 0.01 mm,

$$\Delta W = \left(\frac{W_1 - W_0}{W_0}\right) \times 100 \,, \tag{3.5}$$

where W_0 = Initial weight of the specimen,

W_1 = Weight of the specimen after immersion into water and

ΔW = Percentage of Water Absorption.

3.4 Summary

Based on the potential application of rapidly filling the pipe and sealing it from leaks following tests were selected to characterize the grouts:

1) Free volume expansion of grouts with and without contamination.

2) Curing of grouts (pressure and temperature) with and without contamination.

3) Setting (Gel) time of grouts with and without contamination.

4) Confined compressive strength and stress-strain relationship of grouts.

5) Soaking/water absorption of grouts with and without contamination.

6) Permeability test on grouts cured under confined condition in the pipes.

CHAPTER 4

POLYMER GROUT AND GROUTED PIPES

4.1) Introduction

In this chapter basically the goal is to characterize the available types of grouts. Different tests such as compressive strength, water permeability and physical properties were performed at the initial stage to have an overall screening of the grouts. Also, in all of these tests the effect of potential contaminations in the field was considered to have a more comprehensive study of the grout behavior. After the first stage of grout characterization the grouts with better performance were selected and used to fill and seal pipes and do the related test to evaluate the performance of grout in sealing the pipe.

The pipes at the initial stages had short lengths and small diameters. The material of the pipe for beginning was selected to be PVC. After initial stages the length and diameter was increased to10 feet and 3 inches respectively. The only test that was performed on the grouted pipes was the water leaking test which is similar to permeability test. This test includes all the important and effective factors in the field performance of the grout and the pipe.

Finally after the completion of the medieval stages and deciding on the best and reliable grouts two of them were chosen to be used for grouting the 20-year old abandoned subsea pipes. Abandoned pipes were put under different tests and conditions and also the testing was duplicated to make all the results and observations more reliable. In the following sections all the tests and stages of study are explained and discussed in details.

4.2) Grout characterization

4.2.1) Free expansion monitoring

It is of interest to investigate the curing of grouts under various exposure conditions. Hence curing of grouts under various contaminations such as oil (O) and seawater (SW) were investigated. The selected grouts for this study are named as Grout-1 to Grout-5. Among the available grouts chosen for this study Grout-3 and Grout-5 are produced by mixing two separate components. It is of interest to investigate the effect of contamination on each grout component. In grouts Grout-3 and Grout-5 the way the grout may be contaminated could happen in three ways based on the injections sequence in the field. Hence the possible cases are as follows:

Case 1: Part-A be mixed with contamination then add the part-B

Case 2: Part-B be mixed with contamination then add the part-A

Case 3: Mix Part-A and part-B then add the contamination to the grout mix.

Therefore, based on these three cases two contaminations with two concentrations of 5% and 10% were prepared and tested to determine the rate of expansion and final volume of the generated foams.

Grout-1

For this hydrophobic PU grout water was needed to initiate the reaction. Hence 2.5 % and 10% of water was added and the total rate of expansion was monitored. When the amount of water was changed from 2.5% to 10% the volume of the grout produced was about 30% more but, the foam was weak and softer. Hence it was decided to use 2.5% of water for all the mixes and contaminations were added. The amount of grout used, expansion rate and setting time of each mix are summarized in Table 4.1

Table 4.1 The mix proportions for Grout-1 samples

Mix Name	Control	W-10	O-5	O-10	SW-5	SW-10
Part 1 (mL)	50	50	50	50	50	50
Part 2 (mL)	2.5	2.5	2.5	2.5	2.5	2.5
Water (mL)	2.5	5	1.25	1.25	1.25	1.25
Oil (g)	0	0	2.5	5	0	0
Seawater (mL)	0	0	0	0	2.5	5
Time of start of foaming (s)	25	23	28	31	22	20
Time of foaming completion (s)	145	140	153	160	139	135
Final Expansion Ratio	18.3	25.4	17.3	16.2	24.3	18.0

The pictures of the foam are shown in Figure 4.1

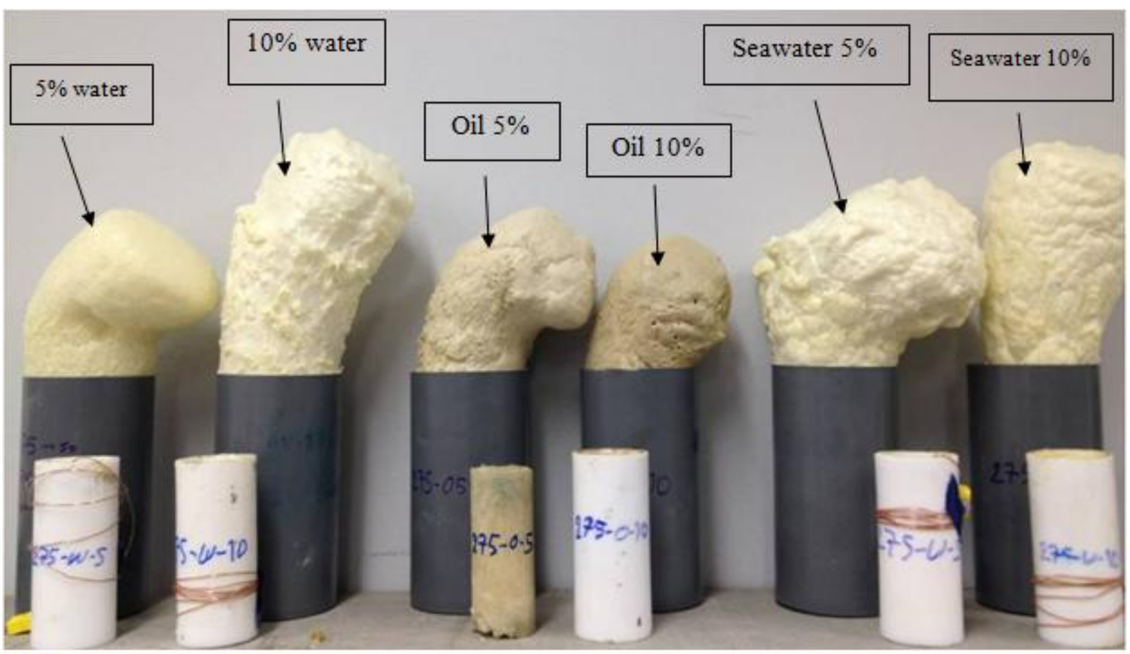


Figure 4.1 Typical shape and structure of foam generated by Grout-1

Besides, the following comparisons with control grout were done:

1) Addition of oil made the foam more rigid but slightly decreased the expansion.

2) Increase of oil decreased the final volume of the generated foam.

3) Addition and increase of SW did increased the free expansion volume of the foam.

4) Totally as the amount of Water or SW increases in the mix the final foam will have softer and weaker structure.

Grout-2

For this grout it is needed that the water be added to the mix as the initiator of the reaction. But, no percentage was suggested by the company so three percentage of 2.5, 10 and 20 were selected to find the visually optimum one. As it could be seen in Figure 4.2 with 10% water we have the most foam generated, so, we add 10% of water in all mixes and add other contaminations. The used amounts of grout chemicals, expansion rate and setting time of each mix are summarized in Table 4.2. In Overall the expansion of this grout in comparison with others was less and no uniform foam was generated. The following were observed:

1) The Oil specimens had the least expansion; however the increase of oil did not change the final volume of the foam that much.

2) In the case with Oil addition lots of air and gas were released and as it could be seen in Figure 4. large voids in the foam are created.

3) The addition of SW decreased the final volume of the foam and the generated foam is more porous and brittle compared to the control foam.

Table 4.2 Mix proportions for samples made with Grout-2

Mix Name	W-2.5	W-10	W-20	O-5	O-10	SW-5	SW-10
Part 1 (mL)	50	50	50	50	50	50	50
Part 2 (mL)	1	1	1	1	1	1	1
Water (mL)	1.25	5	10	5	5	5	5
Oil (g)	0	0	0	2.5	5	0	0
Seawater (mL)	0	0	0	0	0	2.5	5
Time of start of foaming (s)	37	35	32	42	48	36	33
Time of foaming completion (s)	158	155	150	167	175	156	152
Final Expansion Ratio	4.1	10.3	5.6	4.5	3.4	5.1	6.0

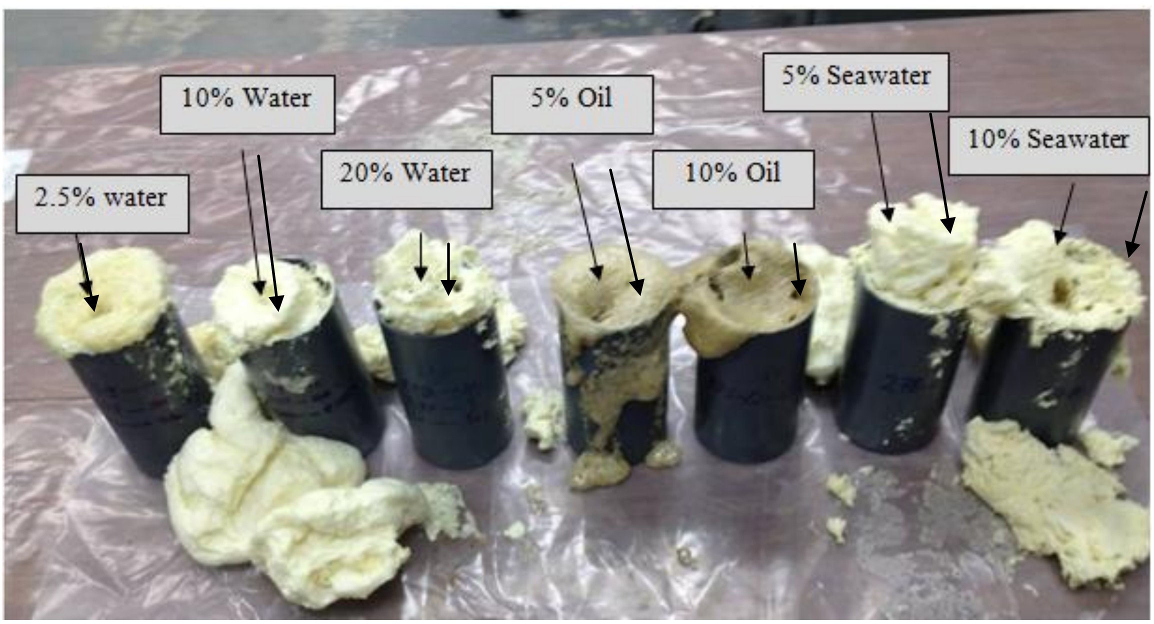


Figure 4.2 Typical shape of the foam generated with Grout-2 and different contaminations

Grout-3

As previously explained, this grout comes in two parts, so the effect of addition of contamination to each part was planned to be studies. Different proportions were chosen to start the screening. The used amounts of grout and contaminations are summarized in Table 4.3.

Table 4.3 Chemical and contamination amounts used for making samples with Grout-3

Mix Name	Pure	O-5	O-10	O-20	SW-5	SW-10	SW-20	O-SW-10	O-SW-15	O-SW-20
Part-A (mL)	50	50	50	50	50	50	50	50	50	50
Part-B (mL)	50	50	50	50	50	50	50	50	50	50
Oil (g)	0	5	10	20	0	0	0	5	7.5	10
Seawater (ml)	0	0	0	0	5	10	20	5	7.5	10
Foaming Start time (sec)	8	9	9	10	7	7	8	9	8	8
Foaming Completion (sec)	35	37	38	41	33	32	36	40	39	37
Expansion Ratio	9.5	2.8	3.5	4.1	18.1	5.3	2.4	3.1	3.5	4.3

During the foaming process of grout the following remarks were made:

1) Initiator has some mild and slow reaction with SW.

2) In all the cases with SW we had a faster reaction and more foam generation.

3) The SW specimens are softer and more brittle than the others.

4) As the SW increased the cohesion of grout reduced and fell apart easily.

5) Totally Oil specimens were denser and remarkably expanded less.

6) The increase of Oil resulted in higher final volume of the foam.

Based on the observations it was decided to extend the extreme of contaminations so that more changes might be observed and if not it is assured that the selected percentage of contamination is satisfactory enough for the rest of the study. So, at this stage we go up to 20% of contamination and also in some case we mix the contaminations to see the effect of that. So different mixes were made and the foams are shown in Figure 4.3 and the following conclusions were made:

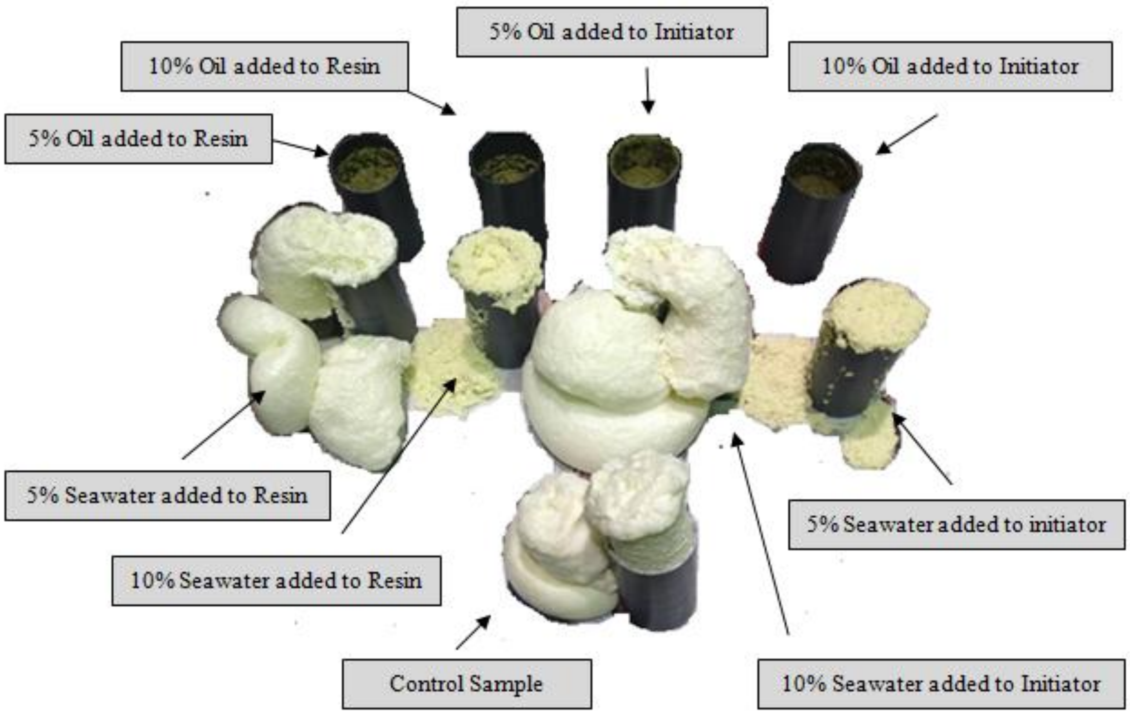


Figure 4.3 Final shape of foams made with Grout-3 and different contaminations

1) As it is seen in Figure 4.4, when the SW increased the initial expansion of the grout was higher, but when the trapped gas was released the foam suddenly collapsed and the final state of the foam was scattered.
2) In the case with 20% Oil the final volume was the highest in all the cases with Oil.
3) In the cases with mixed contaminations the reaction was dominated by the presence of Oil so that as the amount contamination were increases and according more water

existed in the mix the final volume and rigidity of the foam did not change that much and it was more similar to the foams with Oil contamination alone.

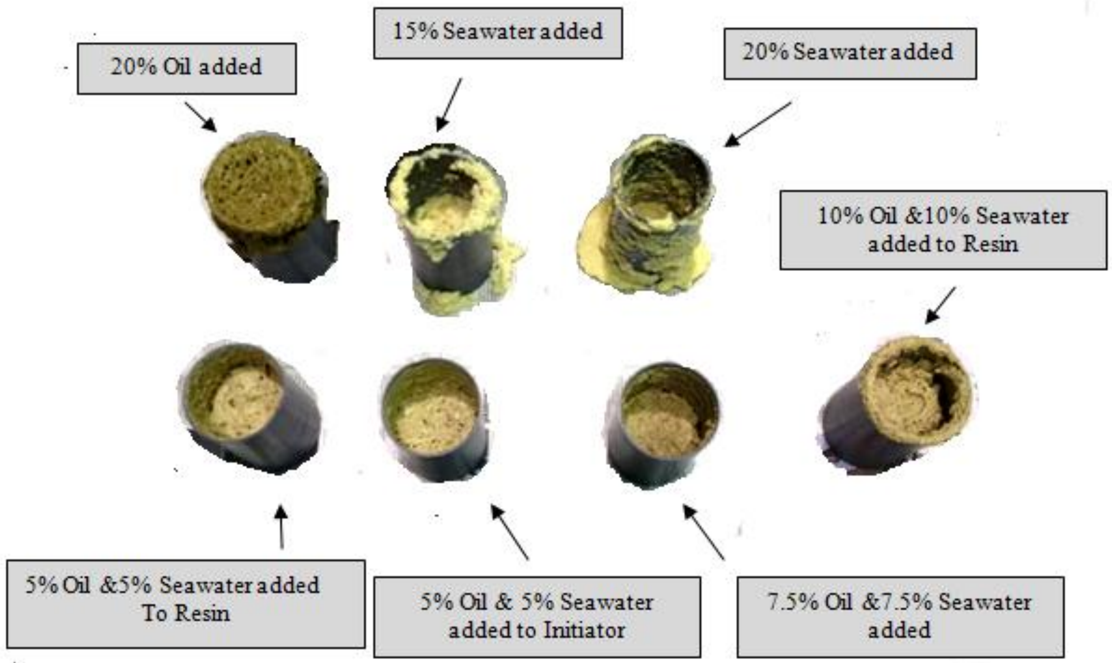


Figure 4.4 Shape of Grout-3 foams with higher dosages of contamination up to 20%

In another part of the study it was noticed that the this grout needs a lot of air for its reaction so to verify this guess two similar amount grout were mixed and poured in the same bottle with same volume and in one them the bottle were closed and as it could be seen in Figure 4.5 the final volume of the grout is really different and also in the closed volume case the reaction stopped at the very beginning (after 10 seconds) but in the other case the reaction proceeded up to 50 seconds. The early stop of the reaction gives the hint that the controlling factor for the reaction is the lack of air not the confining pressure.

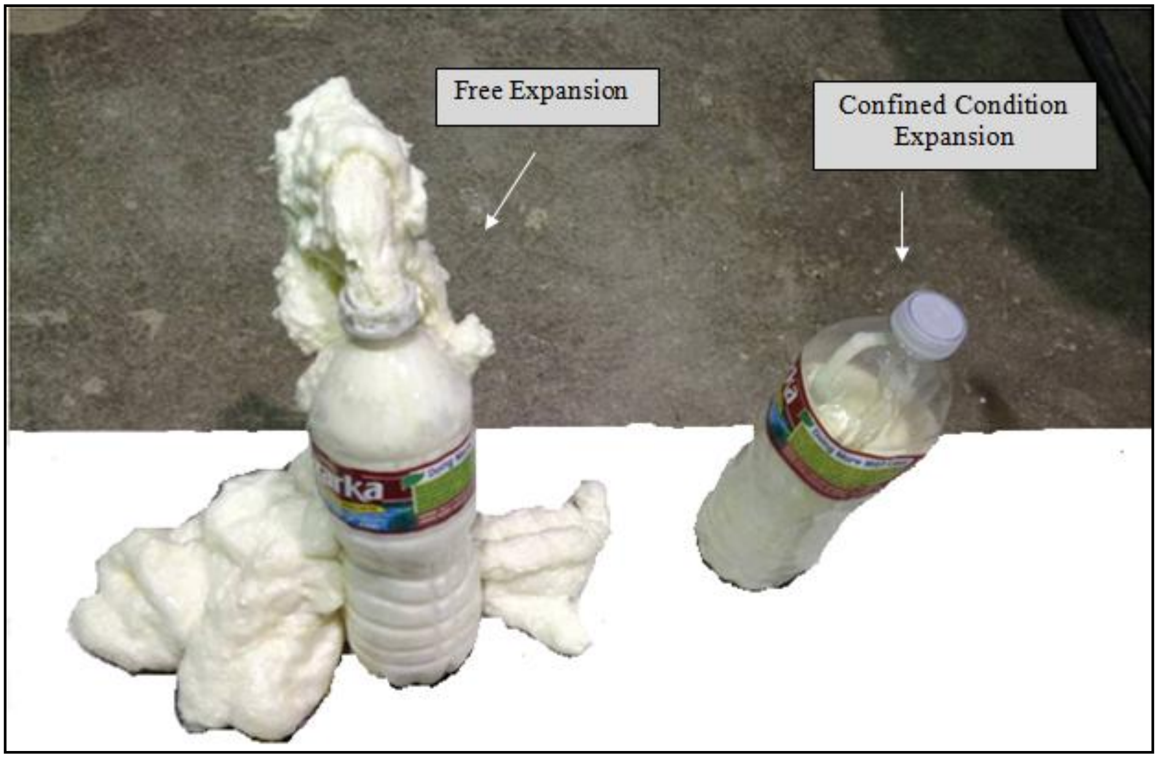


Figure 4.5 The effect of availability of air on the reaction of grout (free expansion versus confined expansion)

Grout-4

This type of grout is hydrophilic and the base chemical should be mixed with water. But, the company did not recommend any specific ratio for adding water. So, four ratio of Chemical: Water of (1:0.5), (1:1), (1:1.5) and (1:2) were tried to see in which case we have the maximum expansion. As it is shown in Figure 4.6 the ratio of 1:1 performed the best so with this ratio we tried different contaminations. As it could seen in all the cases of contamination the total volume of the foam and structure of the grout did not change significantly except for the case that we tried 30% of SW we observed 40% decrease In total volume. The selected amounts for each mix are summarized in Table 4.4.

Table 4.4 Selected amounts of grout and contaminants for samples made with Grout-4

Mix Name	1:0.5	1:1	1:1.5	1:2	O-5	O-10	SW-5	SW-10	SW-30
Part-A (mL)	50	50	50	50	50	50	50	50	50
Water (mL)	25	50	75	100	50	50	50	50	50
Oil (g)	0	0	0	0	2.5	5	0	0	0
Seawater (mL)	0	0	0	0	0	0	2.5	5	15
Foaming Start (s)	32	30	28	31	33	37	32	31	40
Foaming completion (s)	310	300	315	317	321	328	307	304	345
Expansion Ratio	3.8	3.5	2.6	2.0	2.65	2.7	3.3	3.4	2.3

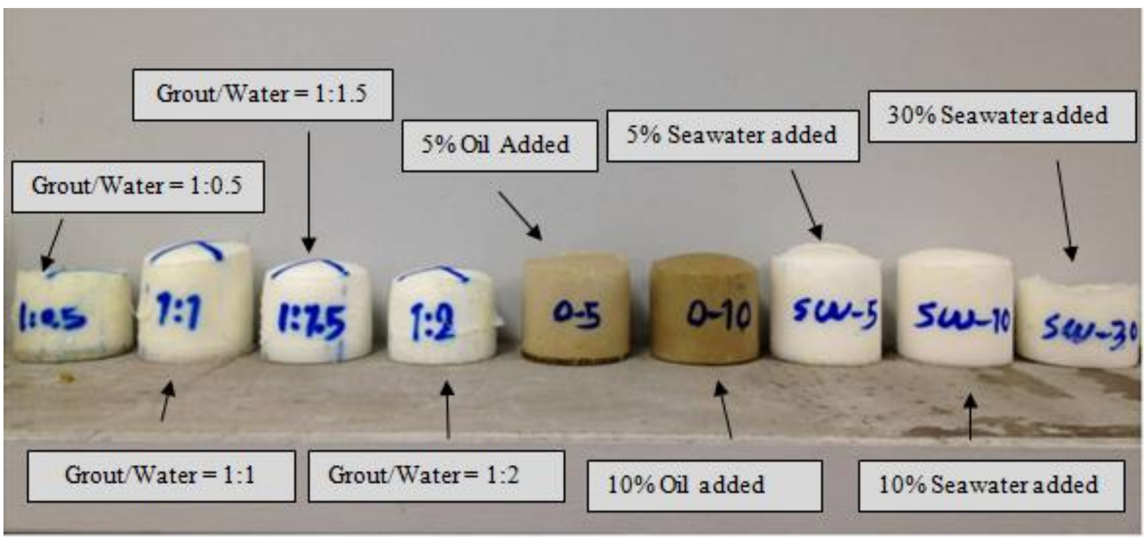


Figure 4.6 Typical shape and condition of the foams made with Grout-4

One of the expected problems with this grout is high rate shrinkage. As it is shown in Figure 4.7 after 8 days all the specimens had remarkable shrinkage that can devalue this grout for long-term performance. Basically this high rate of shrinkage could be attributed to the high water content in foam that vaporizes by the time and results in shrinkage.

Figure 4.7 The shape of grout Type-4 samples after shrinkage (2 weeks after sample preparation)

Grout-5

This grout is also produced in two components. So the same procedure like Grout-3 is done it. The selected amounts for chemicals and the contaminations as summarized in Table 4.5 were mixed and the samples were prepared.

Table 4.5 Amounts of chemical and contaminants for preparing the Grout-5 samples

Mix Name	Control	O-5	O-10	SW-10
Part-A (mL)	25	25	25	25
Part-B (mL)	25	25	25	25
Oil (g)	0	2.5	5	0
Seawater (mL)	0	0	0	50
Time of start of foaming (s)	25	29	33	24
Time of foaming completion (s)	75	82	88	63
Final Expansion Ratio	6.8	7.5	6.2	17.1

Based on what has been observed the addition of the contaminants to each one of them leads to no change. So, it does not matter which part be injected first. Based on the Figure 4.8 and Table 4.5 we can conclude the following notes:

1) The addition of Oil slightly increased the expansion.

2) The specimens with Oil content had a very good adhesion to the molds.

3) The addition of SW increased the expansion almost three times more.

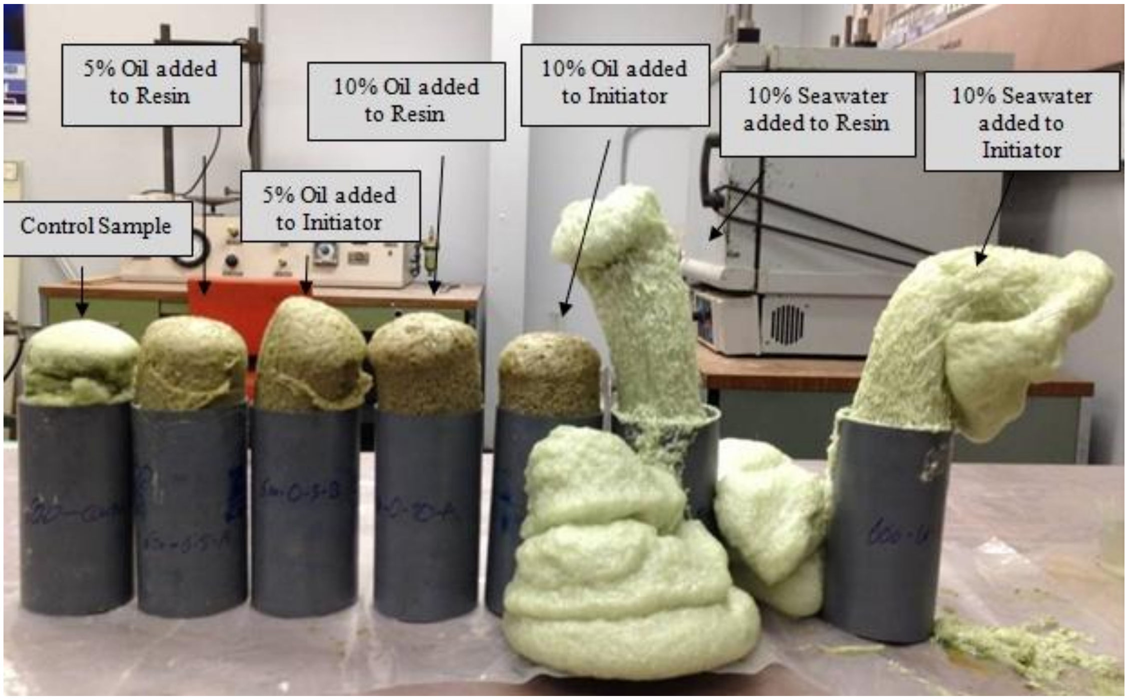


Figure 4.8 Typical shape of foams made with Grout-5 and different contaminations.

By completing this part of study the following considerations should be made:

1) The duration of blending the grout in liquid phase affects the total reaction time and the final foam quality

2) Accessibility of air to all the grouts is an important factor, since in some cases some unreacted grout remained at the bottom of the mold.

3) All the grouts showed a remarkable sensitivity against the water. The reason that the presence of the water leads to such a increase in foam generation should be studied.

Summary

In overall the following observations could be summarized

1) The selected contaminations have noticeable effect on the performance and final quality of the grout and also the type of contaminations are in the condition that can yield good and useful results.

2) It was evident that the water or Seawater increases the rate of expansion and once they are added, more foam could be generated however, the final generated foam has lower density and accordingly weaker structure.

3) It was noticed that the Oil has a very negative effect on the grout and it interferes with the chemical reaction and the total process of grout reaction and foam generation is affected in the negative way.

4) It was seen that in all the cases with Oil Contamination the final volume of the generated foam is less the control sample for all the grouts.

5) Oil and seawater as the contaminations are considered to be part study and further tests and quantifications are needed to be done on them. On the other hand, based on the observations the two dosages of 5% and 10% of the grout weight are fairly good amounts to be used and it is fixed for all types of grout.

4.2.2) Grout curing monitoring

Objective

In practice and the field at the time of mixing and preparing the foam the initial chemical for generating the foam might be mixed with other chemicals existing in the working space and environment that are mostly inevitable. Since, polyurethane is product of chemical reaction, the presence of other chemical might interrupt the reaction and impair the final product of reaction. Therefore, in this stage of study it was intended to add Sea water and Used Oil as the contaminants to the initial mix of grout and study the effects. To have quantitative values for study, the pressure and temperature during reaction were monitored and also after that the foam was formed its unit weight and shrinkage were measured to have an idea of how these contaminations affect the grout.

Materials and Mix Selection

The grouts being used here are named as Grout-1, Grout-2, Grout-3, Grout-4 and Grout-5. And for the contaminants the used car oil and Galveston water were used. Based on the conclusions made in chapter (4.2.1) each of these two contaminants was added as much as 5% and 10% of the weight of the liquid grout components. Besides for each type of grout control specimen without any contamination was prepared. On the other hand, since the Grout-3 does not react in confined condition, it was excluded from this part of study. So, totally for each grout 5 mixes were selected and for the whole report 20 mixes were included.

Controlled Volume test

In this test 25 ml of grout mix was prepared which fills 50% of the mold and other 50% of the mold volume is left free for expansion. The grout is blended for 10 seconds and the then the mold is capped and clamped. During the reaction the temperature and pressure were recorded in 20, 30, 60 and 120 seconds intervals up to 20 minutes and after that every hour up to three hours and at the end after 24 hours the final recording was done. In every test half of the mold was filled with grout chemicals and the half empty space was dedicated for the grout to expand.

Results and Analyses

In this part the test results and obtained curves along with its analysis are presented. At the first step, the performance of each grout in exposure to different contaminations is reviewed and the performance of all grout in exposure to each specific contaminant is compared. In each part the results are brought in separate tables. Fist the results of this test, those with highest pressure and temperatures belonging to each grout are summarized in Table 4.6.

Table 4.6 The maximum pressure and temperature observed during each grout reaction

No	***Grout***	***Pressure (Psi)***			***Temperature (Celsius)***			***Remarks***
		Name	***Max P***	***Time***	***Name***	***Max T***	***Time***	
1	Grout-1	SW-10	119.6	3':00''	SW-10	84.8	4':30''	-
2	Grout-2	SW-5	210.4	0':50''	Control	135	1':45''	-
3	Grout-4	SW-10	44.5	1':30''	Control	33.9	2':20''	-
4	Grout-5	SW-10	82.4	1':15''	Control	96.1	0':50''	-

In the next part each grout is studied separately and the graphs are presented chapter by chapter.

Grout-1

The results collected from the testing of Grout-1 are summarized in Table 4.7.

Table 4.7 Pressure-Temperature records of Grout-2 incorporating different contaminations

Mix	Max Pressure (Psi)		Max Temperature (Celsius)		Unit Wight(kg/m^3)	Expansion %	Water Absorption %	Volume Change %
	Max P	Time	Map T	Time				
O-5	11.0	6:00	54.9	0:30	69.1	1730	520	22
O-10	6.0	1:30	56	0:50	72.3	1619	605	24
SW-5	80.1	5:00	74.4	2:40	46.7	2433	606	2
SW-10	82.4	1:15	93.4	2:20	62.0	1804	468	-4
Control	78.9	2:40	96.1	0:50	86.9	1174	401	3

In the following chapter the graphs of Temperature-pressure curves for different grouts are presented.

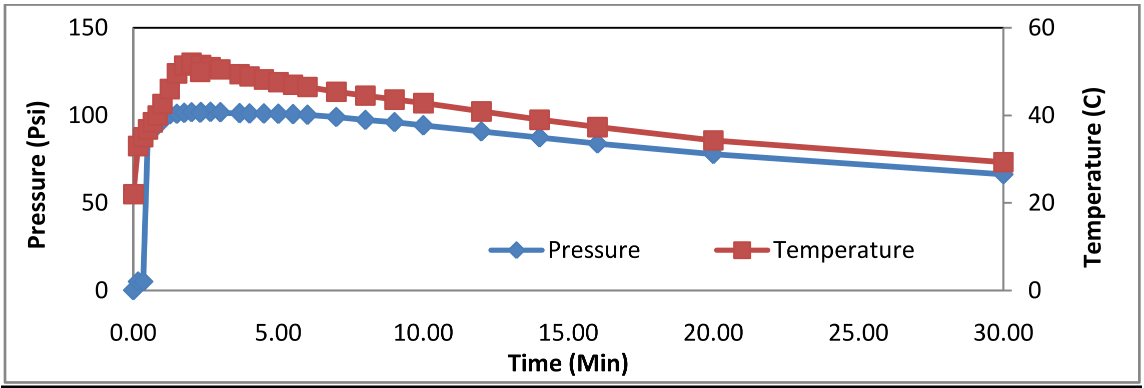


Figure 4.9 Pressure-Temperature curve of Grout-1 with 5 % oil contamination

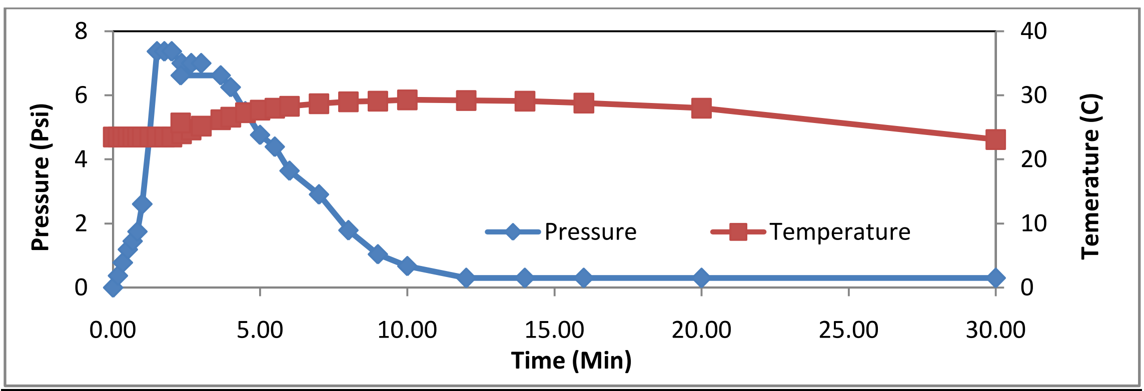


Figure 4.10 Pressure-Temperature curve of Grout-1 with 10 % oil contamination

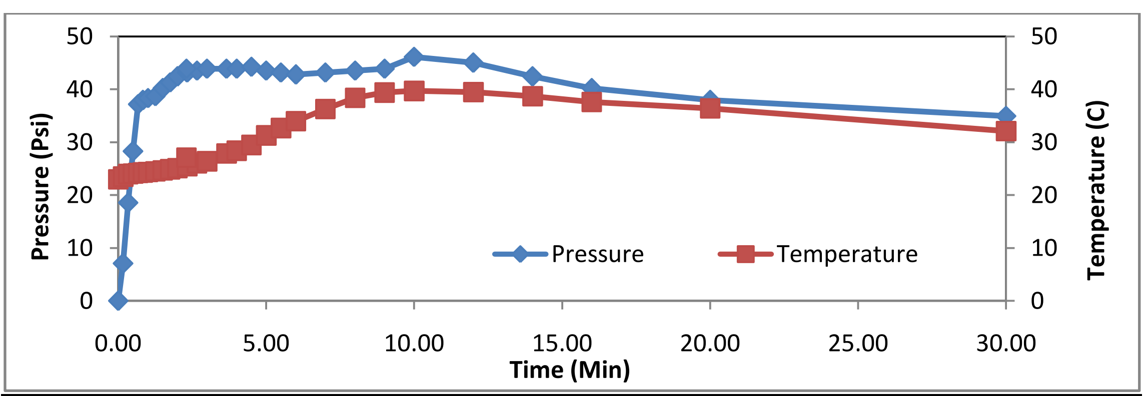


Figure 4.11 Pressure-Temperature curve of Grout-1 with 5% Sea water contamination

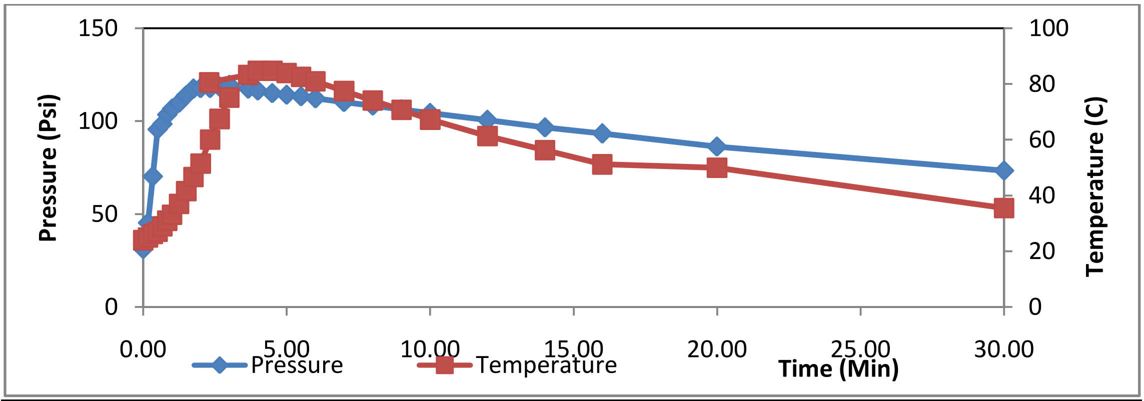


Figure 4.12 Pressure-Temperature curve of Grout-1 with 10% sea water contamination

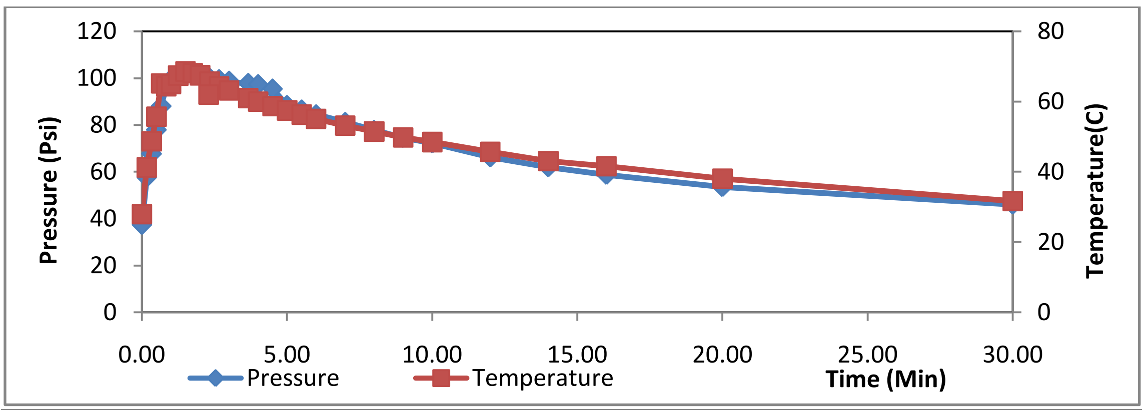


Figure 4.13 Pressure-Temperature curve of Grout-1 Control Specimen

Discussion on Grout-1

It is observed that, as the amount of oil increases the pressure decreases and the same trend happens in the case with pure water. However, in the Sea Water specimens the increase of Sea Water leads to higher pressures so that the highest pressure is observed in the case containing 10% seawater. Also, the change in oil from 5% to 10% has the most remarkable decline in pressure. In the case of temperature the trends are consistent with those in the pressure curves. The behavior of Grout-1 is shown in Figure 4.9 to 4.13.

Grout-2

The data collected during the reaction of Grout-2 are summarized in Table 4.8.

Table 4.8 Pressure-Temperature records of Grout-2 with different contaminations

Mix	Max Pressure (Psi)		Max Temperature (Celsius)		Unit Wight(Kg/m^3)	Expansion %	Water Absorption %	Volume Change %
	Max P	Time	Map T	Time				
O-5	80	1:00	87	1:30	198.3	507	86	-22
O-10	64	1:45	74.5	3:00	169.8	600	117	61
SW-5	210	0:50	127	1:00	219.5	452	203	-18
SW-10	104	1:15	124	1:30	308.0	341	138	-9
Control	111	1:30	135	1:45	38.2	2119	444	28

Pressure& Temperature-Time

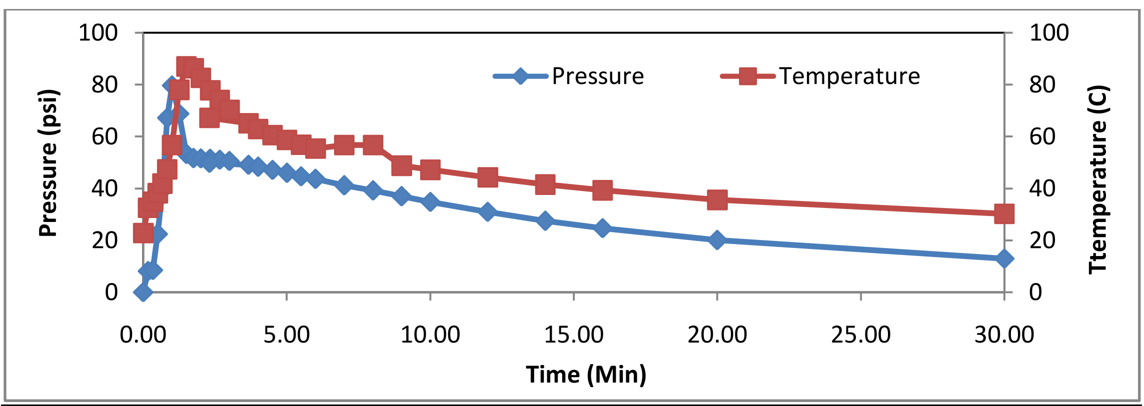


Figure 4.14 Pressure-Temperature curve of Grout-2 with 5 % oil contamination

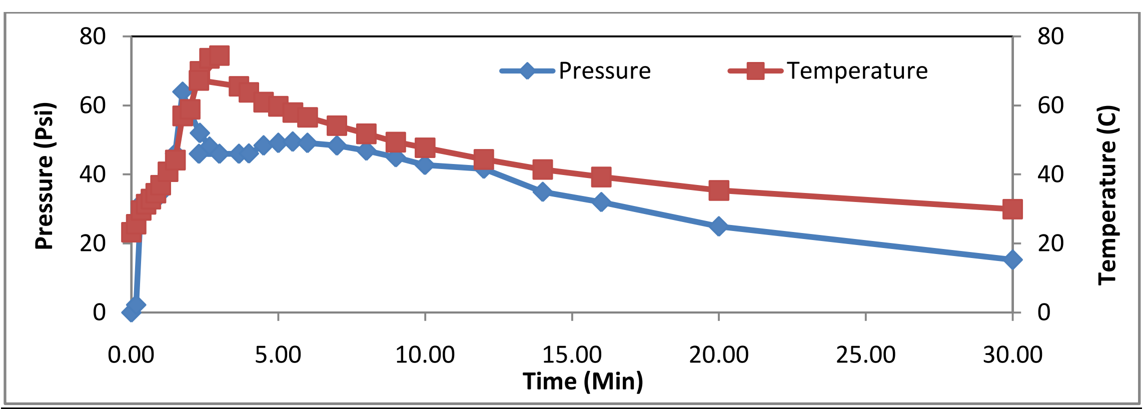


Figure 4.15 Pressure-Temperature curve of Grout-2 with 10 % oil contamination

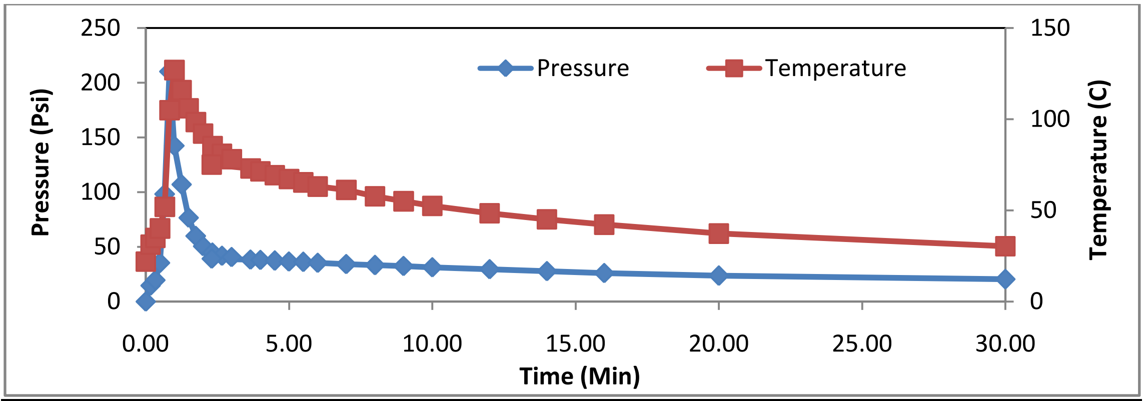


Figure 4.16 Pressure-Temperature curve of Grout-2 with 5% Sea water

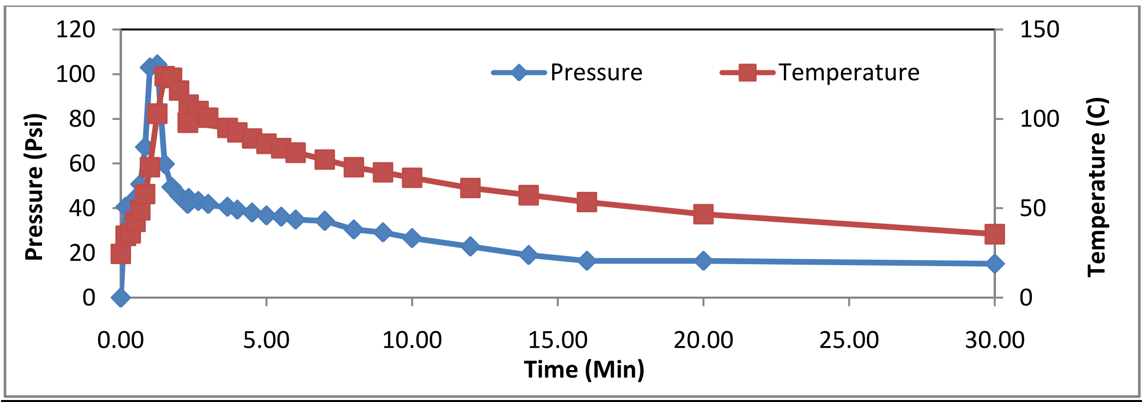


Figure 4.17 Pressure-Temperature curve of Grout-2 with 10% sea water

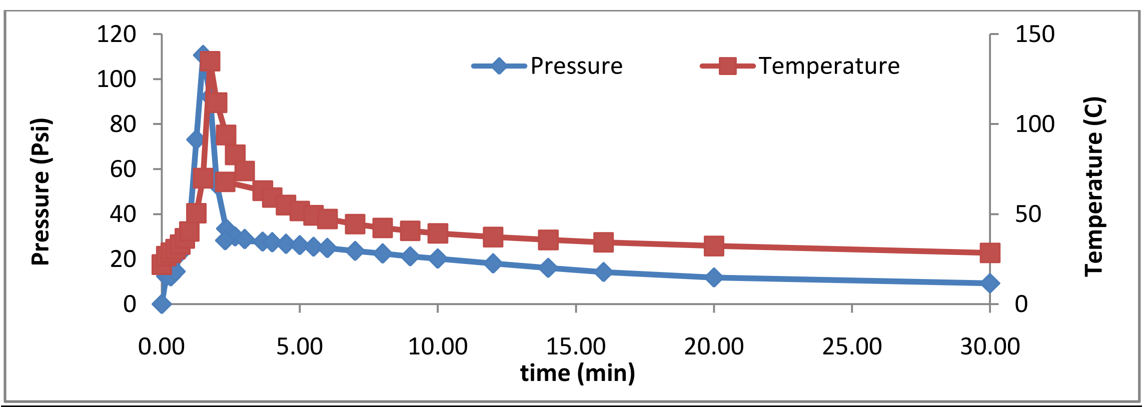


Figure 4.18 Pressure-Temperature curve of Grout-2 Control Specimen

Discussion on Grout-2

Generally, as we see in Figure 4.14 to Figure 4.18, the Seawater specimens have the higher pressure than others. However as the seawater increased the pressure decreased. On the other hand, the oil specimens in the total trend behaved the same but the total pressure of oil specimens by increasing the amount oil decreased. And also the 5% seawater specimen has the fastest reaction since it reaches its peak pressure sooner than the others. The trend in temperature is also consistent with those of pressure, however, the seawater specimens has reached the same peak temperature but with a time gap.

Grout-4

Grout-4 with different contaminations was mixed and its curing was monitored. During the monitoring data were recorded and also after the reaction completion some physical properties were measured that are summarized in Table 4.9.

Table 4.9 Pressure-Temperature records of Grout-4 with different contaminations

Mix	Max Pressure (Psi)		Max Temperature (Celsius)		Unit Wight(Kg/m^3)	Expansion %	Water Absorption %	Volume Change %
	Max P	Time	Map T	Time				
O-5	7	0:40	31.6	0:20	417.1	452	109	-8
O-10	31	0:40	32	0:40	509.0	378	88	-93
SW-5	45	1:30	29.7	2:40	571.6	341	28	73
SW-10	27	10:00	32.7	2:20	409.8	489	3	25
Control	12	5:00	33.9	2:20	548.3	341	48	6

Pressure& Temperature-Time

Discussion on Grout-4

As seen in Figure 4.19 to Figure 4.23, with this grout the increase in the amount of oil led to the increase in the pressure which is the opposite of seawater. The highest pressure was observed in the specimen with the 10% seawater contamination. Also the increase in the amount of oil led to the remarkable increase in pressure. In this case the trend of temperature does not follow the same trend path as the pressure. But totally they went on the same trend and almost in a small range of temperature which means that exothermic behavior of this grout roughly is independent of the type or amount of contamination.

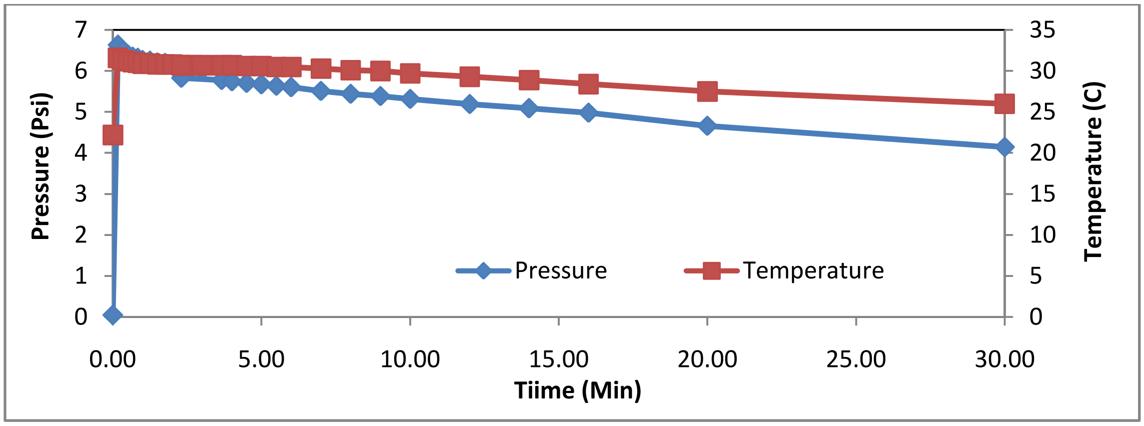


Figure 4.19 Pressure-Temperature curve of Grout-4 with 5 % oil

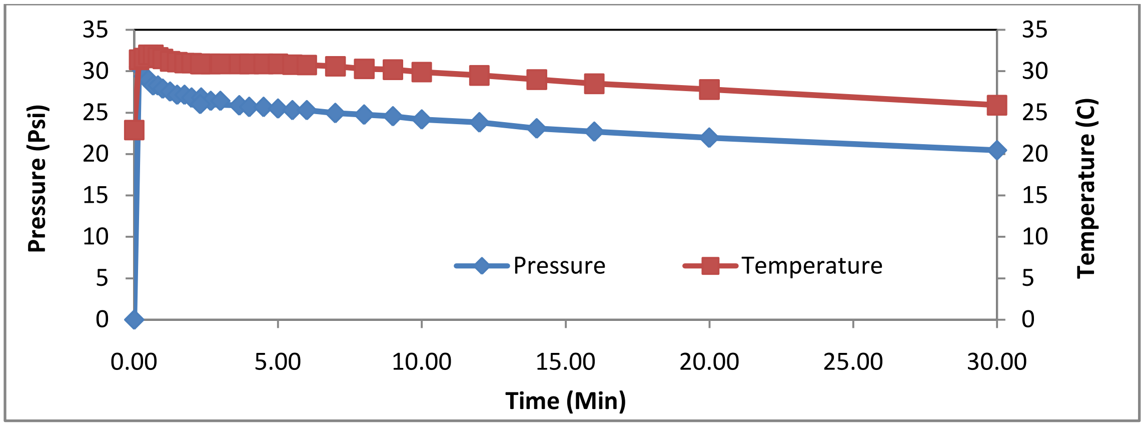


Figure 4.20 Pressure-Temperature curve of Grout-4 with 10 % oil

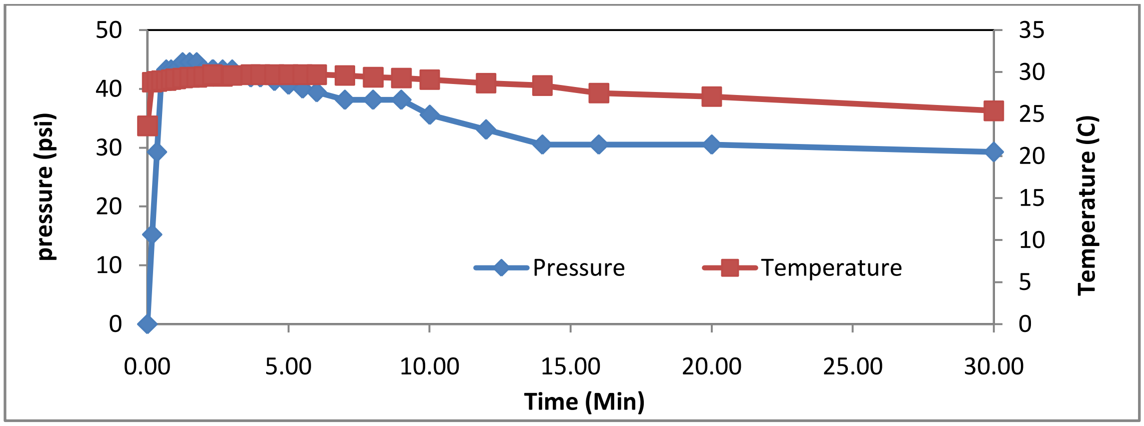


Figure 4.21 Pressure-Temperature curve of Grout-4 with 5% Sea water

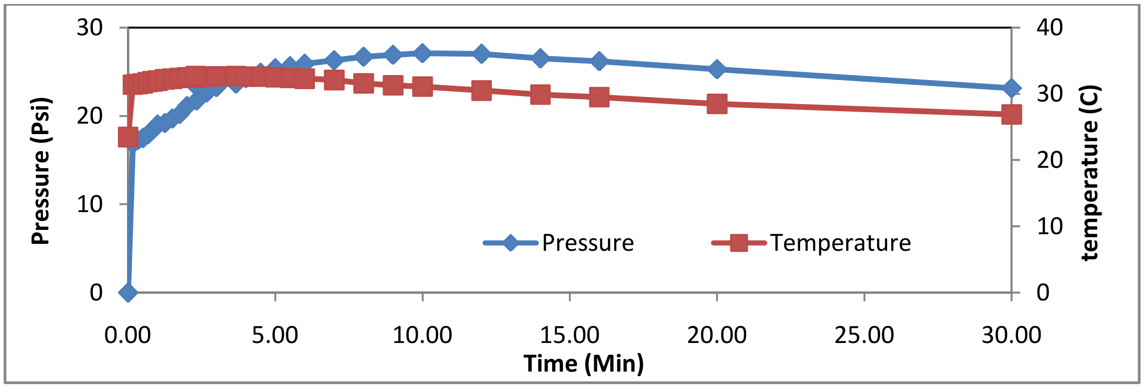


Figure 4.22 Pressure-Temperature curve of Grout-4 with 10% Sea water

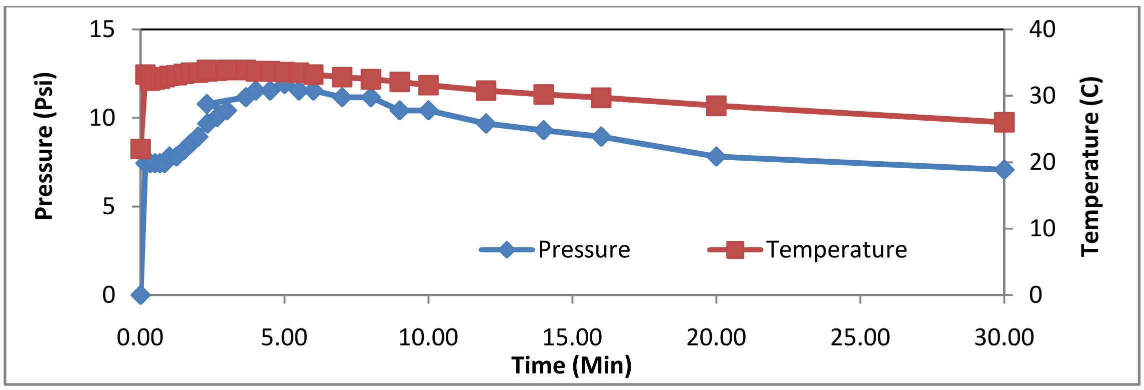


Figure 4.23 Pressure-Temperature curve of Grout-4 control Specimen

Grout-5

The remarkable and key data collected during and after the reaction of Grout-5 are summarized in Table 4.10.

Table 4.10 Pressure-Temperature records of Grout-5 incorporating different contaminations

Mix	Max Pressure (Psi)		Max Temperature (Celsius)		Unit Wight(kg/m^3)	Expansion %	Water Absorption %	Volume Change %
	Max P	Time	Map T	Time				
O-5	11.0	6:00	54.9	0:30	128.7	748	129	3
O-10	6.0	1:30	56	0:50	161.1	619	138	-8
SW-5	80.1	5:00	74.4	2:40	46.7	1989	359	15
SW-10	82.4	1:15	93.4	2:20	57.7	1711	406	1
Control	78.9	2:40	96.1	0:50	99.3	952	72	5

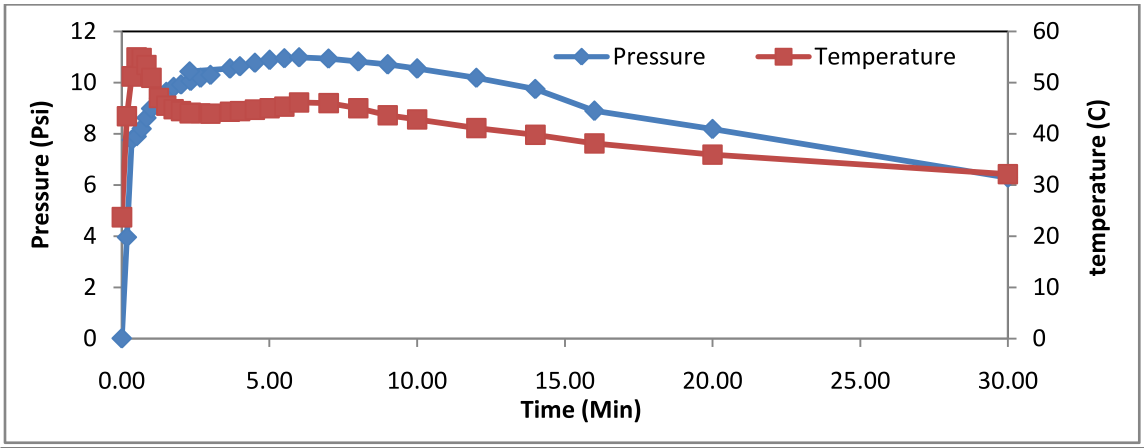


Figure 4.24 Pressure-Temperature curve of Grout-5 with 5 % oil

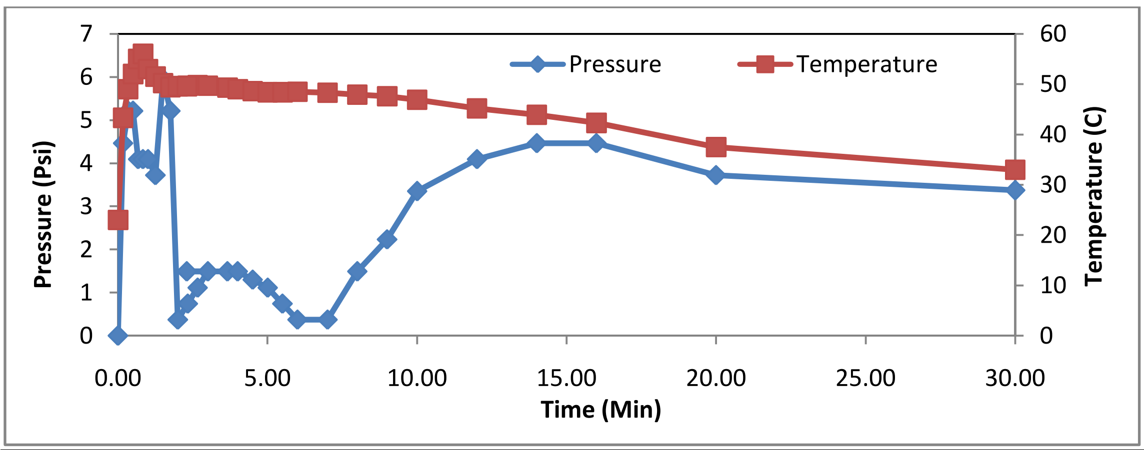


Figure 4.25 Pressure-Temperature curve of Grout-5 with 10 % oil

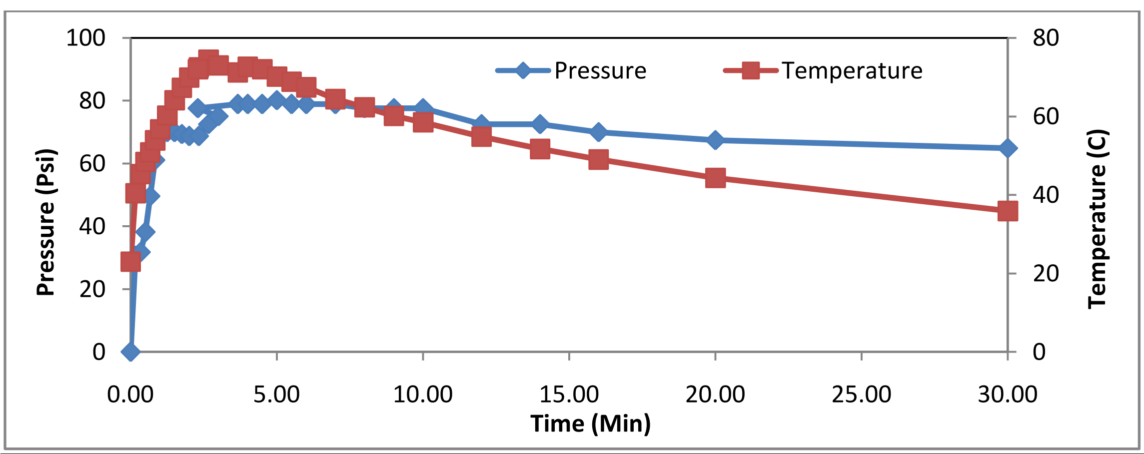


Figure 4.26 Pressure-Temperature curve of Grout-5 with 5% Sea water

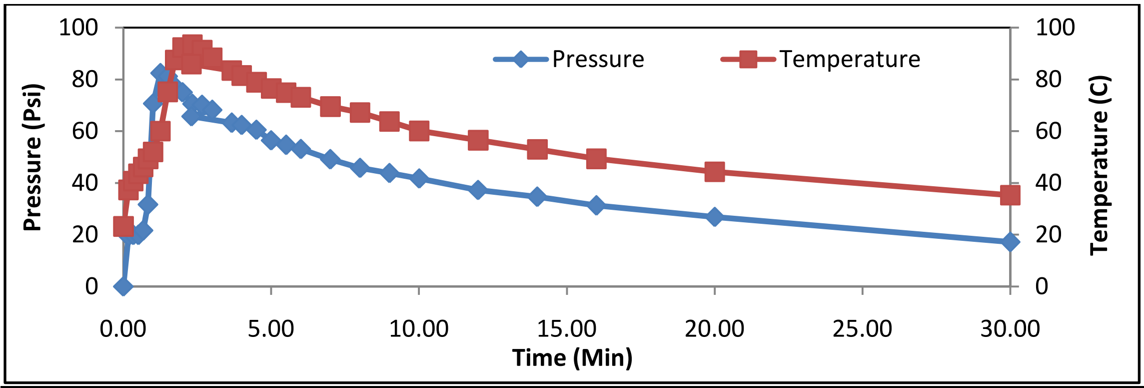


Figure 4.27 Pressure-Temperature curve of Grout-5 with 5% Sea water

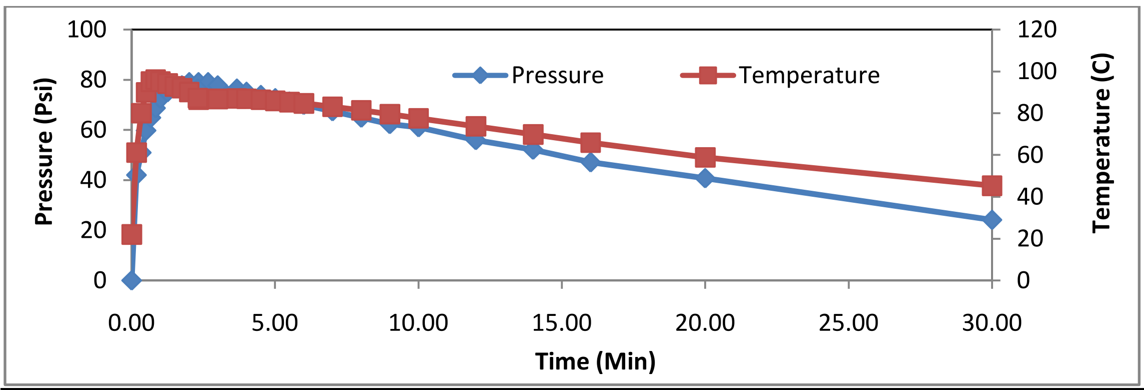


Figure 4.28 Pressure-Temperature curve of Grout-5 Control specimen

Discussion on Grout-5

In this experiment it is apparent that the addition of seawater has a tremendous effect on the reaction and also the moisture could be considered as the catalyst for this type of grout. The point is that in the case with 5% seawater contamination the final pressure is noticeably high. It might be due to the good sealing of this mold and air caused this high constant pressure. Also in O-10 it is inferred that reaction might be interrupted by high dosage of contamination that it does not follow a usual trend. The temperature trend is the same as the pressure and outside of the middle range of time they behave almost the same. The trend and performance of Grout-5 with different contaminations are presented in Figure 4.24 to Figure 4.28.

Comparison of All grouts

After comparing all the grouts in the same graph it is concluded that;

1) In the case with oil the Grout-1 yields the highest pressures and after that Grout-2 is the best.

2) In the case of seawater the Grout-2 has the best performance and right behind it Grout-1 performed well.

3) There is a point that Grout-1 is so sensitive to the concentration of oil.

4) Also Grout-1 in the case of Seawater is also sensitive against the amount of water and as the water increases in the mix the pressure increases.

5) In the case of temperature the Grout-2 has showed the highest values in both cases of oil and seawater contaminations. And also the difference between this grout and the others is noticeable.

6) Also there is another point that the despite of the high pressure of Grout-1 in proportion to other grouts its temperature is far less than the others. Therefore the temperature is not a good representative of the reaction or achievable pressure for Grout-1.

Summary

Totally, apart from this controlled volume test, the free expansion test was initially performed.

1) In those cases Grout-5 showed good expansion and the final generated foam was of good strength and toughness. However it yielded no acceptable results in the confined volume test.

2) Altogether, in all the grouts that have water in their content there was shrinkage problems. This happens especially in Grout-5 which, the addition of water to it leads to remarkable shrinkage.

3) So there is a possible condition that this grout needs a lot air for its reaction and during the closed volume test it cannot reach that needed amount of air so that the reaction was not completed.

4) In the terms of Unit weight the Grout-4 has the highest unit weight and Grout-1 has the lowest. However based on the unit weight the prediction that could be made is the porosity of the produced foam.

5) Based on the results of water absorption test it was observed that the grout Grout-1 and Grout-4 have the highest and lowest water absorption rate respectively. These observations are completely consistent with the unit weight of the mentioned grouts and it could be concluded that the lower the unit weight, the higher the water absorption would be.

6) As it was seen in the shrinkage values, the Grout-4 and Grout-5 have shown the highest and lowest shrinkage rate. The important point was that in some mixes the specimen expanded instead of shrinking and there is no trend that can help us with prediction of shrinkage.

Basically from the results of this test it was intended to choose the best grouts of this group for the rest of study. However the observations of this test alone is not a good and prefect basis for such a judgment and selection so for the rest of study the Grout-1, Grout-2 and Grout-5 will be used for next series of experiments. It is expected that Grout-1 and Grout-2 perform as the best and almost the same.

Although the Grout-1 performed well in the case of pressure, but in the case shrinkage it has the weakest performance that leaves us with the hint that utilizing of Grout-1 demands more study and consideration since the shrinkage is not a negligible problem, especially in the case that the purpose is sealing.

4.2.3) Unit weight

For this test the foam was made in the containers with known volume. After the foam was generated the container was filled with water and the volume of water used to fill up the container was measured. By subtracting this volume from the total volume of container the volume of foam was obtained. The measured unit weights of all grouts are summarized in Table 4.11.

Table 4.11 Unit weight of all grouts incorporating different contaminations

	Unit Weight (kg/m^3)				
	Grout-1	**Grout-2**	**Grout-3**	**Grout-4**	**Grout-5**
O-5	69.1	198.3	128	417.1	128.7
O-10	72.3	169.8	118	509.0	161.1
SW-5	46.7	219.5	123	571.6	46.7
SW-10	62.0	308.0	157	409.8	57.7
Control	86.9	38.2	63	548.3	99.3

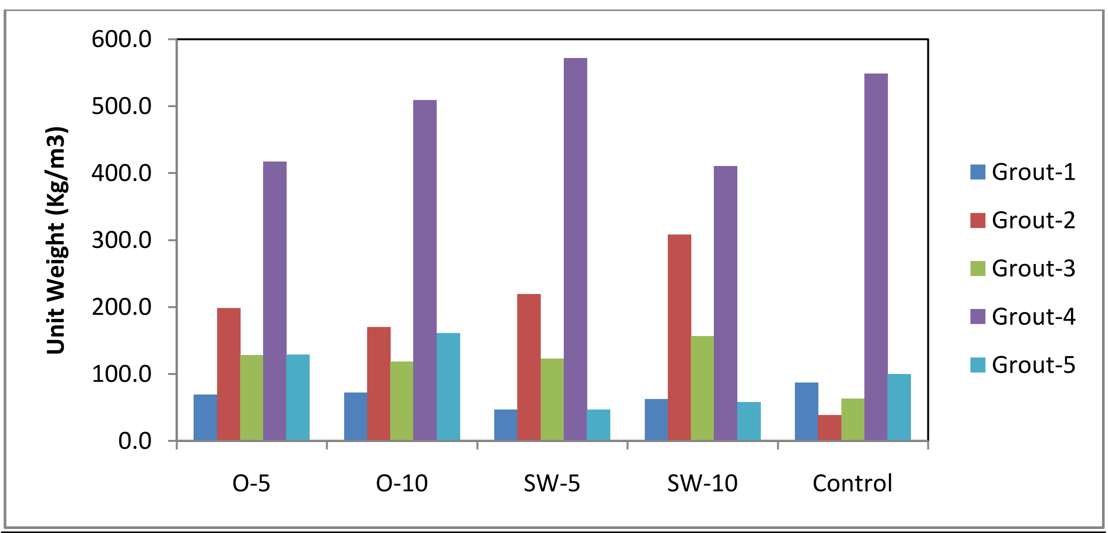


Figure 4.29 The Unit weight trend of all grouts versus the contaminations

Discussion on Unit weight variation

Grout-1

As it seen in Figure 4.29, totally, contamination decreases the unit weight of grout. Besides, as the amount of sea water increases, the unit weight also increases.

Grout-2

This grout is highly sensitive against the contamination. In average cases with contamination the unit weight increases 5-7 times more than the control specimen. This sensitivity is highest against Seawater and as it is increased the Density also increased.

Grout-3

In this case it is observed that the contamination increased the density. Especially in the case with Seawater, the increase of Seawater led to further increase in Density.

Grout-4

When the Oil is added to this grout the density decreased in both cases. However, in the case with Seawater no steady pattern could be noticed in change of Density.

Grout-5

It was noticed that Seawater has a remarkable effect on the Foaming and the Density of the grout, in the way that once the seawater is added the density dropped to the half. On the other hand, the Oil increased the density up to 1.6 times more.

Summary

As it is seen in Figure 4.29 Grout-1 has the lowest unit weight and the Grout-4 has the highest Unit weight. On the other hand the Grout-1 has also revealed the lowest sensitivity against the type or concentration of contamination. And totally there is no logical trend between any change in the contaminations and the unit weight of each grout.

The smallest and largest unit weights belong to (Grout-1-Sw-5) and (Grout-4-SW-10) respectively.

4.2.4) Water Absorption

For this parameter, the specimens were soaked in water for 24 hours and then the saturated foam was weighed and also the foam was already weighed in dry condition. So the difference between these two weights is absorbed water and by this values the water absorption percentage were calculated. The Water Absorption of all grout with different contaminations are summarized in Table 4.12.

Table 4.12 Water absorption of all grouts incorporating different contaminations

Water Absorption (Weight %)					
	Grout-1	**Grout-2**	**Grout-3**	**Grout-4**	**Grout-5**
O-5	520	86	223	109	129
O-10	605	117	326	88	138
SW-5	606	203	467	28	359
SW-10	468	138	259	3	406
Control	401	444	423	48	72

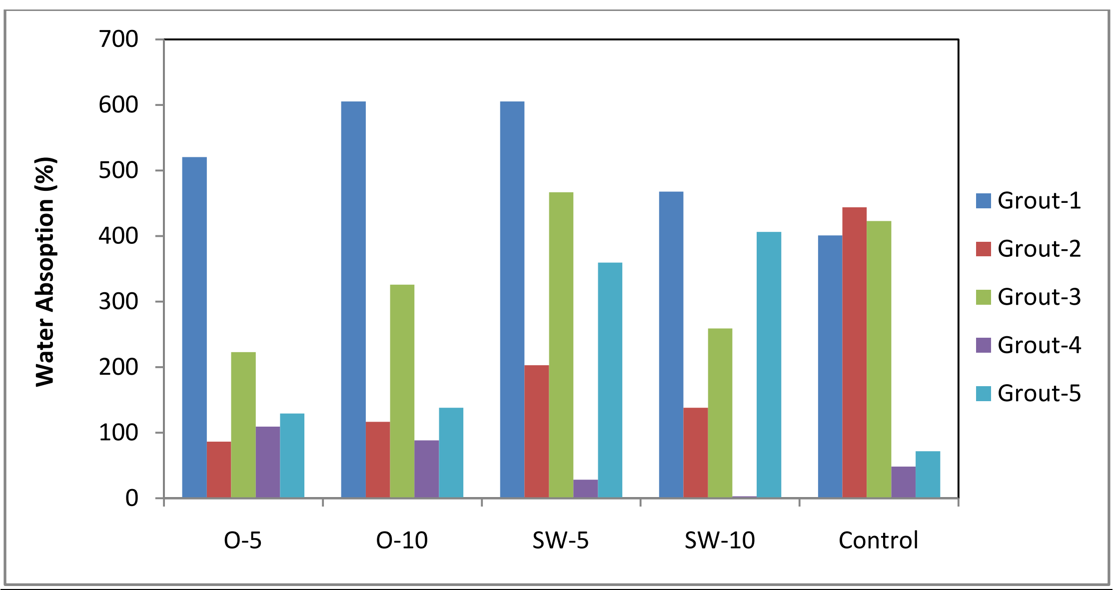


Figure 4.30 Water absorption trends of all grouts versus the contaminations

The performances of all grouts and with different contaminations are shown in Figure 4.30. In the following chapter the performance of each grout is discussed.

Grout-1

As it seen, the contamination caused the increase in water absorption. However, increase of seawater led to decrease of water absorption and inversely, Increase in Oil led to increase in Water Absorption.

Grout-2

Generally, the contamination resulted in a tremendous decrease in water absorption as much as 80% in some cases. Also, the oil decreased the water absorption more than the Seawater contamination

Grout-3

In most of the contaminated specimens, the water absorption decreased. Once the amount of oil increased the water absorption also increased and the reverse trend observed for Seawater addition.

Grout-4

The oil contamination has increased the water absorption up to 2 times more than the control specimens. On the other hand, the addition of seawater resulted in the decrease of eater absorption. Furthermore, as the amount of Seawater increased, the water absorption declined remarkably.

Grout-5

Generally, the contaminations had adverse effect on the water absorption and increased the water absorption in all the cases. Besides, the water absorption had more remarkable effect on the increase of water absorption. In average the seawater increased the water absorption five times more than the control specimens.

Summary

It is observed that Grout-1 has the highest water absorption rate. This observation is consistent with its unit weight that grout Grout-1 has the lowest unit weight so it has the highest porosity. On the other hand grout Grout-4 showed the lowest water absorption that this fact is also again consistent with its unit weight which is the highest among all the grouts. Again in this case no special trend between the type and concentration of contamination and the water absorption could be made. In this case the grout mix (Grout-4-SW-20) has the lowest water absorption equal to 3%. The mix (Grout-1-SW-5) and (Grout-1-SW-10) showed the highest water absorption equal to 606% which is noticeably high.

4.2.5) Soaking Volume Change

As it was mentioned previously there is no standard method to evaluate this parameter. Therefore, simply after 24 hour soaking the specimens in water, by the same method as the unit weight, the volume before and after soaking was measured and the relative decrease in volume is considered as the soaking volume change. The measured soaking volume changes of all grouts with different contaminations are summarized in Table 4.13.

Table 4.13 Soaking volume change of all grouts incorporating different contaminations

Shrinkage (Volume %)					
	Grout-1	**Grout-2**	**Grout-3**	**Grout-4**	**Grout-5**
O-5	22	-22	12	-8	3
O-10	24	61	40	-93	-8
SW-5	2	-18	-8	73	15
SW-10	-4	-9	-7	25	1
Control	3	28	15	6	5

Discussion

In this test it was observed that some of the specimens expanded and some others shrank. So the negative values indicate the expansion in the results. In the Grout-4 it is observed that when the oil is added the specimen expands and if sea water is added it shrinks. For rest of the grout no acceptable trend could be guessed. Altogether it could be concluded that Grout-5 has the lowest shrinkage and Grout-4 has the highest. The range of change of volume is between (-93% to 73%). In addition, Grout-5 showed the least sensitivity against the type and concentration of contamination. As it is shown in Figure, Grout-4 with oil contamination has expanded during the soaking. On the other hand, when seawater is added as contamination it has shrunk. Also, in Grout-2 and Grout-3 when the seawater is added, the grout has expanded after soaking.

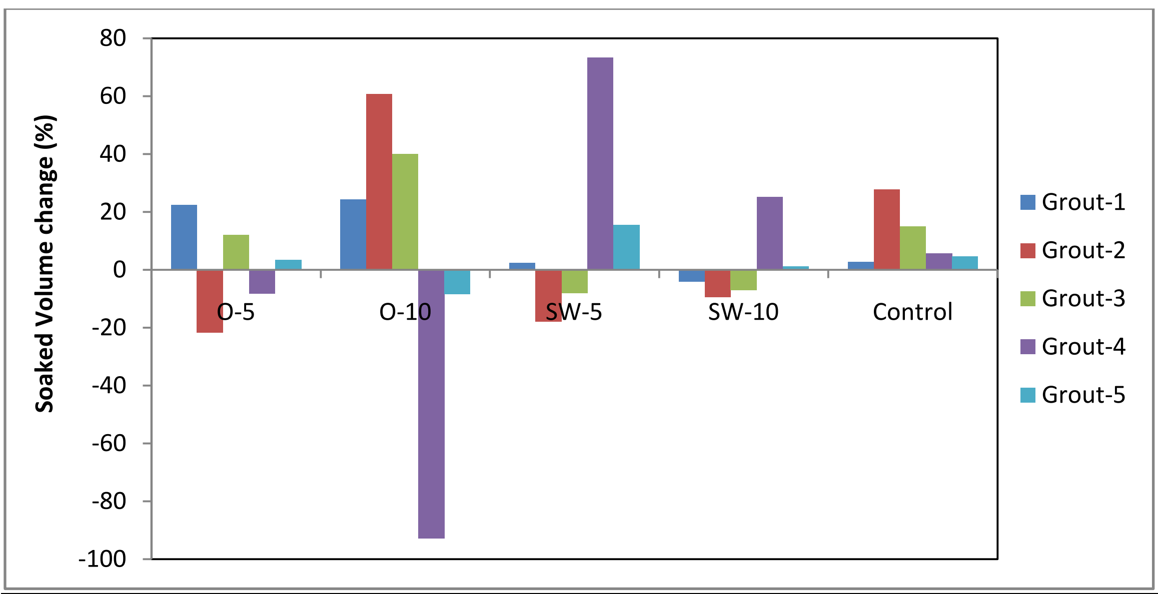


Figure 4.31 Soaked volume changes of all grouts versus the contaminations

4.2.6) Confined Compressive Strength Test

The specimens were loaded at the displacement rate of 0.01 inch/minute. The selected mixes are those with the highest pressure and temperature from the temp-pressure test and 7 mixes were selected and 2 specimens of each mix were prepared and tested. The Stress-Strain curves of the selected mixes are shown in Figure 4.32 to Figure 4.38.

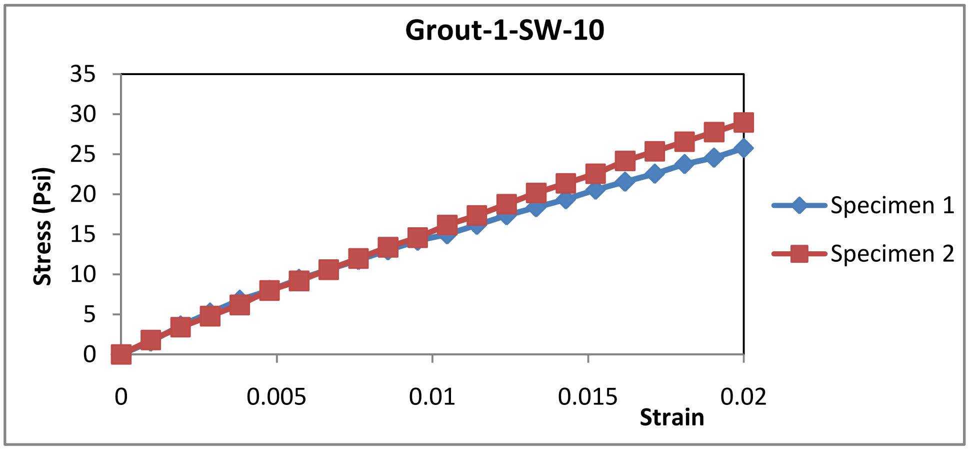


Figure 4.32 Grout-1-SW-10 stress-strain Curve

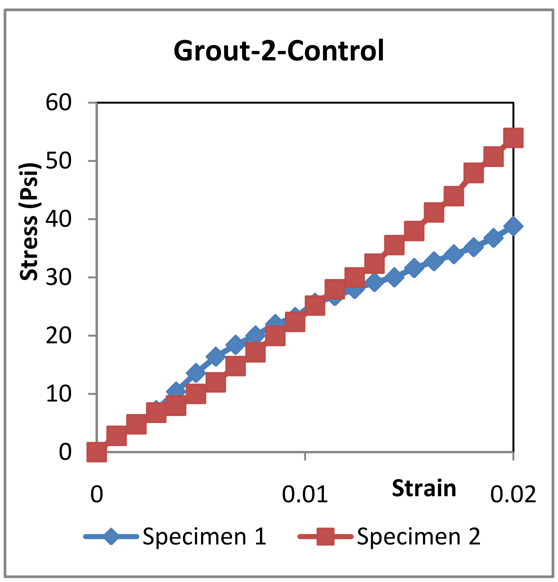


Figure 4.33 Grout-control stress-strain curves

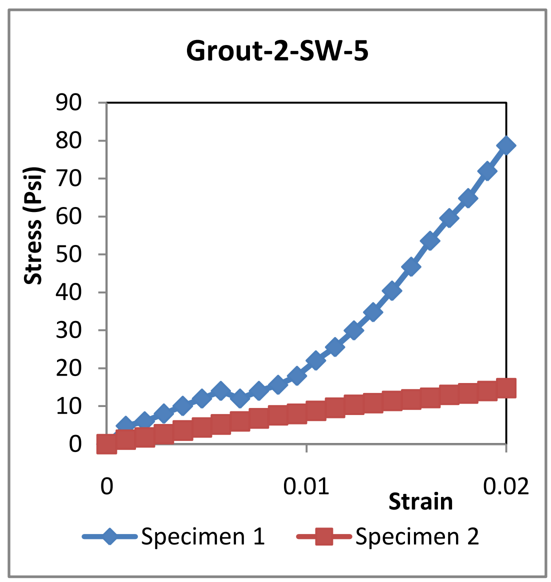


Figure 4.34 Grout-2-SW-5 stress-strain curves

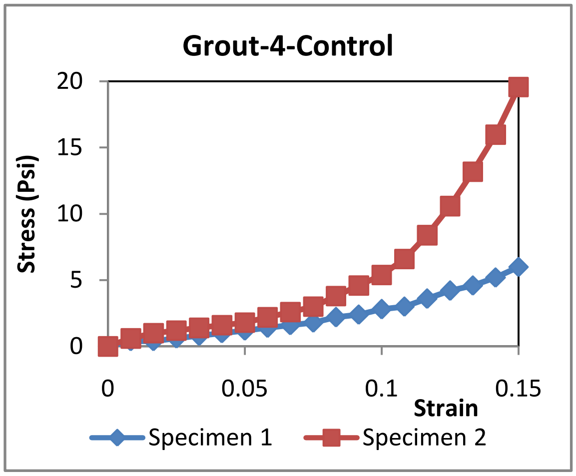


Figure 4.35 Grout-control stress-strain curves

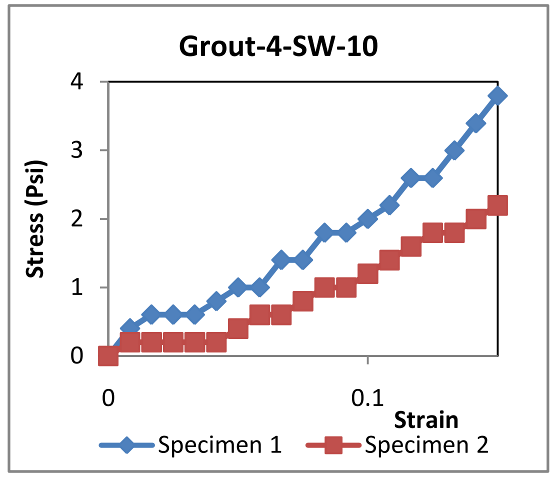


Figure 4.36 Grout-4-SW-10 stress-strain curves

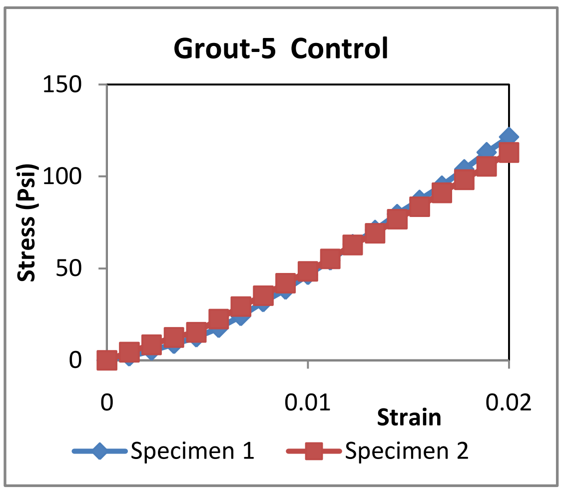


Figure 4.37 Grout-5-control stress-strain curves

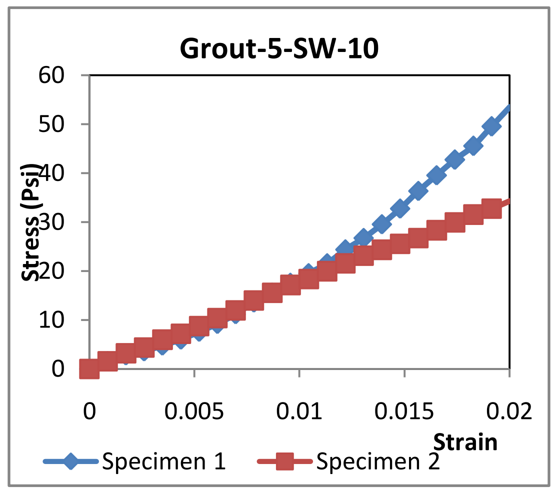


Figure 4.38 Grout-5-SW-10 stress-strain curves

The Grout-5-control has the highest rigidity than the others or generally speaking it could be understood that this grout has the highest Stiffness. Grout-4 in all the mixes has remarkably the lowest rigidity; hence, we had to load it up to high strains to observe any change in the load. The overall trend of all grouts are brought in Figure 4.39 for comparison of all mixes.

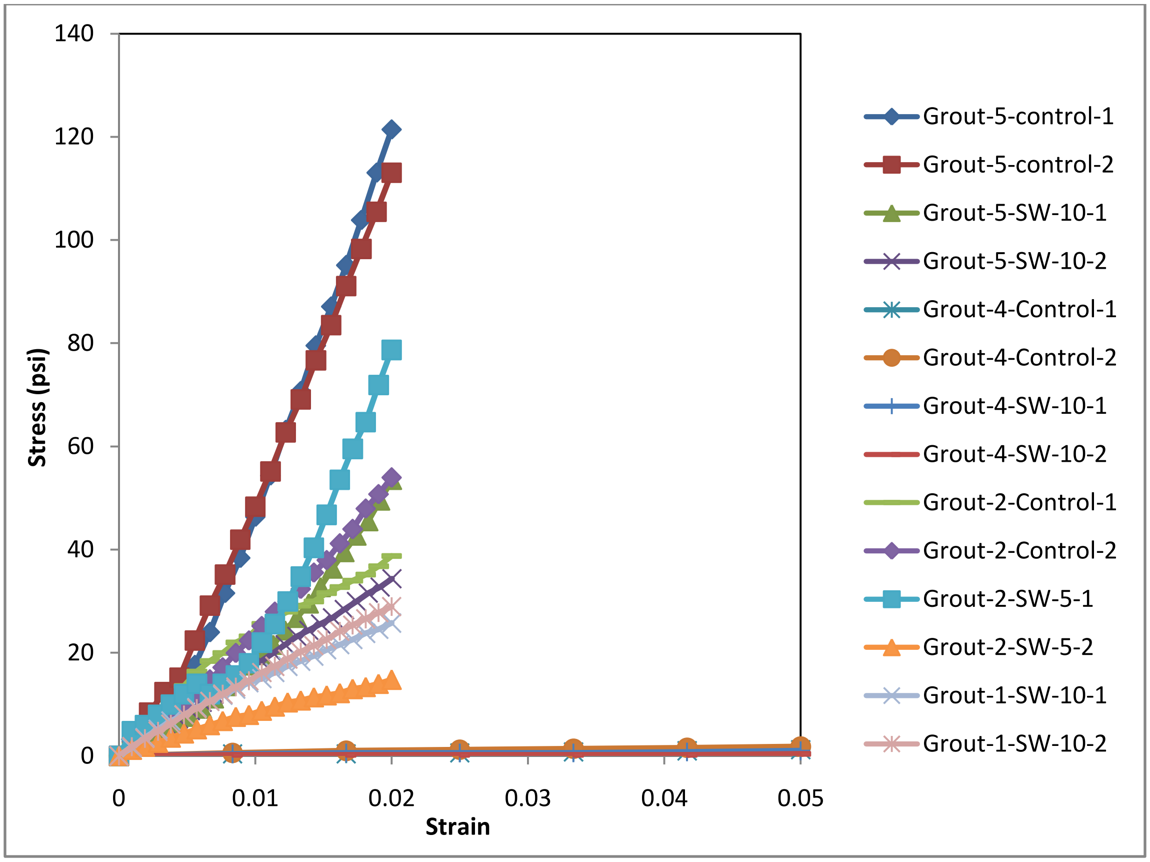


Figure 4.39 All grouts stress-strain curves

4.2.7) Permeability test on Specimens Cured under confined condition

Introduction

In this part of the research we performed the Permeability test on the specimens made in the confined condition and in the PVC pipe. The test is done on two types of specimens with different ages. The first category is specimens with an age of less than 3 hours and the other one is with 5 weeks age. The main constraint was that what pressure we should use for this test. The problem is that some specimens at a certain pressure are extruded thus; the test cannot be proceeded on them. So the tests were performed at relatively low pressures to the extrusion of specimens. The pressures of 25 and 50 Psi were chosen to do this study. The 50 Psi were tested only on the specimens that yielded good results in 25 Psi test. On the other hand, another important parameter was the duration of the test that can affect the value of permeability. So it was decided that for the specimens with high permeability the test be running for 5 minutes and for those with lower permeability will continue to 30 minutes or even to 1 and 4 hours. The Specimens were 2 to 3 inches long and all with the diameter of 1.25 inch. For this test 7 mixes were chosen from the previous tests. It should be mentioned that among the 5 week old specimens those made with grout 315 has shrunk remarkable and was removed from the pipe so the test could not be done on them. The final calculated values of permeability are brought and discussed in the following chapter. Hereafter we use three abbreviations as follows:

P=Pressure, T_c= Curing Time, D_t= Test Duration

Test Results

For each mix, 2 specimens were prepared and tested and the presented data are the average value of them. The curves are based on 4 categories as follows.

1) All the mixes tested within 3 hours after preparation at pressure of 25 Psi with different test durations.
2) Mixes tested within 3 hours after preparation at pressure of 25 Psi and 30 minutes duration.
3) Mix of (Grout-5-Control) tested within 3 hours after preparation with increasing pressure and test duration.
4) Mixes tested at the age of 5 weeks and pressure of 25 Psi and for 30 minutes.

So, based on this categorization the data are presented below.

1) All mixes (P=25 Psi and D_t =Varying)

In this comparison curve the effect of time is ignored and tried to compare the values with the most similar basis. As it seen in **Error! Reference source not found.** the Grout-5 is highly sensitive to Sea water and as it is seen the sea water tremendously increased the permeability as much as 100 times more. On the other hand the interesting point is that in Grout-2 and Grout-4 the addition of sea water decreased the permeability. But on the other hand it could be attributed to the presence of more water that leads to more reaction and production of foam.

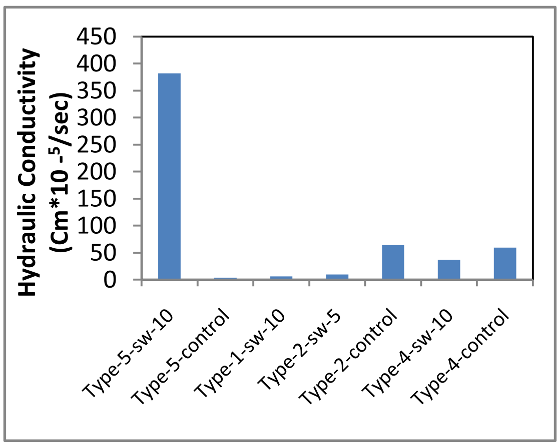


Figure 4.40 Hydraulic conductivity at P=25psi and D_t=~

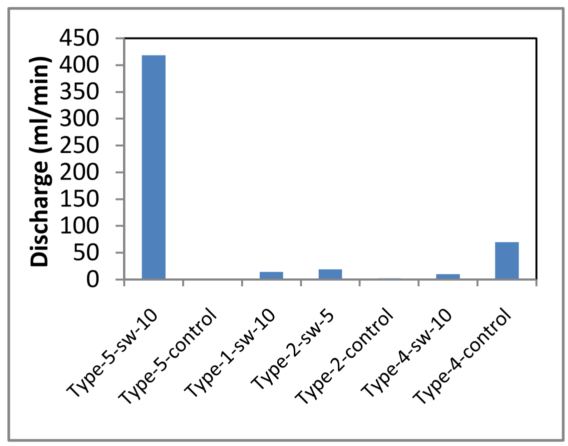


Figure 4.41 Discharge rate at P=25psi and D_t=~

Table 4.14 Hydraulic conductivity and density of tested grouts at 25 psi

Name	Grout-5-sw-10	Grout-5-control	Grout-1-sw-10	Grout-2-sw-5	Grout-2-control	Grout-4-sw-10	Grout-4-control
K(Cm*10^5/Sec)	381.63	3.67	6.22	9.19	63.76	36.46	59.08
Density(g/cm^3)	0.39	0.445	0.455	0.375	0.325	0.62	0.59

Also it is evident that the salts in the seawater did not have much adverse effect on this property. Totally Grout-1 and Grout-2 performed among the best specimens by also having less sensitivity against Sea Water. The graph and the Table of results are shown in Figure 4.40 to Figure 4.41.

2) Mixes with T_c< 3hr, P=25 Psi, and D_t= 30 min

Here no specific and different observation is obtained and as it is apparent except for (Grout-5-sw-10) we have good low permeability.

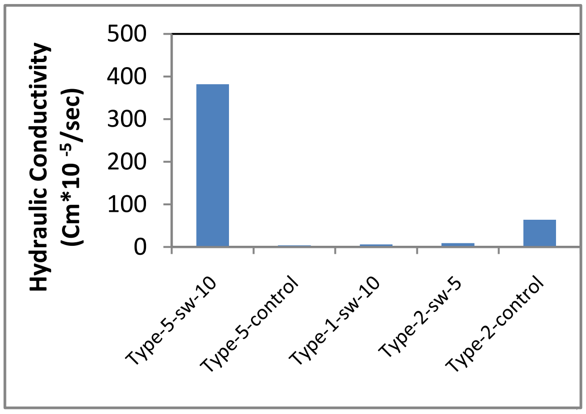


Figure 4.42 Hydraulic conductivity at P=25psi and D_t=30 min

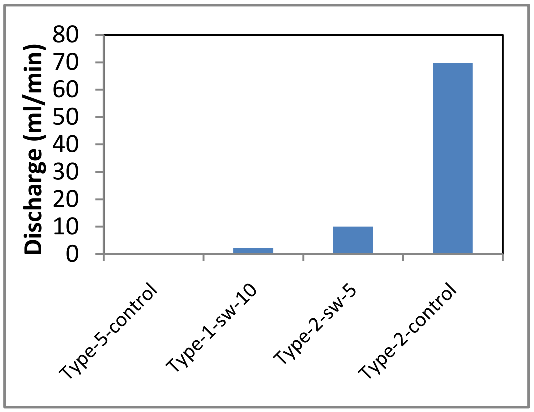


Figure 4.43 Discharge rate at P=25psi and D_t=30min

Table 4.15 Hydraulic conductivity and density of grouts for 30 min

Name	Type-5-sw-10	Type-5-control	Type-1-sw-10	Type-2-sw-5	Type-2-control
$K(Cm*10^{-5}/Sec)$	381.63	3.67	6.22	9.19	63.76
$Density(g/cm^3)$	0.39	0.445	0.455	0.375	0.325

3) Mix of (Grout-5-Control) T_c < 3 hr, P=Varying, and D_t= Varying

In this part since the mix of (Grout-5-Control) has the performance it was decided to put under more test with different conditions. So it was tested at four different conditions. (25 Psi for 1': 35''), (25 Psi for 30':00) (50 Psi for 30':00) and (50 Psi for 4:30':00) and the results are presented below. As it is seen in Figure 4.42 and Figure 4.43 both the time and the pressure has the increasing effect on the permeability, but totally the effect of pressure is more than effect of time and overall performance of this grout and mix is good and even after 4:30 hours and with 50 Psi pressure it has a very low permeability rate.

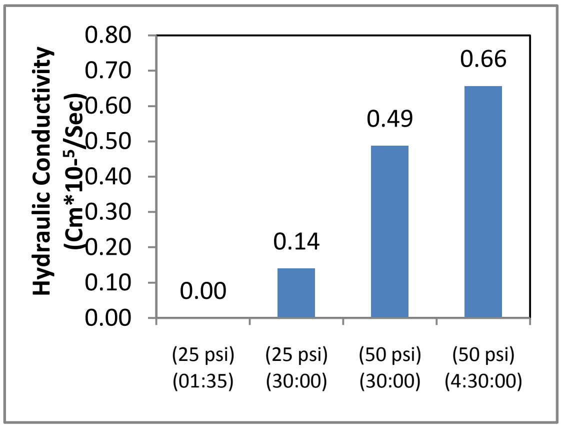


Figure 4.44 Grout-5-control Hydraulic conductivity at P=~ and D_t=~

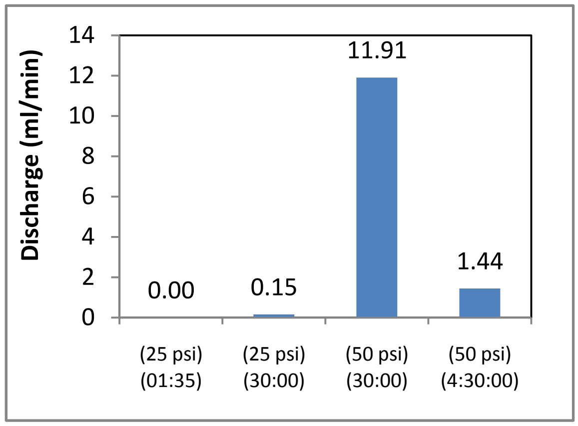


Figure 4.45 Grout-5-control discharge Rate at P=~ and D_t=~

Table 4.16 Hydraulic conductivity and density of Grout-5

Name	(25 psi) (01:35)	(25 psi) (30:00)	(50 psi) (30:00)	(50 psi) (4:30:00)
K(Cm*10^{-5}/Sec)	0	0.14	0.49	0.66
Density (g/cm3)	0.445	0.445	0.445	0.445

4) Tc=5-Week, P=25 Psi, and D_t= 30 min

As it is understood from Figure 4.44 and Figure 4.45, Grout-1 and Grout-2 performed almost the same except the amount and type of contamination. On the other hand, it is seen that the effect of sea water on Grout-5 mixes much less different than the 3 hour specimens. This fact gives the idea that due to high shrinkage of Grout-5 after time its good performance decreases remarkably.

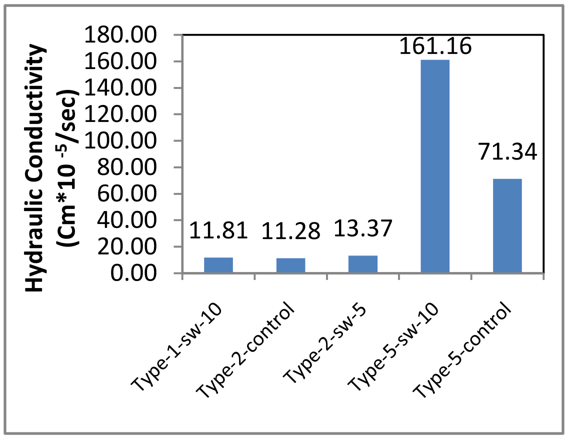


Figure 4.46 5-Week old grouts hydraulic conductivity at P=25 psi and D_t=30 min

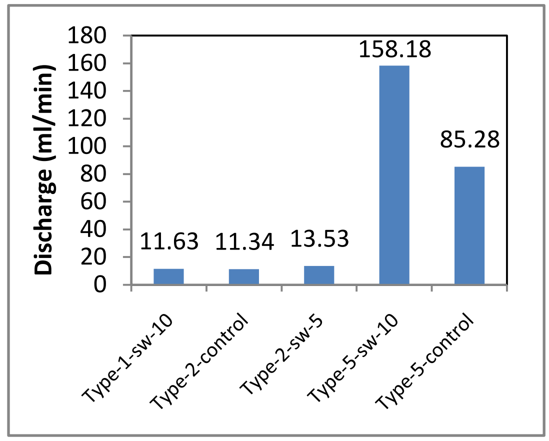


Figure 4.47 (5-Week old grouts discharge Rate at P=25 psi and D_t=30 min

Table 4.17 Hydraulic conductivity and density of 5-week old grouts

Name	Type-1-sw-10	Type-2-control	Type-2-sw-5	Type-5-sw-10	Type-5-control
K(Cm*10 $^{-5}$/Sec)	11.81	11.28	13.37	161.16	71.34
Density (g/cm3)	0.455	0.325	0.375	0.39	0.445

Summary

After the entire test the following observations were made:

1) This type of permeability test is highly dependent on the duration of the test.

2) The curing type remarkably affects the quality and adhesion of the grout to the molds.

3) By the time, in all the specimens the shrinkage happened and basically this phenomenon is due to the presence of water in the grout mix.

4) The selected pressure for doing the test is an important factor that changes the permeability for an individual specimen and might yield unreliable values.

5) In the early age test the Grout-2 showed a sensitive performance against the sea water contamination in the way that the added sea water reduced the permeability.

6) In the early age test Grout-5 performance were impaired by adding sea water to its mix in the way that it sea water addition tremendously increased the permeability.

7) Grout -4 is only applicable in low pressure conditions

8) Totally in both early age and long term performance the Grout-1 performed as the best and the Grout-4 as the weakest.

Observations and Notes during the Test

Alongside with the discussions the following observations and notes were made during the test that should be taken into account

In the 1.25 inch diameter 4 inch long specimens the following problems had to deal with.

1) Due to the age of some of grouts they were removed from the pipe so we could not do the test on them. So, this test for some grouts is applicable only in early ages.

2) The sealing of the detachable parts were possible with Silicone Glue, So, it needs time to be fully cured and be able seal the setup up to 100 psi. The best curing time for all available Silicone Glues in the market for high pressure is at least 24 hours. So we are not able to test the grout within the age of less than 24 hours.

3) During the filling the setup with water some air gets into the network which is inevitable. So, before starting the test we should make sure that there is no air in the tubes, or if so, we should just try to have water on top of the specimen where the pressurized water is applied to the grout sample.

After testing the first series of specimens which were cured 28 days it was observed that their permeability is so high and is by no means justifiable and acceptable, so it was planned to make a new series of specimens and test them within 6 hours of preparation. There is lucky point here that; due to the short length of the specimens and highly porous structure of the grout we are able to perform the test with low pressures. This fact helps us to do the test even 2 hours after applying the Silicon Glue. So the final plan turned out to make the specimens and test them in less than 1 hour after preparation. Based on this plan we started the test and the following observations were made:

1) The system first was tested up to 50 psi with a series of specimens being installed in the setup. The Grout-4 specimens were extruded and although the specimens are just 2 hours old but still the permeability was high, but in spite of the fact the test proceeded.
2) The Grout-4 specimen extruded at the pressure of 10 psi.
3) Based on our observations and judgment we start and continue the test at the pressure of 25 psi as the first stage.
4) The Grout-2 had a high very high permeability so, we measured the discharge only for 5 minutes and then we removed it from the setup.
5) After 20 minutes from the beginning of the test the sound of bubbling could be heard, this indicated that the tank is empty. Here noticed another constraint for our test which is the capacity of the water tank.
6) The Grout-5-SW-10 had relatively high permeability and at the time of (1`:35``) some sound were heard and the specimen slid in the pipe which means the interface of grout and pipe was lost.

The test was stopped and the specimens were removed.

7) For Grout-4 we had to test at very low pressure, we made new specimens with that grout and tested them at pressure of 5 psi.

4.3.1) Injection Methodology

Based on the all observations in the previous stages of this project, it is deduced that either in long or large diameter pipe injection stage operation is inevitable. Therefore, in order to achieve the best quality and efficient grouting we should have an especial procedure for injection. On the other hand, due to the expansive property of the Polyurethane grouts, if we can provide a confined or semi- confined environment during the foaming of the grout, we will have much better sealing provided by the grout. This fact originates from the point that in the totally free space, the grout can foam in any direction. Now, in the pipe if we block the movement of the grout along the pipe therefore, the only way that grout can expand is in perpendicular direction to the longitudinal axis of the pipes. Due to this phenomenon, the grout starts to press against the wall of the pipe and densify. In this condition, after the completion of the reaction we will have much better interface between the grout and pipe.

On the other hand, in the cases with diameters more than 2 inches, because of the poor vertical foaming of the grout, the only way to have good foam generation the grout should be injected in horizontal layers. However, in the case that with grout in layers, since the number of interfaces increases the chances of water permeation increase. To support this idea it could be referred to the fact that during this study all the water leakage was observed to be through the interface. So, there are more interfaces either between the layers of grout or grout and pipe, the chance of water penetration will increase.

Based on the available condition in our study there is no need to focus on the layer injection method and we start to explain about the procedures of stage injection in one layer and the logic behind it.

Stage Injection

Actually, based on what already have been observed we should think of a method that dictates to inject the least possible amount. The point is that once a large amount of grout is injected the reaction of chemical is reality impaired and the efficiency of the reaction decreases. Based on this fact, we should follow this principle and develop the idea to do the injection in stages with relatively small amounts of grout. Furthermore, we should provide the condition of confined volume for densification of grout during foaming. So, by considering these two factors, we can offer the following stages.

Initial Injections

This stage is aimed to build two barriers on either end of the pipe that can work as plug and provides the confined condition. Actually this injection is done in a way that we drill a hole at the centerline of the pipe and we insert the injection tube in the pipe and guide it to the ends and inject the grout and let the foam to harden. For this stage we have two options for the type of grout to be injected. First one is to use the same grout as the one that is selected for the whole grouting operation. Second is the pre-mixed grout which is in the form of the foam once it comes out of the container. However the related problem with the second option is that we will have two different materials being mixed after the completion of the operation and this fact might lead to some defects. However, in the case the pipe in the field is sloped we have no choice except for using the second option. In this stage 10-15 % of the total designed amount is injected at each end. It means that 20-30 % of the total is injected at this stage. However, it is obvious that if we use the second option none of the main grout is injected in this stage. After each injection at each end we should plug the hole.

Main Injection

After completion of the first stage, we should inject the whole remaining grout at once which is 70-80% of the total designed amount. After the injection we should plug the injection hole and let the grout to foam and densify.

Now a couple of questions arises that should be answered:

1) How long should the grout be mixed and when should it be injected?

2) What ratio of the total amount should be injected at each stage?

3) What length of the pipe should be confined and grouted during each series of stages?

4) What spacing between the injections of initial and main injection should be selected?

Regarding the mixing procedure, the best option is that to mix the grout outside the pipe and then inject it. This task helps us to assure the quality of mixing and also minimize the interference of the contaminations with grout because; if the grout is mixed in the pipe the chance if being mixed with contaminations will be much more.

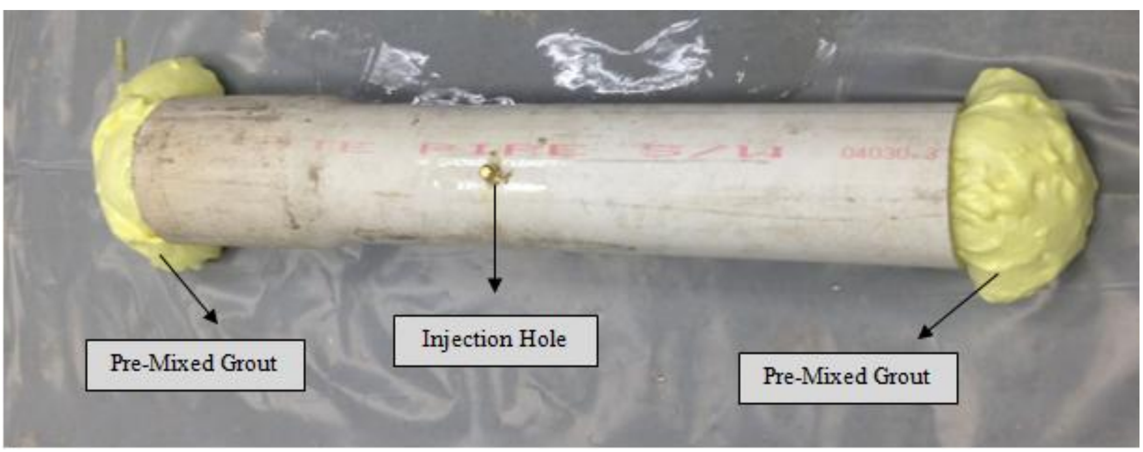


Figure 4.48 Typical condition of a pipe after the initial injection stage

However, answering all the above questions are not an easy job; so, we start by some random configuration. So, we chose a 30 inch long with diameter of 3 inches. And, for the initial stage we use the pre-mixed grout to check how it performs. The pictures of the pipe after initial stage and main injection are shown in Figure 4.48 and Figure 4.49.

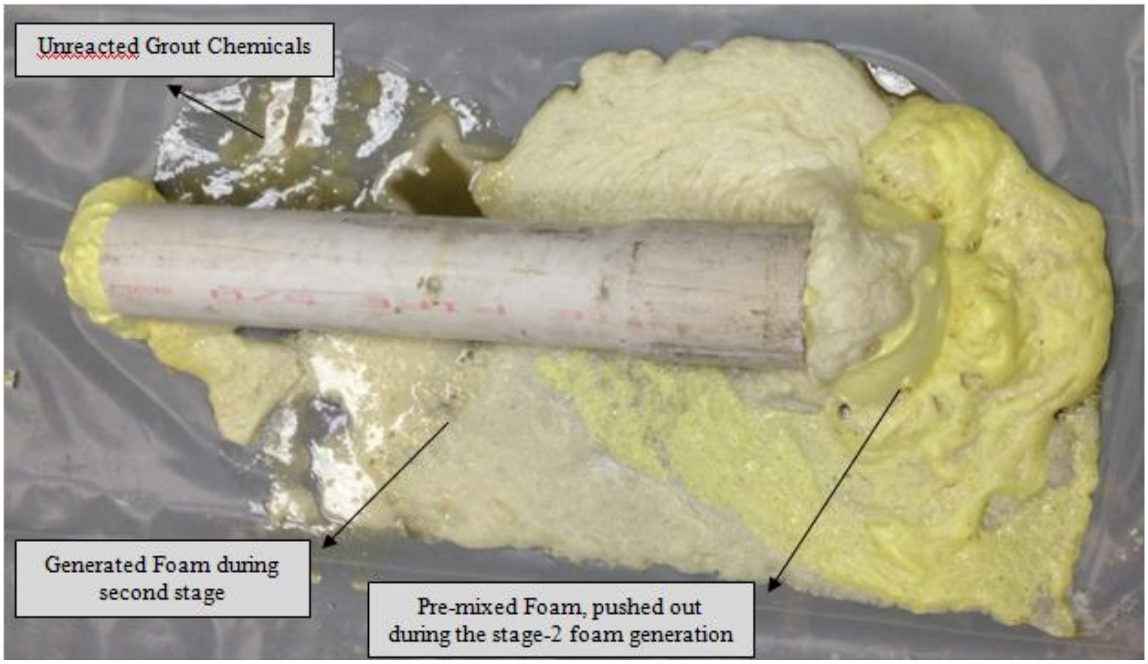


Figure 4.49 Typical condition of the 3 inch pipe after main injection

As it was observed the grout during the main injection pushed out the foams that were supposed to provide the confined condition for us. It also shows that pre-mixed grout as it was already tested, does not have good adhesion to the pipe. So, this grout is not recommended for the initial injection. However, it could be used in the cases that we have sloped pipe. In that case the, since the pre-mixed grout is injected in the form foam and has high viscosity, it does not flow downstream and the foam stays at the injection zone. Now, this foam can work as an edge or barrier that holds the second grout which is in the liquid phase until it starts to foam and blocks the section. So, we can conclude that in the case of sloped pipe we have three stages:

1) Pre-mixed grout injection and building the barrier against the slope.

2) Initial injections

3) Main Injection

At this point we should pass the procedure for case of the sloped pipe and focus more on the flat pipe and dealing with the questions.

Observation

Up to the previous tests all the injections were in the pipes that were aligned vertically. In this stage we will have the injection in pipes in the horizontal position. The reason for this is obvious that in field we have the pipes horizontally laid on the ground.

At this point some basic questions come to mind that should be dealt with:

1) How much grout should be injected the pipe?

2) What length should be chosen for the pipe?

3) With what procedure the injection should be done?

Amount of injected grout

All the cases were confined condition and the ratio of the initial chemical to the total volume of pipe was (0.5:1), so, since here in 1.25 inch pipes that are grouted horizontally we want to compare the results we should use the same ratio. Meanwhile we should fully cap the ends of the pipe to have the confined condition during the foam generation. But for the 3 inch diameter case since it is similar to the field so we will not cap the ends and also we cannot leave them fully open. So, we should consider a condition that can simulate the infinite pipe in the best way. Since the condition of pipe is not fully confined, appropriate amount should be considered that can perform optimally.

Pipe Dimension

Based on the above questions it was decided to consider the ratio of diameter to length of the pipe as the dimension factor. This factor gives us the option to test different pipes with different diameter. So, the ratio of 1:5 was selected. On the other hand the procedure of grouting in the field is in the way that the pipe is grouted form a hole in centerline of pipe length. Then, after the injection the pipe will be cut into half and will be transported on-shore. So, based on this fact we should select pipe the length of twice the needed and grout it form the centerline. After the injection we should cut it into half and perform the permeability test on each half. It is planned to have two diameters of 1.25 and 3 inch PVC pipes. So the corresponding length will be 12 and 30 inches respectively. The reason that we have chosen these two sizes is in two ways. The diameter of 1.25 is chosen to be able to compare the data with results of the test performed on the grouts foamed under confined condition. The diameter of 3 inch is selected since in the field we will have 3 inch oil pipes that should be grouted. So, the 3 inch is our max limit.

The Procedure of mixing and Injection

First the idea was that the different components of the grout being stored in separate containers and then they be injected through different tubes and then mix them in tube and the final mixed grout being injected out of the tube into the pipe. However the problem with this method was that we should have a very accurate and calibrated discharge of each container. Time was spent on this idea, but, due to the inaccuracy of the valves of the containers and based on the available equipment it could not be relied on the final mixes made by this method. Therefore, another option is that to pour each component in the pipe in sequence and blend them by air blow through tube and in the pipe until the reaction starts. And, the last option is that to mix the grout completely in cup or bowl and when it is ready inject it in the pipe. The advantage of the last option is that the effect of the contamination on the grout mix is minimized since the interference of the contamination is less effective on the mix rather than the unmixed grout components. So second method was used and grout components were poured part by part and blended in the pipe. In the case with contaminations first the contaminations were poured in pipe and then pour the grout components were injected. This procedure simulates the real condition in the field in an acceptable way.

Grout Injection in Long Pipes

As it was concluded before, the confinement has a tremendous effect on the curing and sealing capability of grout. Therefore, it is needed to think of a method that can provide a confinement for the curing of grout. The optimized amount of grout was obtained from previous studies (explained in chapter (4.3.4)) were done on 5 feet long pipes. The final pattern was that to inject 12.5% of the total amount at the ends of the pipe as the "Initial injection" that provides confinement for next stage of injection. After this stage, the remaining 75% is injected as the "Main Injection" at the centerline of pipe. Then, for 10 feet long pipe it was decided to follow the same pattern of injection for each 5 feet length of pipe. So, this pattern could be repeated in consecutive sections of pipe based on the occurring pressure. The patterns are shown in Figure 4.50 and Figure 4.51.

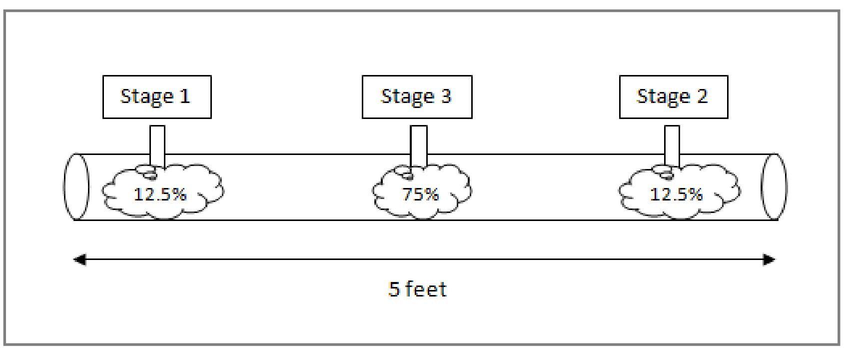


Figure 4.50 Typical stage injection of grout in a 5 feet long pipe

The percentages showed in figures are the percentage of the total amount of grout planned to be injected. In the case of 10 feet long the percentage belongs to the total amount 5 feet long pipe. Since, the length is doubled, the amount is also doubled and the pattern is overlapped at (stage 3). So, in (stage 3) the injected amount is 25% instead of 12.5%.

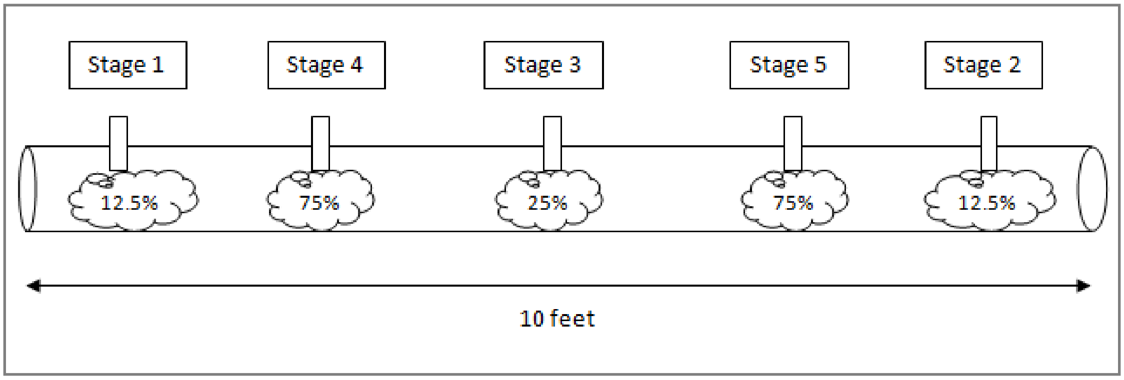


Figure 4.51 Stages of grouting along the 10 feet long pipe

4.3.2) 1.25 inch diameter grouted PVC pipe

Grout-1

The selected pipes for this test have the diameter and length equal to 1.25 and 12 inches respectively. The ends are fully capped with tape and (75 ml) of grout liquid was injection in all the specimens with added contamination of sea water (SW) and oil (O) as much as 5-10% of weight of the grout. Then all the specimens were tested under the pressure of 30 Psi for permeability test. In the Figure 4.52 we can see that from top to bottom the effect closing the injection hole. Top: 30 seconds after reaction the plug was removed, Middle: the hole was from the start of reaction opened and the bottom the hole was plugged until the end of reaction. They are the same mix and same amount (Grout-1-SW-5). In Figure 4.54 we can see the cross section of cut pipes. The left two half are the pipes that after 30 second the plug were removed and on the right was constantly open.

Figure 4.52 Three conditions of plugged, unplugged and 30 seconds plugged of injection hole

It indicates that the reaction of this grout is sensitive to air and free volume to expand. Finally it was decided to plug the hole, but inject the air inside the pipe and through the grout liquid to enhance the reaction. In Figure 4.53 the SW cross sections of grouted pipes are shown.

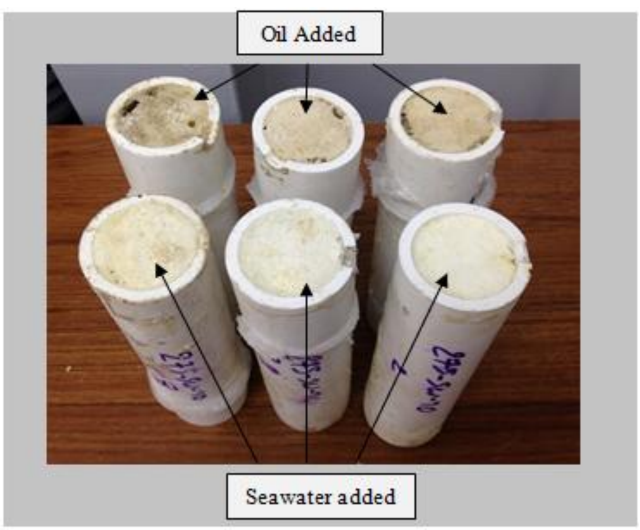


Figure 4.53 Grout-1 cross section with seawater and oil

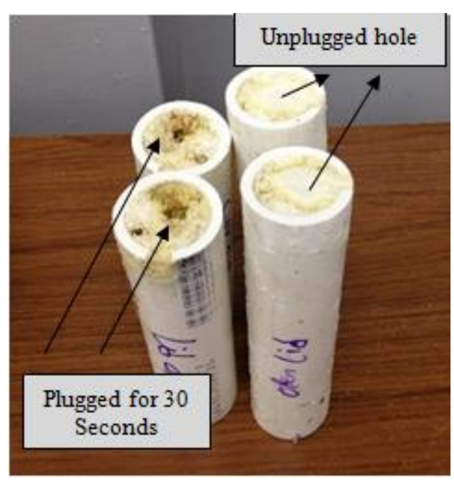


Figure 4.54 The effect of injection hole plugging on grout

Air Pressure Drop

In Figure 4.55 the trend and performance of specimens at different pressures are shown. Totally it could be concluded that the air leakage is rather independent of the applied pressure, however it has gradual increasing trend. Also the Oil specimens have a little lower air leakage. In average we can say that we have air leakage from 10-15 Psi in sealed pipe with Grout-1.

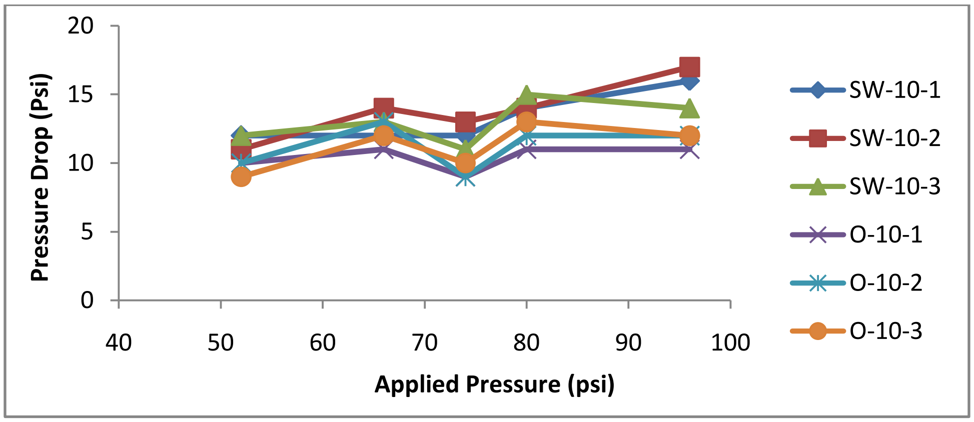


Figure 4.55 Air pressure drop test on Grout -1

Permeability Test on Air Pressure Tested Specimens

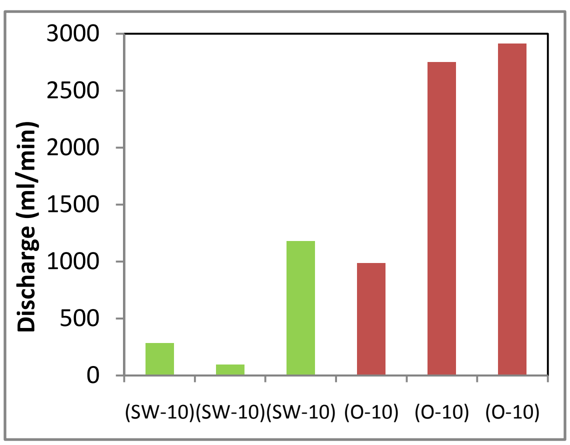


Figure 4.56 Discharge rate of Air pressure tested pips grouted with Grout-1

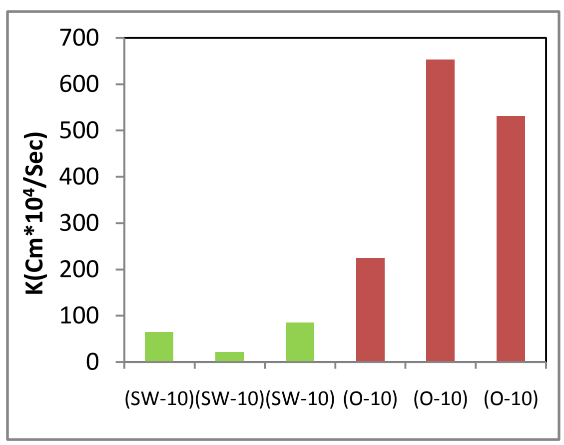


Figure 4.57 Hydraulic conductivity of Air pressure tested pips grouted with Grout-1

In the test first the specimens were tested with air and then they were tested by pressurized water. As it is seen in Figure 4.56 and Figure 4.57, the pipes with Oil contaminant have higher permeability than the Sea Water. The SW specimens performed mostly the same but the O specimens have relatively different performance which is indicative of varying performance of this grout in Oil contaminated environments. Although the Oil specimens did better in Air test, in permeability test the SW specimens performed better.

Permeability Test on Intact Specimens

In this case as we see in Figure 4.58 and Figure 4.59 the Oil specimens performed better. This is exactly opposite of what happened in the previous test, so it could be guessed that initial air pressure has tremendous effect on the specimens.

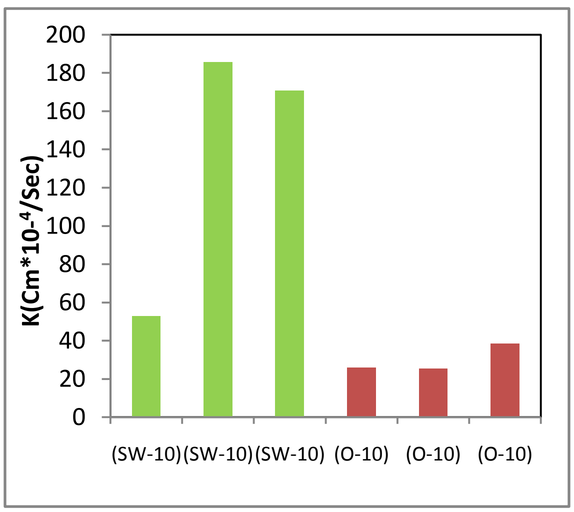


Figure 4.58 Hydraulic conductivity of intact specimens of Grout-1

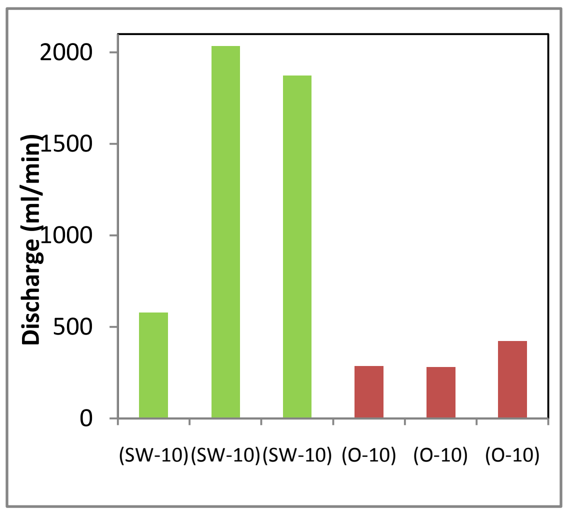


Figure 4.59 Discharge rate of intact specimens of grout-1

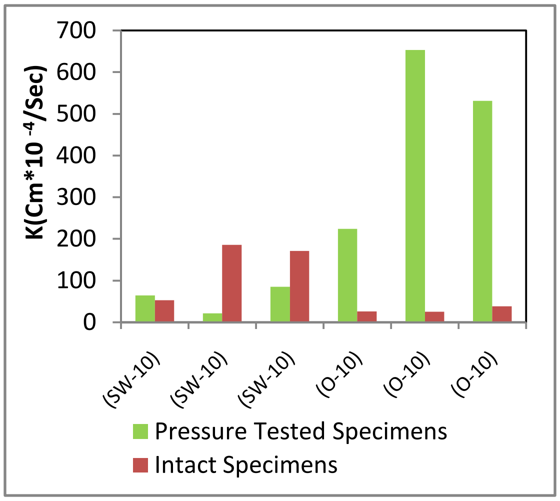


Figure 4.60 Comparison of hydraulic conductivity of air pressure tested and intact pipes grouted with Grout-1

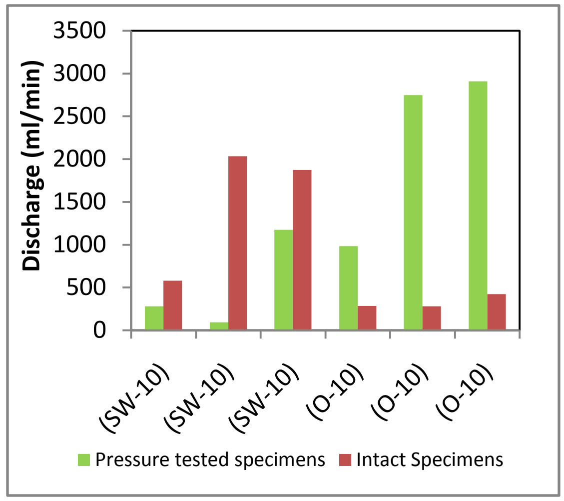


Figure 4.61 Comparison of discharge rate of air pressure tested and intact pipes grouted with Grout-1

Also, it is possible that during the air Pressure test the specimens might be extruded and the interface between the pipe and grout was lost. In Figure 4.0 and Figure 6.1the two groups of specimens were brought in a same chart that we can compare. Another thing is that the difference between the cases is so high which approves the high effect.

Grout- 2

This grout was injected in the same way and also in one case the effect of open injection hole was observed. In Figure 4.62 the top picture shows that on the two sides of the pipe we do not have the symmetric foaming of the grout which could be seen from the grouts being pressed out. In the picture at the bottom, the specimens from left to right are the SW, O, SW with open injection hole are shown. It is apparent that in all the cases the final foam is highly porous, especially in the case with Oil contamination.

Figure 4.62 The puffed out Grout-2 under confined condition, reacting with Oil

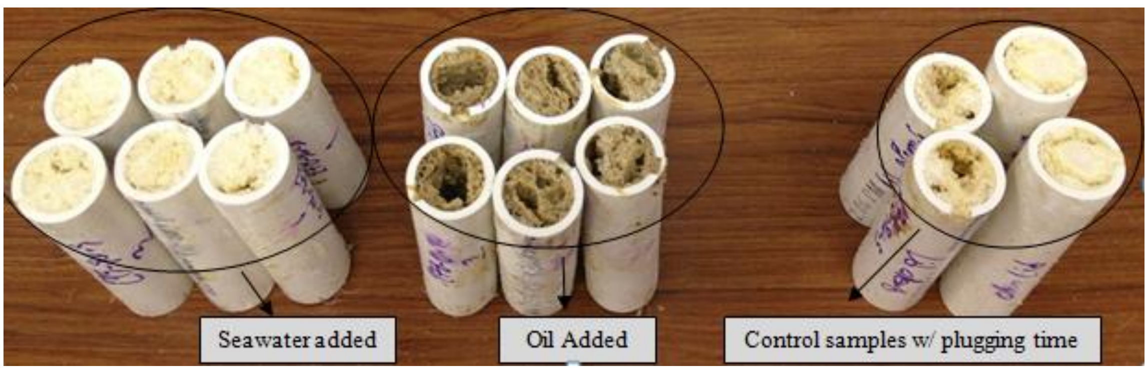


Figure 4.63 The cross section of pipes grouted with Grout-2 and different contaminations

Permeability Test

After doing the permeability test the results are shown in Figure 4.64 and Figure 4.65. Overall, the grout did not show so much sensitivity to the type of contamination. But, it performed rather better in the case of sea water addition. On the other hand, the overall performance of the grout is much weaker than the Grout-1 and this could be predicted and expected from the appearance of the specimens.

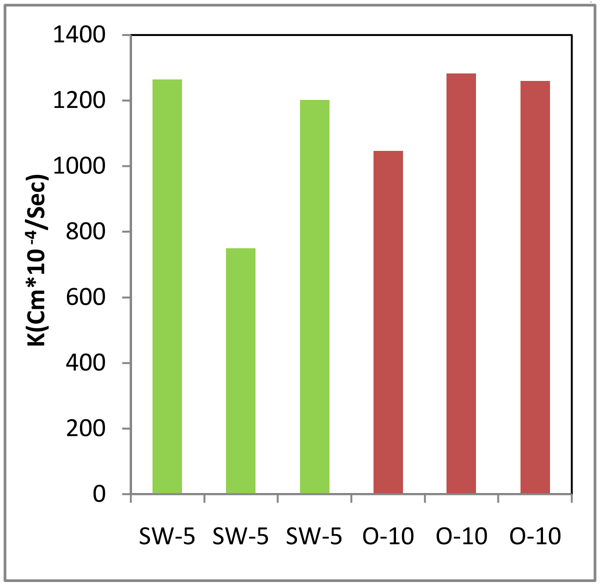


Figure 4.64 Hydraulic conductivity of pipes grouted with Grout-2

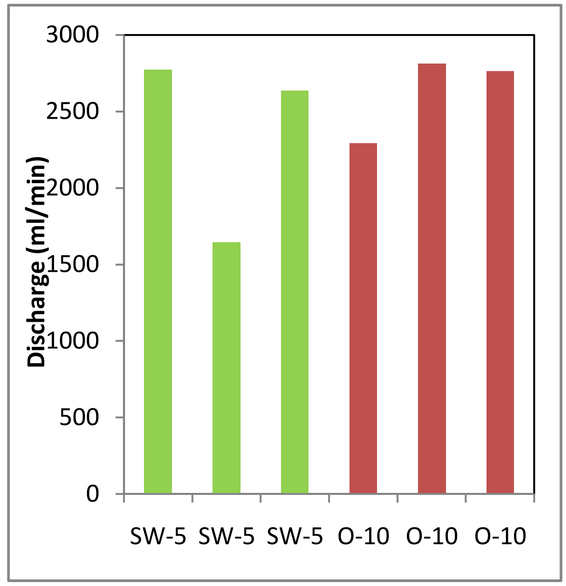


Figure 4.65 Discharge rate of pipes grouted with Grout -2

Air Pressure drop Test

In the air pressure test as we see in Figure 4.66 the oil specimens performed better than the SW ones. Also, the interesting point is that the oil specimens and somehow the SW specimens have similar trends.

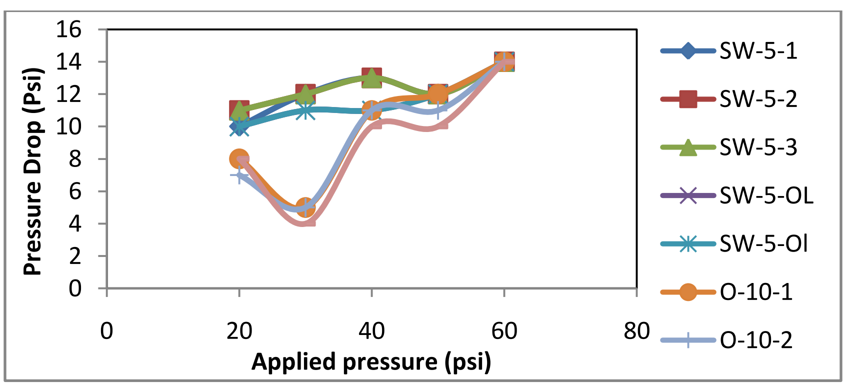


Figure 4.66 Air pressure test on pipes grouted with Grout-2

This performance is similar to the Grout-1. Again, here the air leakage trend has gradual increase by increasing the pressure. Also, at the end we see that at the pressure of 60 Psi all the pipes have the same value which is evident of the extrusion of the specimens.

Grout- 5

The prepared specimens of Grout-5 are shown in Figure 4.67. We can say that in this case we have better symmetry of the foamed grout on both sides of the pipes. And the volume of grout being foamed out of the pipe is higher than the other grouts.

Figure 4.67 Foaming of Grout-5 under confined condition

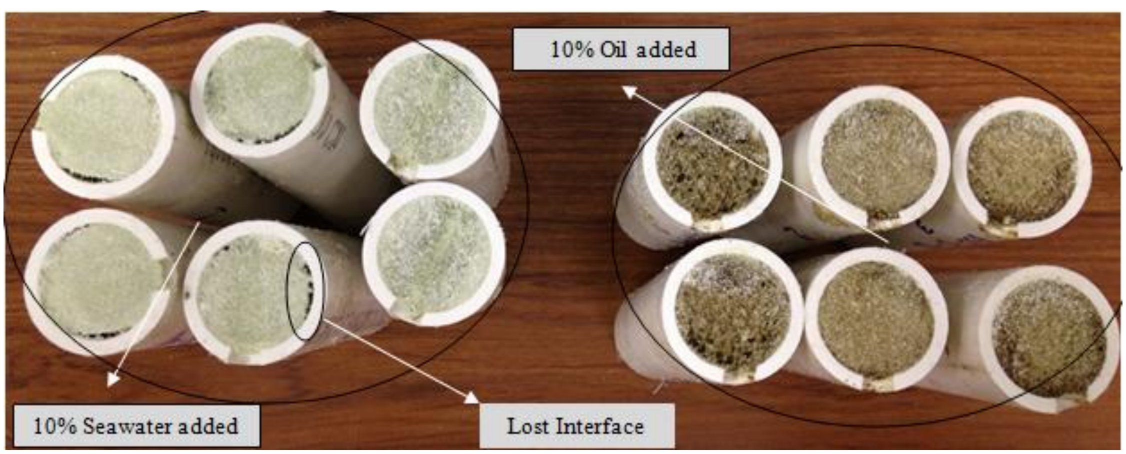


Figure 4.68 The cross section of pipes grouted with Grout-5

The cross sections of the cut pipes are shown in Figure 4.68. The six pipes on the left are SW and the right are oil specimens. Here we can see that the SW specimens have some voids at the interface with the pipe.

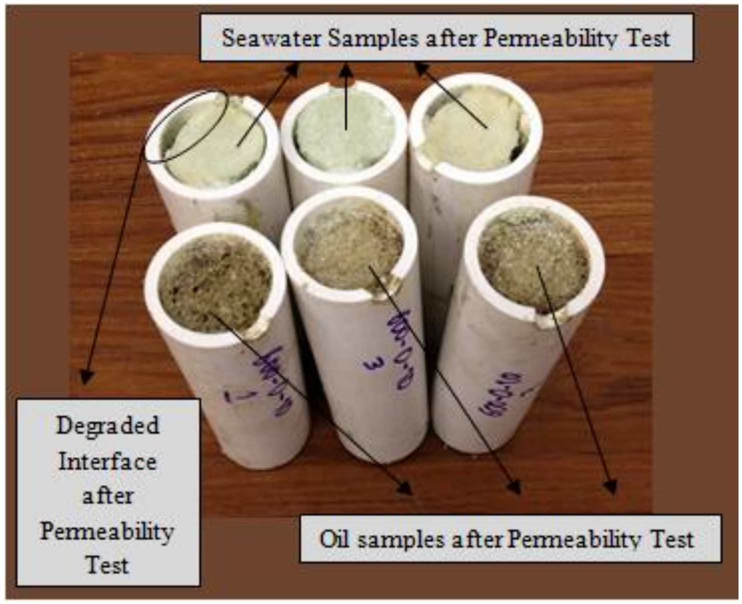


Figure 4.69 Cross section of grouted pipes with Grout-5, after the permeability test

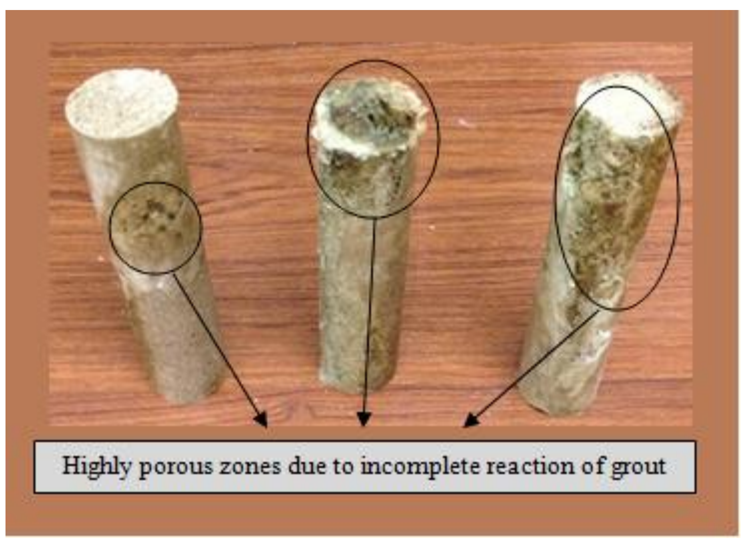


Figure 4.70 The extruded Grout-5 with oil contamination

In Figure 4.69 in the left picture the specimens after the permeability test are shown. As it is apparent, the interface of the grout and pipe is almost lost. Apart from this, the grout shrank and softened. In the right picture the extruded specimens re shown and we can see that structure of the foam along the pipe is not uniform in none of the specimens.

Permeability at 10 and 30 Psi

For this grout it was decided to test the specimens at different pressures. In Figure 4.71 and Figure 4.72 the results of the test at pressure of 10 Psi is shown. Totally the grout performed better in SW condition than Oil Condition. And, also at oil condition the specimens performed remarkably different which indicates the varying foaming of grout 600. As we see in Figure 4.73 at 30 Psi test, the permeability of Oil specimens decreased a little but the SW showed noticeable increase of permeability by increasing the pressure.

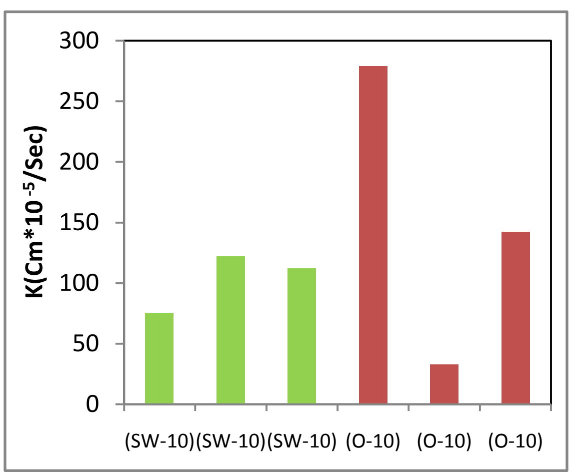


Figure 4.71 Hydraulic conductivity of Grout-5 at 10psi

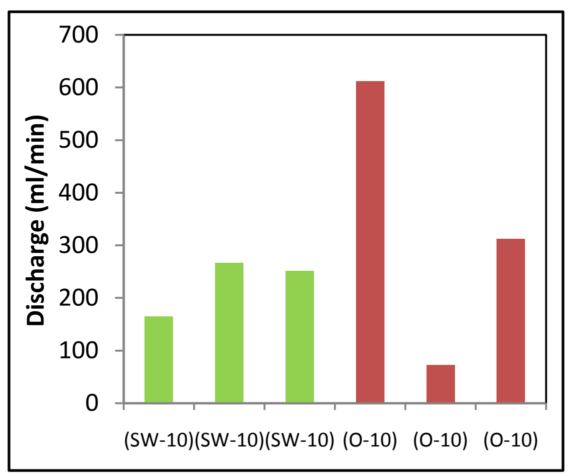
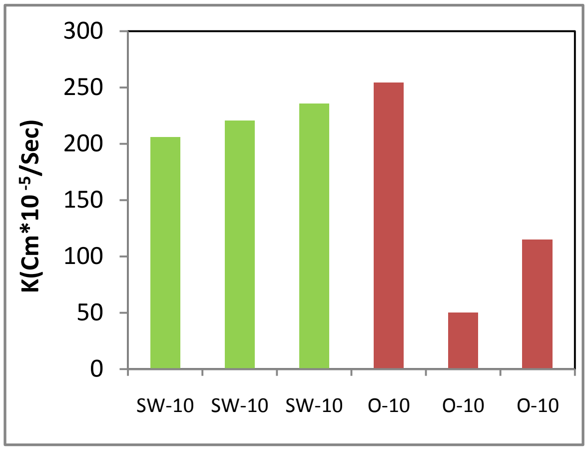


Figure 4.72 Discharge rate of Grout-5 at 10psi



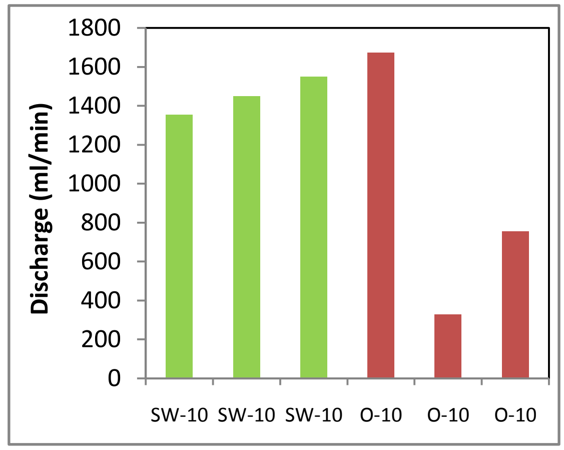
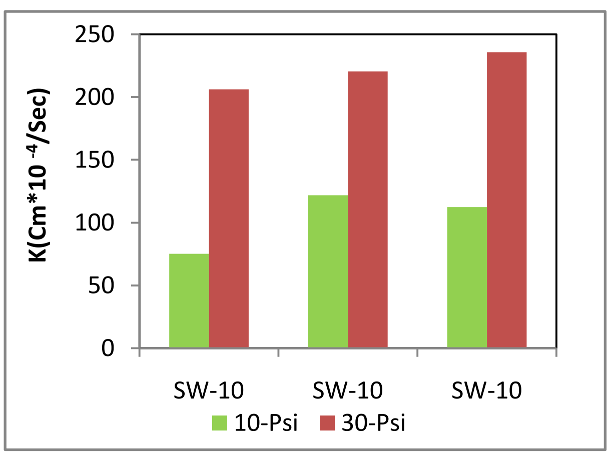


Figure 4.73 Hydraulic conductivity of Grout-5 at 30psi

Figure 4.74 Discharge rate of Grout-5 at 30psi

Permeability at 60 and 70 Psi and Effect of Pressure on Permeability

As we consider the effect of pressure on the permeability in Figure 4.75 and Figure 4.76, it is seen that in SW specimens, as the pressure increases the permeability increases. Moreover, in oil specimens, by increasing the pressure the permeability decreases.



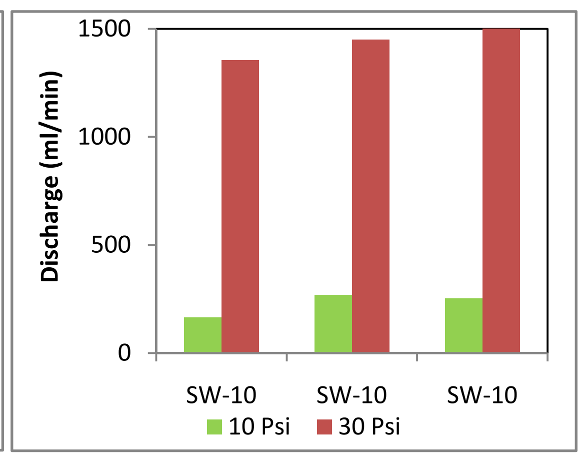


Figure 4.75 Effect of pressure on hydraulic conductivity of Grout-5

Figure 4.76 Effect of pressure on discharge rate of Grout-5

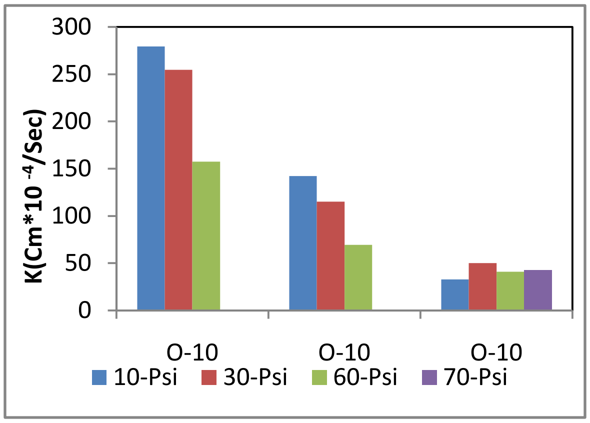


Figure 4.77 Effect of pressure on hydraulic conductivity of Grout-5 with oil

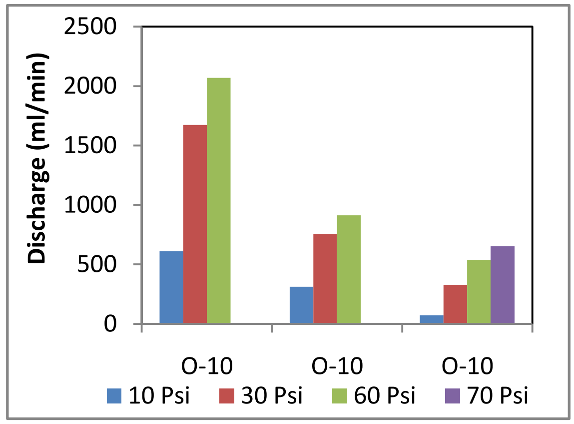


Figure 4.78 Effect of pressure on discharge rate of Grout-5 with oil

The oil specimens had a good performance and it was chosen to be put under more pressures and was tested under 60 and 70 Psi and the results are shown in Figure 4.77 and Figure 4.78.The trend is still the same again the permeability decreased.

Air Pressure Test

Again for this grout we see that in oil specimens the air leakage is less than the SW specimens. Also the specimens follow a similar trend and both increasing by increasing the pressure. But in overall we can say that the oil specimens are roughly independent of the pressure applied. The trend is illustrated in Figure 4.79.

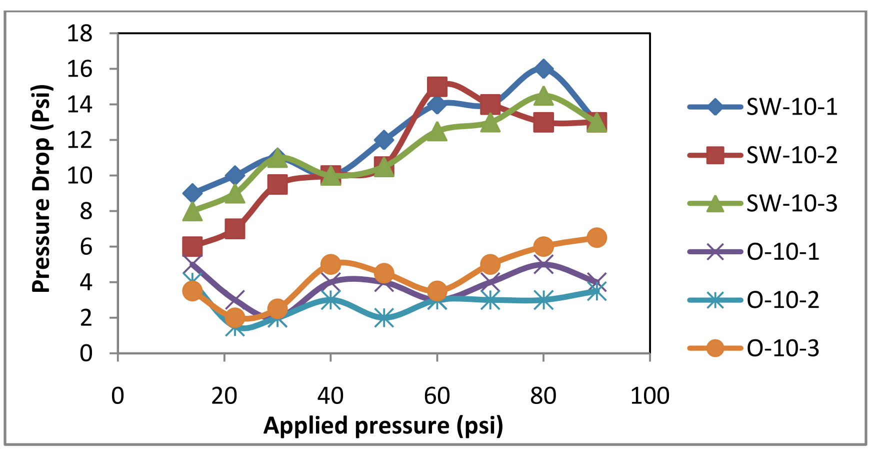


Figure 4.79 Air pressure test on grouted pipes with Grout-5

Observations and Notes during the test

1.25 inch Diameter PVC Pipes

Two tests of permeability and extrusion were selected to be done. Three 1 foot long pipes were grouted then cut in half. Thus far we have 6 remaining samples to be tested. One half from each pipe with a total of 3 samples were picked for each of the permeability and extrusion test. The reason was to repeat the test for each grout type being made from 3 separate mixes. The test is planned to be done within 3 hours after preparation of the grouts. Based on the configuration of test setup it was decided to do the extrusions test first then we do the permeability test.

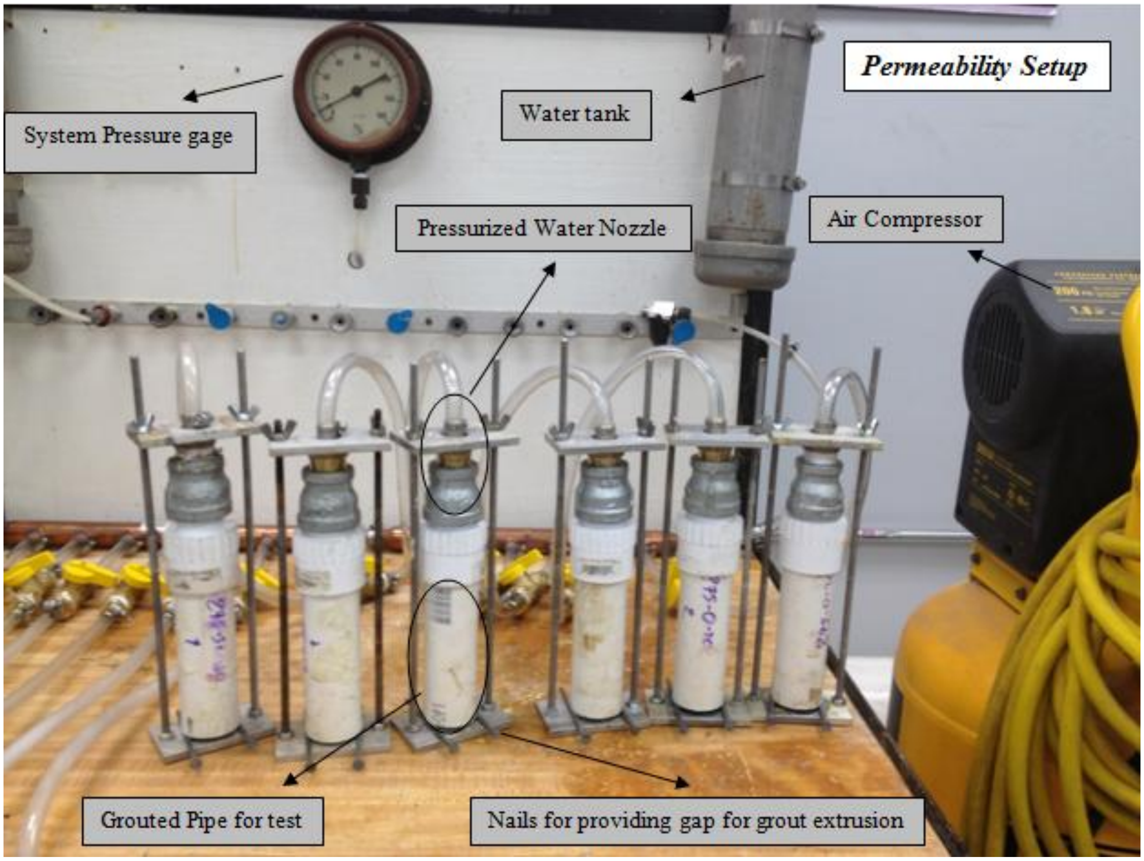


Figure 4.80 Typical configuration of the permeability and extrusion test setup

Extrusion Test

We start with pressure of 5 psi and will increase it every 5 minutes for 5 psi. As it could be seen in Figure 4.80 in order to make the extrusion possible we should have provided some gap between the pipe and the end plate shown in Figure 4.80. So, we have put some nails on either side of the pipe in the way that the distance between two nails is greater than the thickness of the grout in the pipe so that it can slide of the pipe. Once it is extruded we can see it at the bottom of the pipe being blocked by the end plate.

The test was started and the following observations were made:

Grout-1

1) The reaction of Grout-1 was complete and the final generated foam in the pipe was uniform in all directions.

2) Grout-1-O-10 showed a major air leakage at pressure of 10 psi as if there is no sealing provided by the grout in the pipe.

Grout -2

1) This grout was in overall sensitive to air and the reaction was really slow due to confined condition and in some sections of the pipe the reaction was incomplete.

2) Oil specimens did not perform well and did not seal the pipe since there were relatively huge voids through the grout.

3) In order the mitigate the problem of air sensitivity of the Grout-2 it was decided to do injection in 3 different pipes and change the confined condition in 3 different ways.

a) We injected the grout and plugged the injection hole. After 1 minute we removed the plugged in order to let the trapped gas out and let the reaction continue.

b) We injected the grout and let the hole opened so that while the foam is being generated comes out of the hole.

c) We injected the grout and plugged the injection hole permanently like other sample.

The three pipes are shown in Figure 4.81.

As it is seen in the Figure 4.81 the case that we opened the plug after 1 minute the unreacted grouts started to come out of the hole. In the case with open hole it is obvious that due to the abundance of the air all the grout reacted completely and it is all foamed.

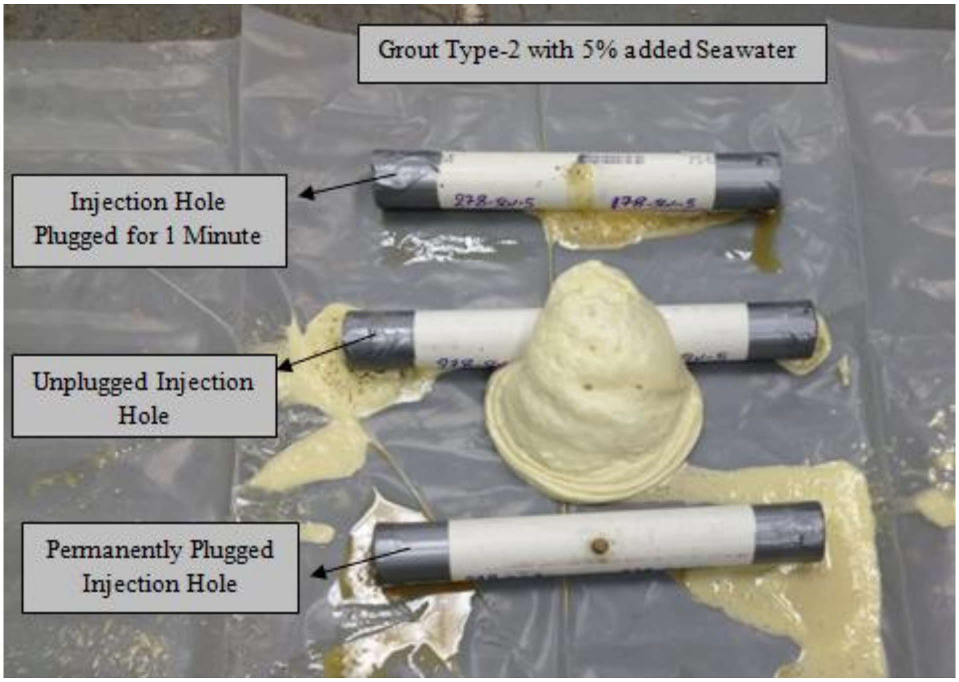


Figure 4.81 The effect of plugging time on the foam puffing out

Grout-4

As it was anticipated this grout was highly sensitive to air and its reaction was interrupted in confined condition could not be completed. So, this grout was omitted for this set of experiments.

Grout-5

The specimens of this grout were with both sea water and oil contamination. In the specimens with SW contamination after the extrusion test although, they were not extruded but the grout in the pipe was crushed and became fragile. Also, only one of the oil specimens was extruded at pressure of 50 psi.

4.3.3) 3 inch diameter grouted PVC pipe

For this test the 3 inch pipes were cut into 15 inch length pieces. The first question was that how to cap the ends to have a similar condition to infinite pipe and at the same time it will practical in the field for the sloped condition. So, first we tried to cap the ends by initial injection of Pre-mixed grout foam and waited for 10 minutes to foam completely. The final shape of the pipe is shown in Figure 4.82. After that the main injection from the mid-length and after foaming of polyurethane the final shape is shown in Figure 4.82.

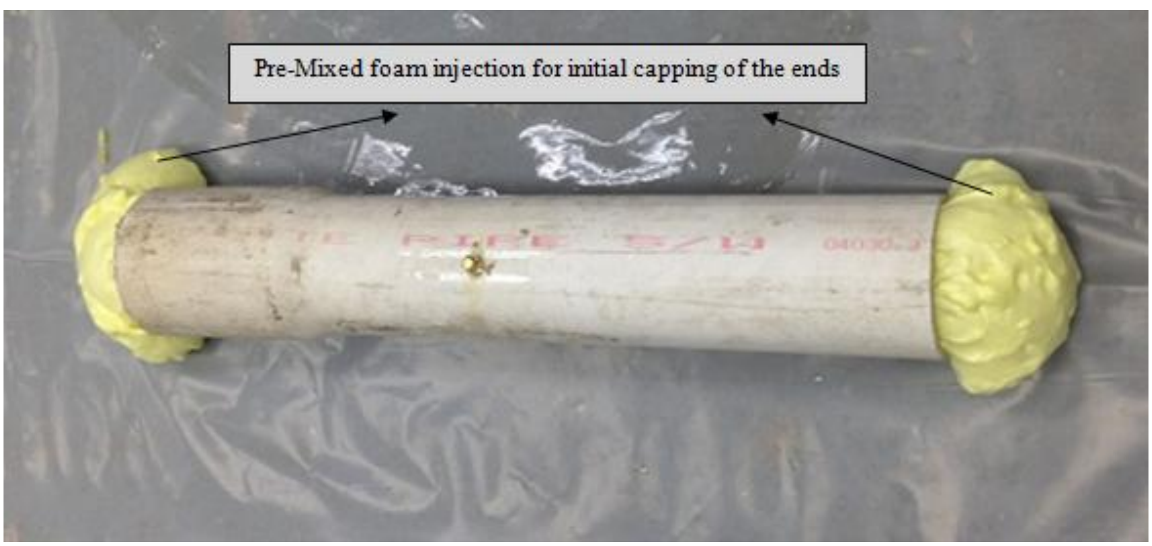


Figure 4.82 Capping the ends of the pipe with Pre-Mixed foam

After the main injection as seen in Figure 4.83, the formed foam is asymmetrical and also Grout-1 was partially mixed with Pre-mixed foam. The total physical appearance and foam did not look satisfactory and defective. So it was decided to partially block the end with tapes like what is shown in Figure 4.84 and Figure 4.85.

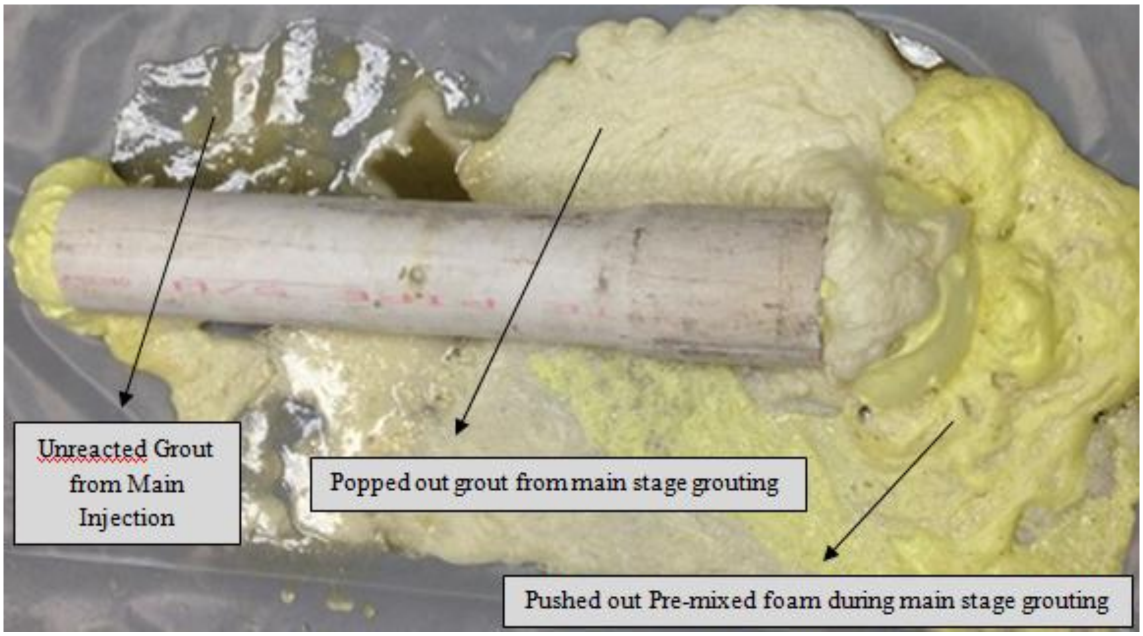


Figure 4.83 The condition of capped pipe after the main stage grout generation

Figure 4.84 Prepared 3 inch pipes for grouting with horizontal positioning

Figure 4.85 End capping of 3 inch pipes to simulate the infinite length of pipe

For this part of the research we followed the same trend in the way that the ratio of initial grout volume to the empty volume of the pipe is constant for all sizes of pipes and types of injection. So in this part the (1050 mL) of grout liquid were poured in the pipe and by blowing the air inside it was tried to blend and mix the grout to start the foaming process.

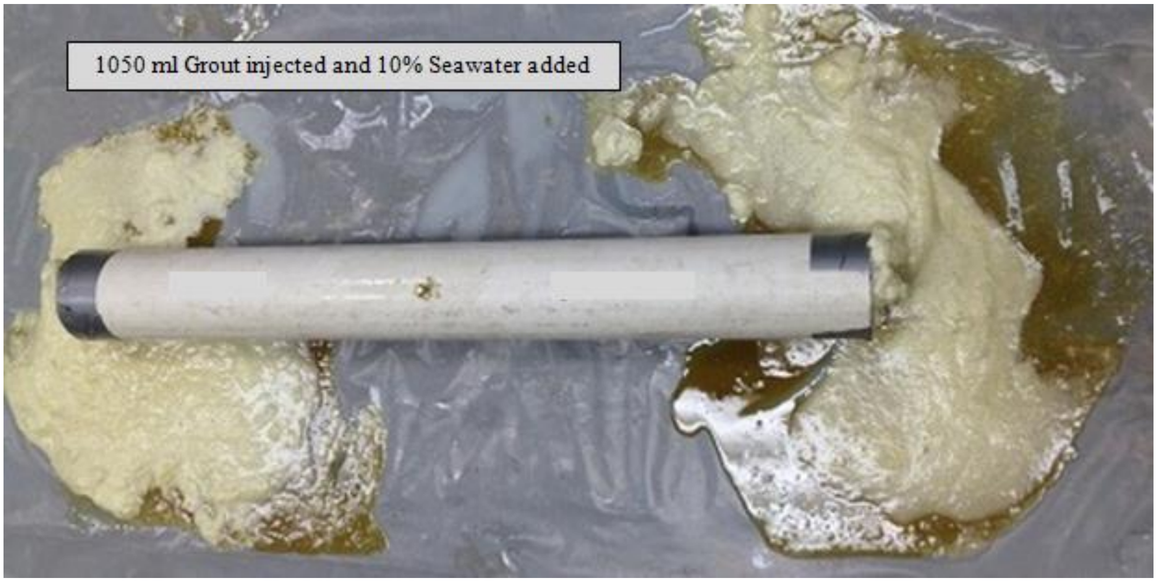


Figure 4.86 3 inch pipe grouted with 1050ml Grout-1

The first pipe is shown in Figure 4.86. As it is apparent, lots of unreacted grout was squeezed out by the foaming grout and large amount of grout was wasted. So it was decided to decrease the amount to the half and at the second time (525 mL) grout was poured and the final form of foam and the sealed pipe is shown in Figure 4.87 which is much better and almost no wasted unreacted grout.

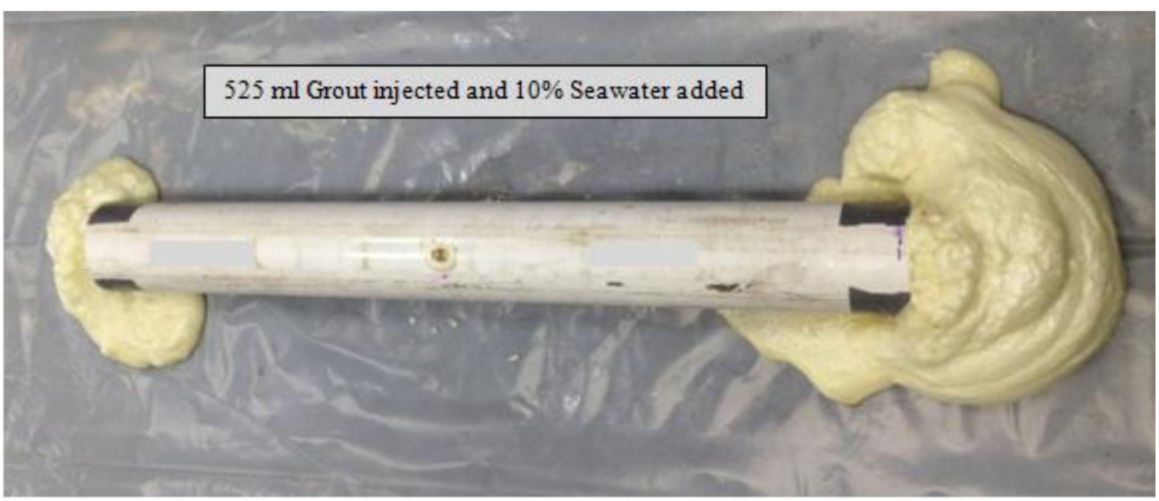


Figure 4.87 3 inch pipe grouted with 525 ml Grout-1

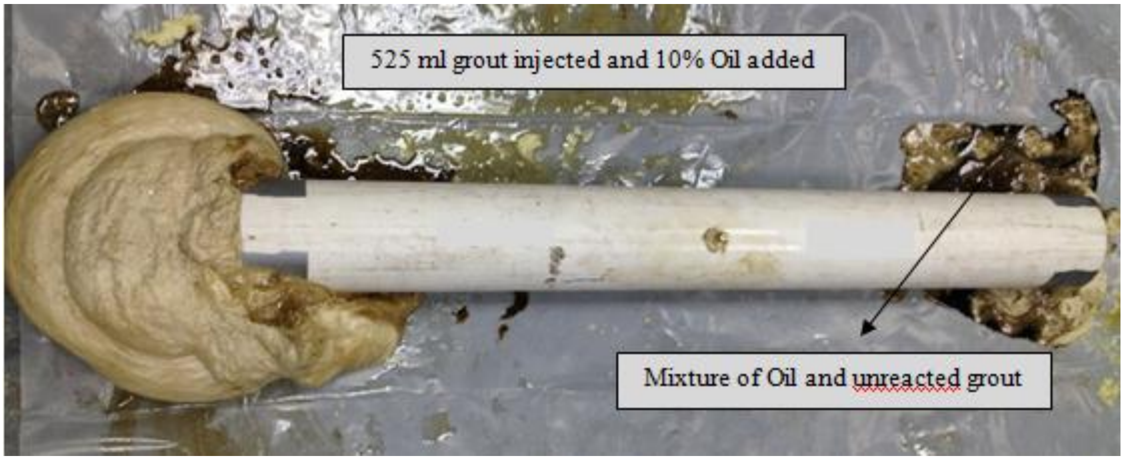


Figure 4.88 Foam generation of Grout-1 with oil contamination

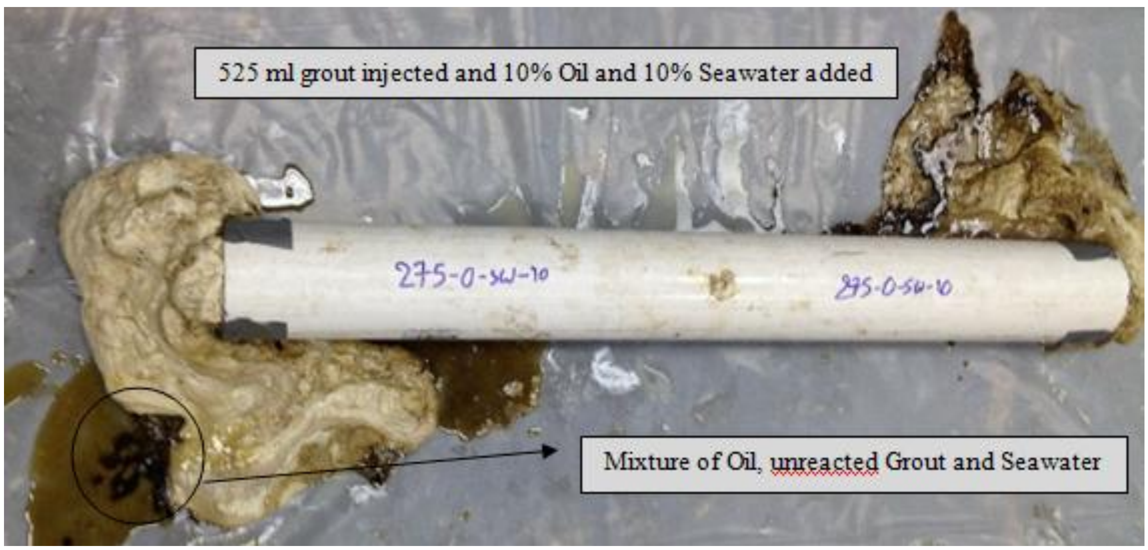


Figure 4.89 Foam generation of Grout-1 with seawater and oil contamination

After that the type of injection was selected, it was decided to simulate the contamination in the field. The 10% sea water, 10% oil and combination of 10% oil and 10% sea water were the three selected types of contamination. The nomination of these are (…-SW-10),(…-O -10) and (…-O-SW-10) respectively. In the following part the cross section and results of the tested grouts and pipes are shown.

Grout-1

The pipes filled with Grout-1 are shown in Figure 4.88 and Figure 4.89. As we can see the case SW-10 showed a good symmetric foaming. However the case O-10 does not have same amount of foam being squeezed out from both ends.

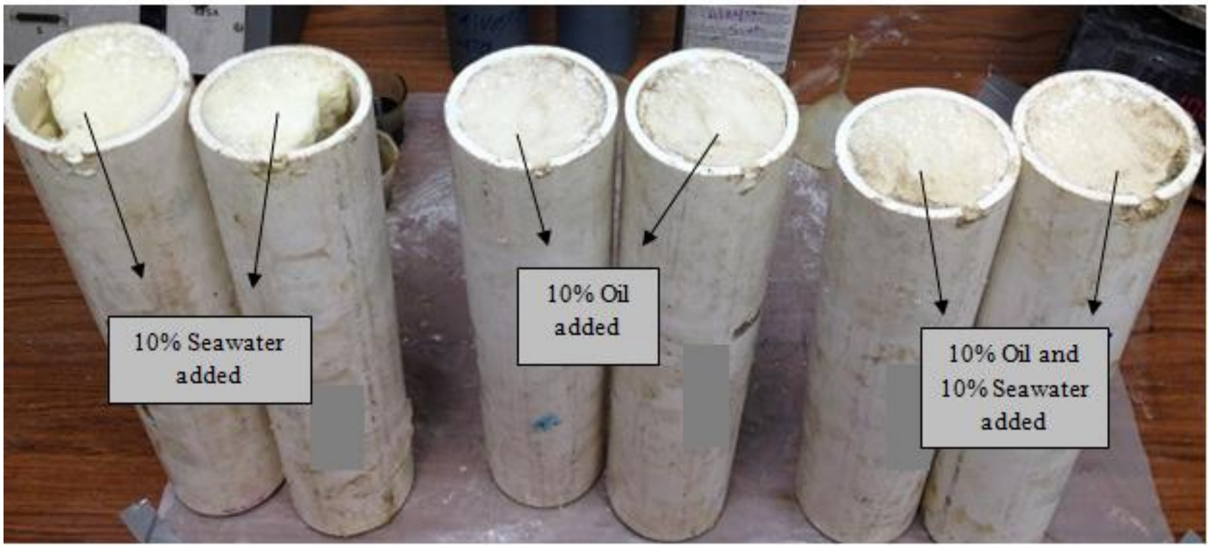


Figure 4.90 Cross section of 3 inch pipes grouted with Grout-1 and different contaminations

Figure 4.91 Cross section of 3 inch pipe grouted with Grout-1 and with Seawater contamination

And the case O-SW-10 falls between two others and has more acceptable foaming than the O-10. The cross sections of the tested filled pipes with Grout-1 are shown pictures of Figure 4.. O-10 and O-SW-10 are almost the same from the appearance. But the SW-10 Is not filled completely with grout and in Figure 4. the hollow section of the pipe more visible. In Figure 4.92 and Figure 4.93 the results of the permeability test are shown. For the 3 inch pipes all the specimens were tested under pressure of (20 Psi). As it was expected the (SW-10) has the highest permeability and the two others performed similarly.

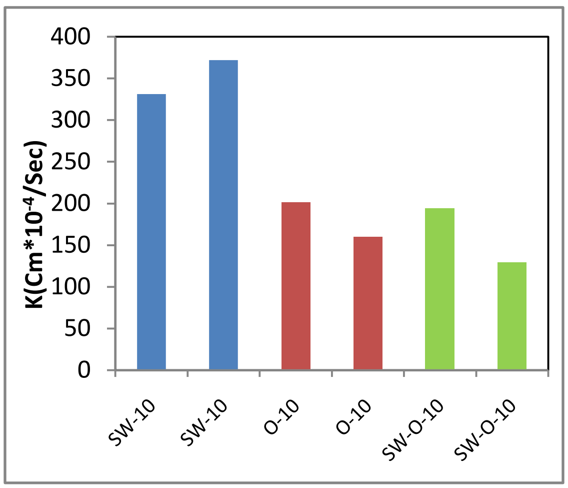


Figure 4.92 Hydraulic conductivity of 3 inch pipes grouted with Grout-1

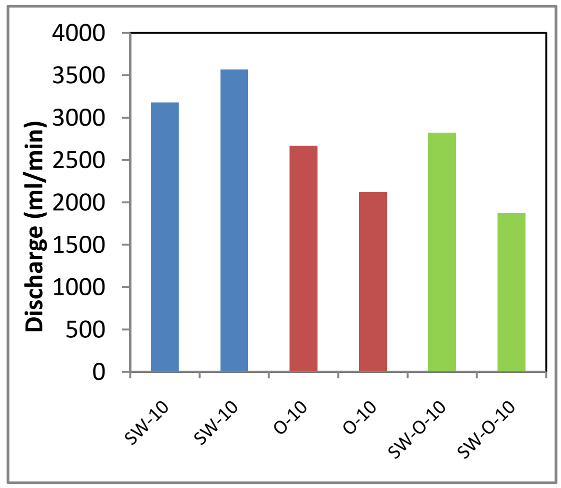


Figure 4.93 Discharge rate of 3 inch pipes grouted with Grout-1

Grout-2

The grouted pipes with Grout-2 are shown all in Figure 4.94. In overall the generated foam in all the cases is less than the corresponding ones in Grout-1 specimens. This fact gives the hint that Grout-2 is highly sensitive against the contamination. Again in this case the foaming is asymmetric and in the case of (O-SW-10) even no foam is squeezed out that indicates the high effect of contamination on the reaction. In Figure

4.95 the cross section of filled pipes could be seen. From left to right we can see the cases (SW-10), (O-10) and (O-SW-10). And as we see and expected the quality of the grout being foamed is decreasing.

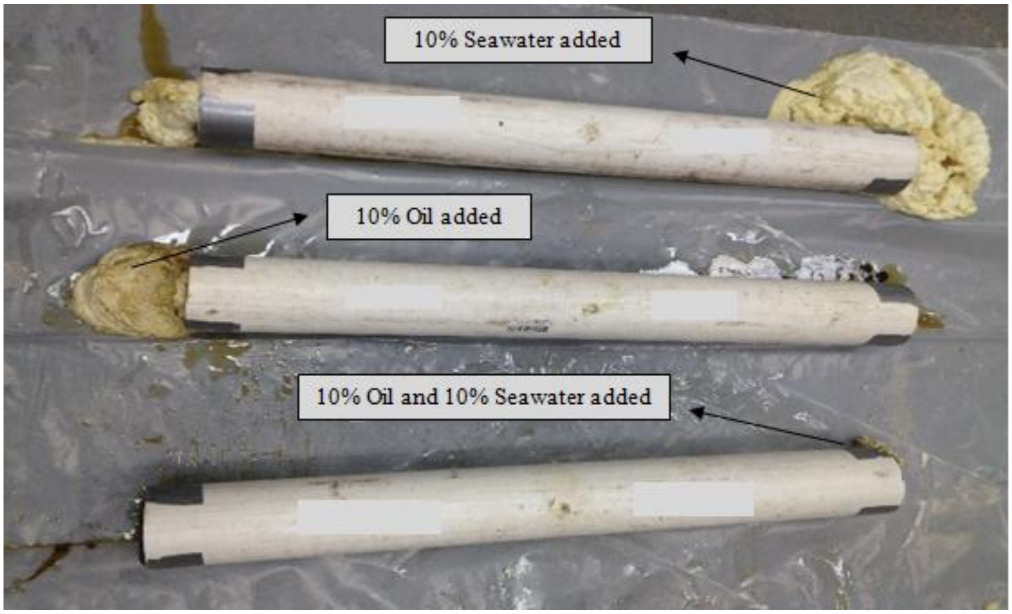


Figure 4.94 Foam generation of Grout-2 with different contaminations

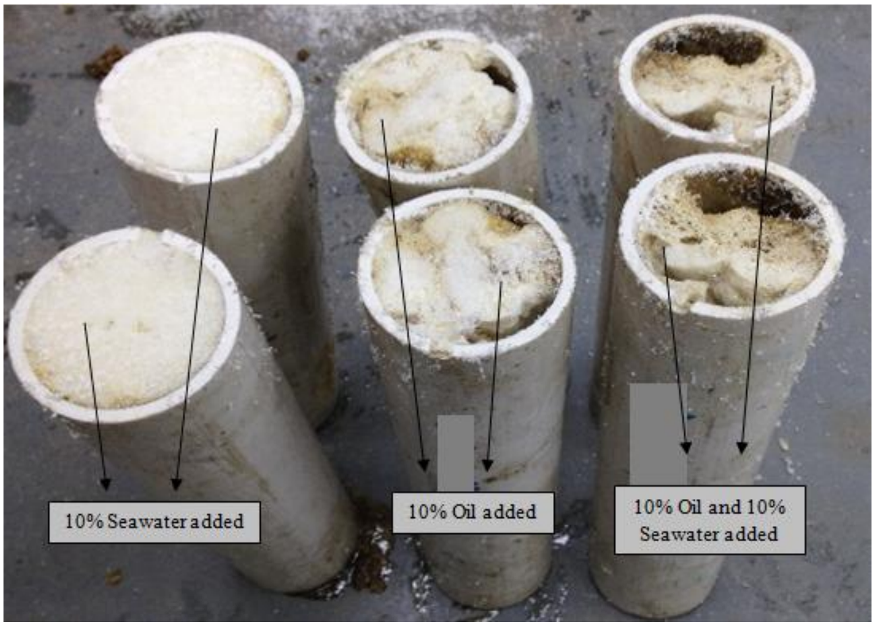


Figure 4.95 Cross section of the grouted 3 inch pipes with Grout-2 and different contaminations

The results of Permeability test on the pipes are shown in Figure 4.96 and Figure 4.97. Again here as it was expected from the appearance of the section the case SW-10 has the lowest permeability the case O-10 has the highest. However, totally the values are higher than the permeability of Grout-1 specimens.

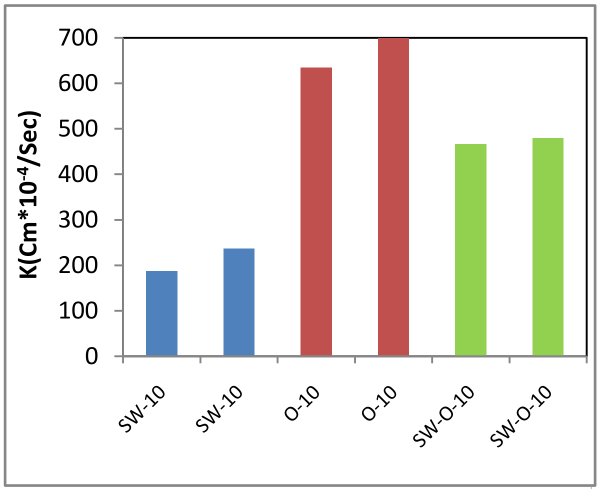


Figure 4.96 Hydraulic conductivity of grouted 3 inch pipes with Grout-2

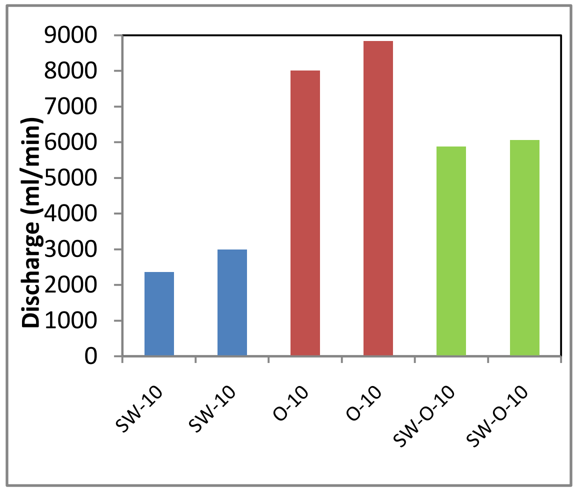


Figure 4.97 Discharge rate of grouted 3 inch pipes with Grout-2

Grout-3

In this grout cross section of the pipes after the grouting is shown Figure 4.98. From left to right we can see the cases (SW-10), (O-10) and (SW-O-10). Altogether the case (O-10) seems to be the weakest. And the unexpected part is that the foam of (SW-O-10) has better quality than the case (SW-10). In Figure 4.99 the grouted pipes after the permeability test are shown. All the specimens have tremendous shrinkage after being exposed to water and apart from that they were highly softened.

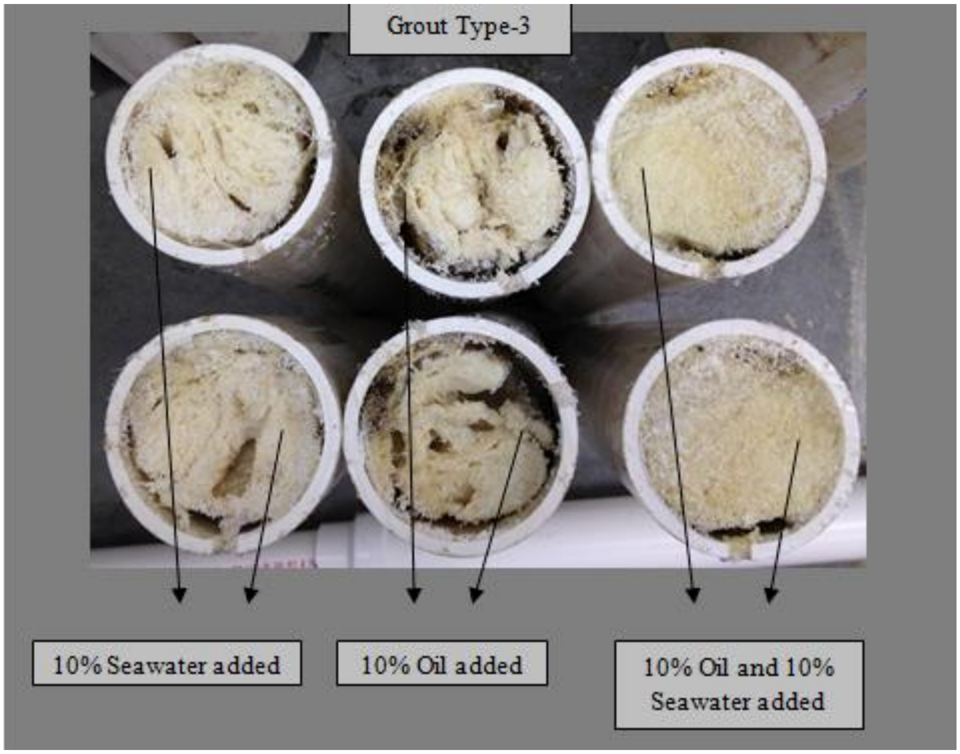


Figure 4.98 Cross section of the 3 inch grouted pipes with Grout-3, before permeability test

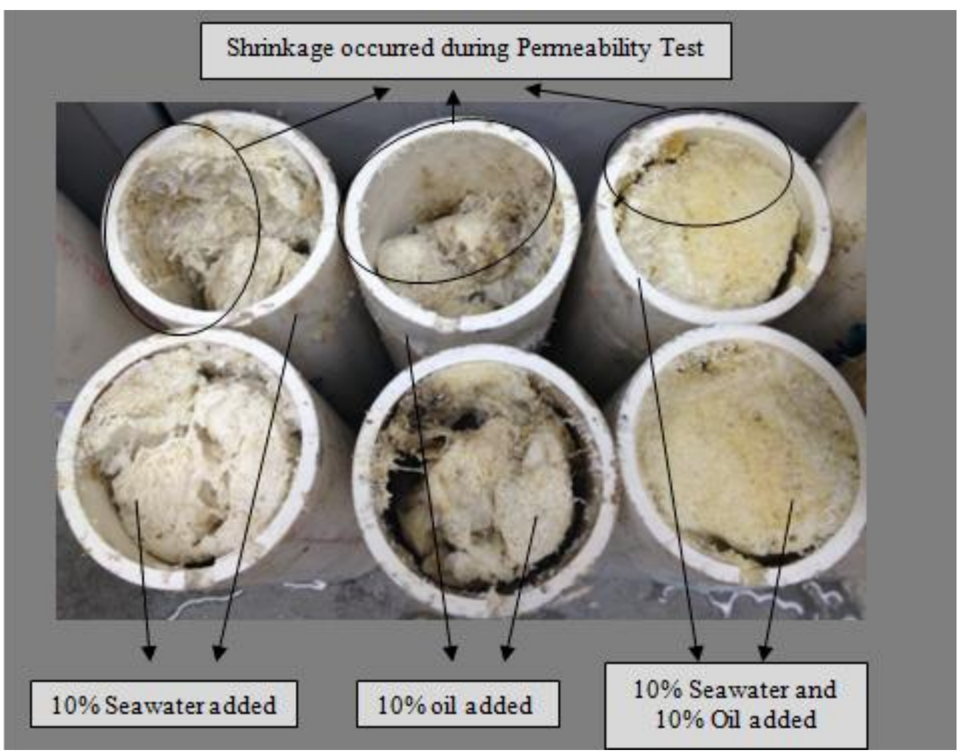


Figure 4.99 Cross section of the 3 inch grouted pipe Grout-3, after Permeability Test

In Figure 4.100 and Figure 4.101 the test results of permeability test are shown. Here we face a contrast that the in spite of the bad appearance of the cross section of the case (O-10) it has the lowest permeability. The two other cases performed almost the same relatively the same as Grout-1 and much better that Grout-2.

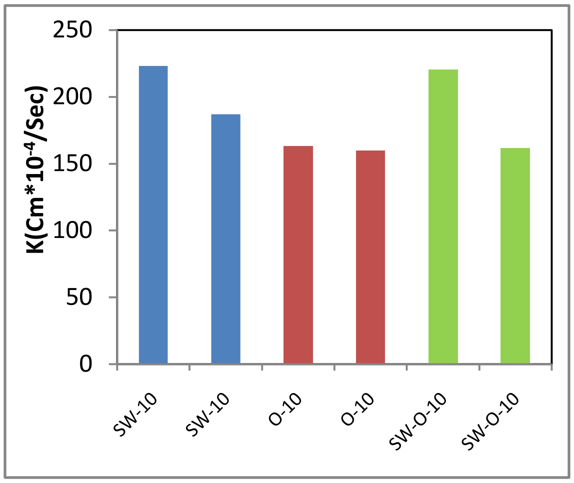


Figure 4.100 Hydraulic conductivity of 3 inch grouted pipes with Grout-3

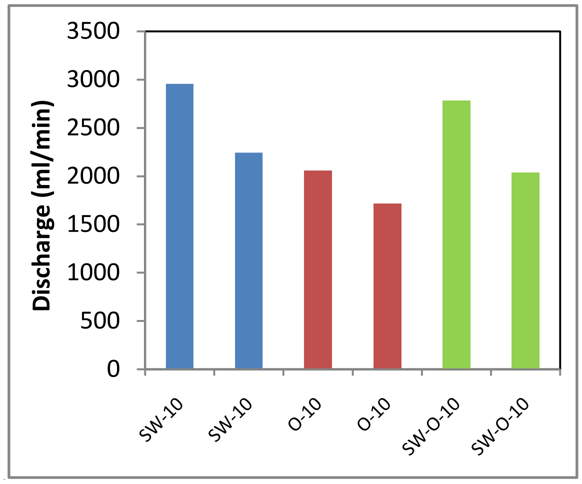


Figure 4.101 Discharge rate of 3 inch grouted pipes with Grout-3

Grout-5

The image of filled pipes with Grout-5 is presented in Figure 4.102. Here we see that in case (SW-10) the generated foam is no symmetric and the case (O-10) the reaction is impaired due to the interference of oil and no foam came out of the ends. In the case (SW-O-10) we have a condition in between (SW-10) and (SW-10). In Figure 4.103the cross section of the pipes cut from the middle could be seen. The quality of the grout observed is compatible with exterior appearance of the grouts being foamed.

Figure 4.102 Foaming of Grout-5 in 3 inch pipes with different contaminations

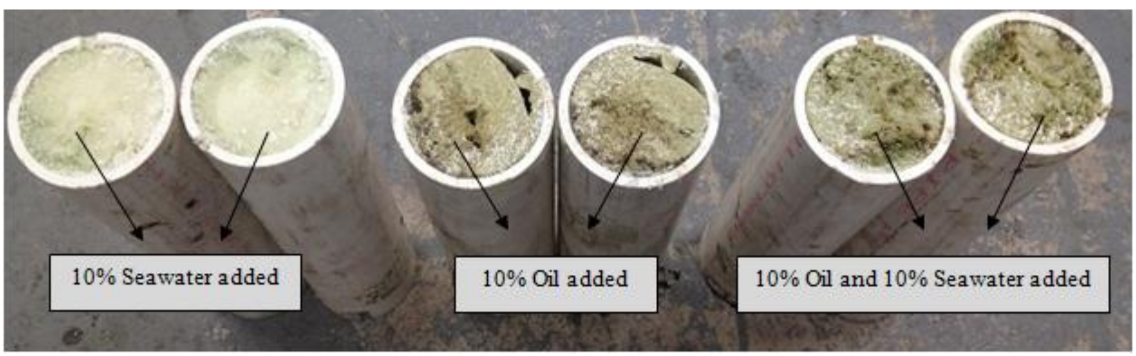


Figure 4.103 Cross section of 3 inch grouted pipes with Grout-5 and different contaminations

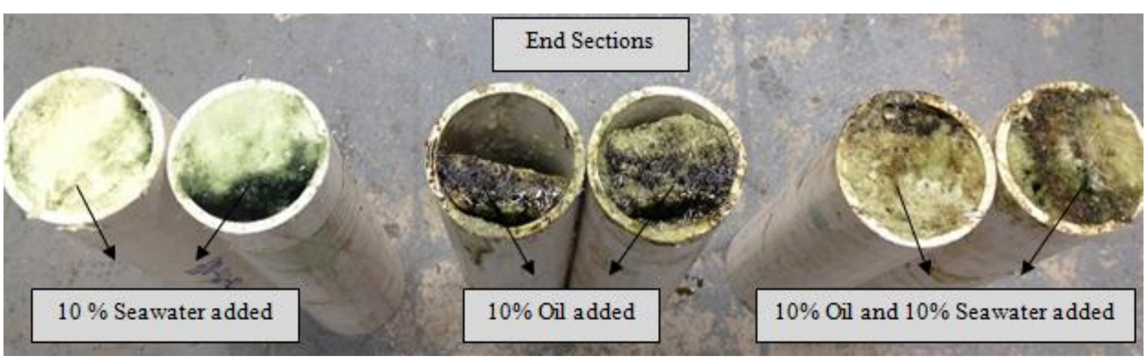


Figure 4.104 Section of semi-open end of the 3 inch grouted pipes with Grout-5

In Figure 4.104 the cross section of the pipe at the semi-opened ends could be seen that indicates in the case (O-10) we have very low quality foam being generated.

In Figure 4.105 and Figure 4.106 we see the results of permeability test. Totally they have similar performance. However the difference between the half pieces of each pipe indicates the asymmetric generation of the foam inside the pipe. Also in contrast with our expectation the case (O-10) has the lowest permeability.

Altogether the Grout-5 performed more independently from the contamination in comparison with other grouts. Also it exhibited the best performance among all grouts.

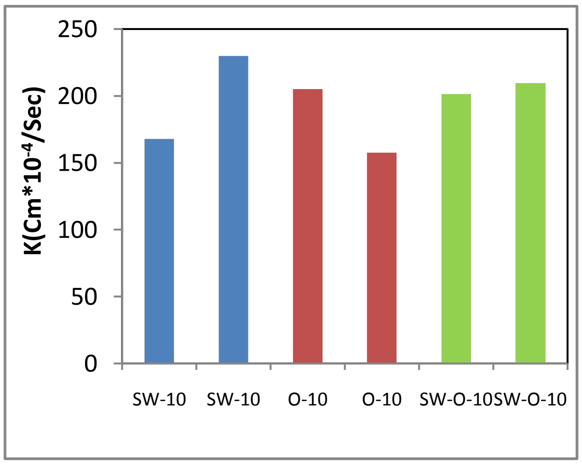


Figure 4.105 Hydraulic conductivity of 3 inch grouted pipes with Grout-5 and different contaminations

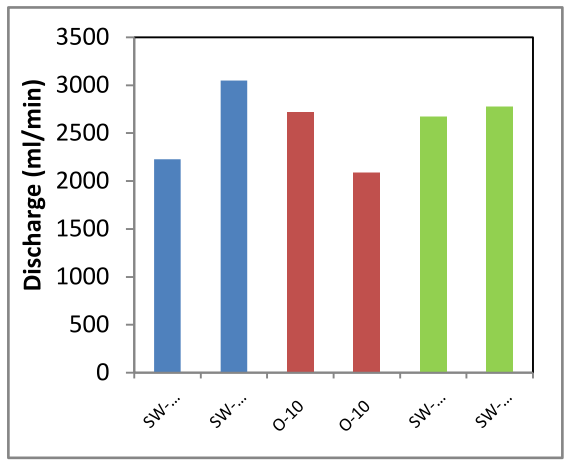


Figure 4.106 Discharge rate of 3 inch grouted pipes with Grout-5 and different contaminations

Apart from the collected data their discussions, the following observations and notes were made and taken during the tests that should be taken into account.

Observations

At first it was planned to keep the ratio of grout to free volume of the pipe constant in all pipe sizes during the study. However, the first thing that was observed in the case of 3 inch pipe grouting was that the amount selected grout is more than needed. This was basically concluded from that we have seen during the foaming of the grout lots of grout chemicals was coming out of pipe and this mainly happened since we capped the end of the pipes just partially. So, we grouted one pipe with Grout-1 and we kept the ratio of grout to free volume constant and, in another case we injected half of that amount so that we can compare the effect of this decrease in grout amount.

Table 4.18 The effect of the amount of injected Grout-1 on the Permeability

Grout (grams)	Pressure (psi)	Length (inch)	Diameter (inch)	Duration (Seconds)	Water (grams)
1050	21	15	3	13	803
525	19	15	3	10	563

As it is seen in Table 4.18, although the amount of grout was decreased but the permeability was decreased, which indicates that in the case with less amount of grout it can react more efficiently. So based what have been observed we use the half of the ratio of grout to free volume for all the 3 inch Diameter pipes. During the foaming of the grout and also after that the foaming was completed we had the following observations.

Grout -2

The O-10 and O-SW-10 samples considered as failure. This was basically mentioned because of that in these cases the grout could not build up completely so they could not seal the pipe. However, in the case SW-10 the pipe was filled with grout.

Grout-3

1) Because of high volume liquid chemicals that is injected initially in the pipes, the chemicals on the surface because of the good access to air start to foam so it forms a layer on the remaining chemicals that has not reacted yet and prevents their access to air so their reaction is interrupted. In order to solve this problem we inserted a tube through the chemicals after the injection, and then the air was blown in the liquid

grout for 60 seconds. By doing this visually it was observed that foam generation improved significantly since this grout is sensitive to air.

2) After cutting the grouted pipes to half to check the cross section of the filled pipe it was seen that the SW-10 samples were rigid and tight. However, the O-10 and SW-O-10 samples were soft and somehow immature especially at the center of the pipe.
3) Once the test was done the grouted pipes the O-10 samples grout were softened and SW-10 and SW-O-10 specimens fell apart that indicates this grout is remarkably sensitive and vulnerable against moisture.

Grout-5

1) In this case again lots of grout chemicals remained unreacted. Basically one layer of grout foamed on the top and prohibited the access of the air to the remaining of liquid grouts. So, their reaction was interrupted.
2) This grout does not foam well in vertical direction and it tends to develop along the horizontal direction. So, this grout is not a good option for large diameter pipes and in the case that it is used; it should be injected in separate layers and build up the section of the pipe layer by layer.

Recommendations

Generally, in order to improve the performance of grouts in large diameter pipes it is suggested that the grout be injected in layers and in the form of stage operation. Since, these Polyurethane grouts do not foam vertically well.

Pre-Mixed Grout

For this type of grout we have limitations for the amount of injection since as the grout comes out of the spray it is in the form of foam so can inject it until the pipe is filled. Basically this limitation hinders the condition of having dense foam. Anyway we injected this grout in the pipes until it was filled and let to have the reaction completed and the foam being hardened. Two after the injection we cut the pipe from the centerline and opened the caps and observed the following:

1) A little bit of foam started to come out of the pipe it means that this the lack of air has stopped the reaction.
2) The cross section of pipe at the centerline was almost empty and only 10% of it was filled with grout. Totally this grout has a very poor performance and also it is very sensitive to air and the final foam is very weak and non-uniform.

Suggestions

For filling a pipe this grout is by no means appropriate and not recommended. However, for one case it very useful and applicable. In the condition that pipe in the field is sloped; once the grout is injected until it is liquid it starts to flow downstream. So, before the main injection we can inject this type of grout and since it is in the form of foam does not flow and sticks to pipe, then, when the liquid grout is injected the existing foam acts as a barrier and blocks the flow of grout until it starts to foam. By this mean we can have the grout to foam in the location that we desire.

4.3.4) Long grouted PVC pipes

At this part of the study the 1.25 inch PVC pipes were injected and filled with grouts and the Water leaking test was performed on them. The difference here is that the injection is done in stages so that we have a couple initial injections and then we do the main injection(s). Another important factor for permeability is the length of the Pipe to be tested. So, first we tested the 5 feet long pipes and based on the data and case of need we test the 10 feet long pipe. Initial injections are done at the ends of the pipe and the main injection is done at the center of the pipe. In the following part the permeability test results of 5 feet and 10 feet long pipes are presented respectively.

5 feet Long

As it was observed during the tests, in the case of 5 feet long pipe injection we could not have complete sealing at the pressure of 100 psi. In all the tested grouts, we see that the Grout-1 performed as the best. However, as it is seen in Figure 4.107, from pressure 50 psi and above, the permeability decreases, this observation could be justified that at 50 psi or less a part grout inside was skidded and was pressed against another piece of grout and as the pressure increased the grout was deformed and due to the Poisson`s effect it starts to expand laterally and push against the wall of the pipe and prevent the flow of water. The shape of the compressed foam is shown in Figure 4.108. On the other hand we see that Grout-5 performed as the worst and the same thing was observed in it but at higher pressure and at 80 psi. And the only case that we could have complete sealing was Grout-2 and up to the pressure of 30 psi.

Grout-1

The foam inside the pipe grouted with Grout-1 was removed from the pipe after testing. As it is seen in Figure 4.108 the right half of the grout is the compressed part due to pressure from the stiffer grout on the left half side.

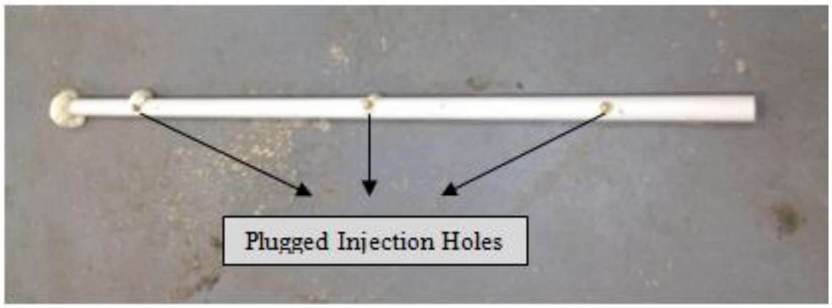


Figure 4.107 3 hole injection on 5 feet long Pipe

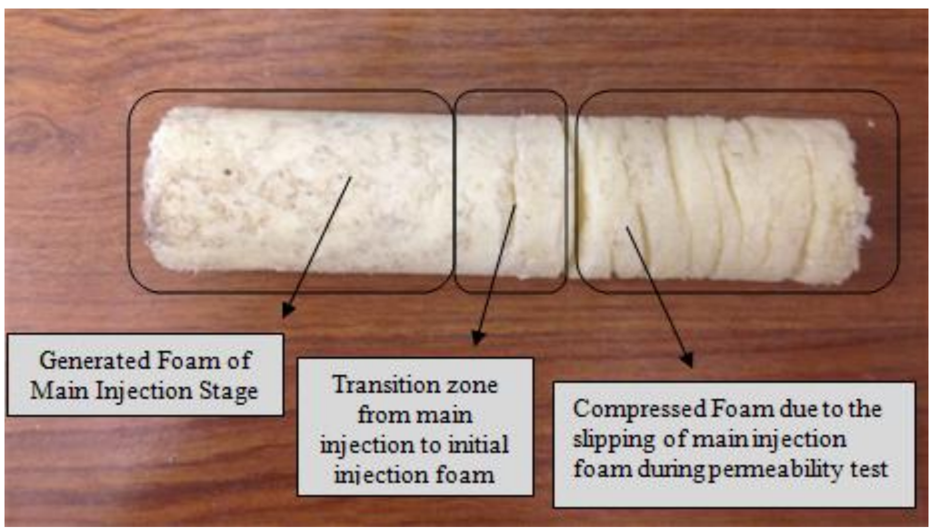


Figure 4.108 The shape of compressed foam in the pipe grouted with Grout-1

As it could be seen in Figure 4.109, the foam generated during the two phases of grouting has a mixed condition that is formed during two consecutive sections. The brighter color on the top is grout from second stage which is denser and of better quality and the other part with darker color, is of lower density and is formed during the initial injection. Besides, in Figure 4.110 the grout removed from mid-length between two injection holes is shown. In this case the uniform foaming of grout could be observed. The discharge trend of 5 feet pipe grouted with Grout-1 is shown in Figure 4.111.

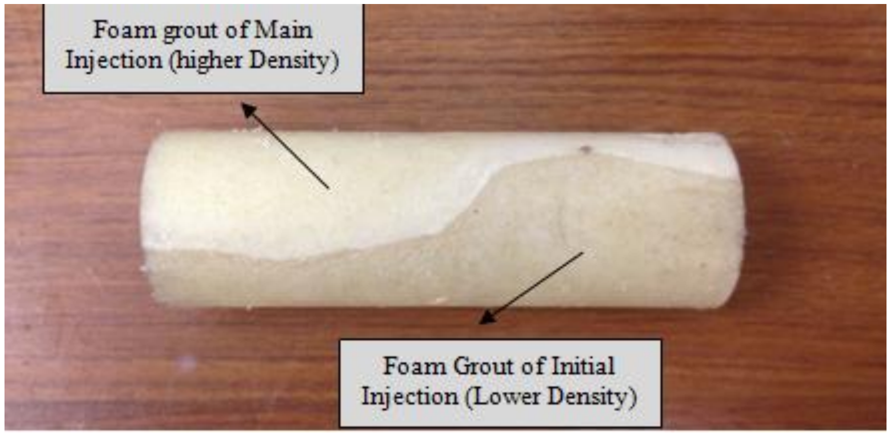


Figure 4.109 Encounter zone of foams generated during initial and main injection

Figure 4.110 The structure of the foam at the mid-length of the grouted pipe with Grout-1

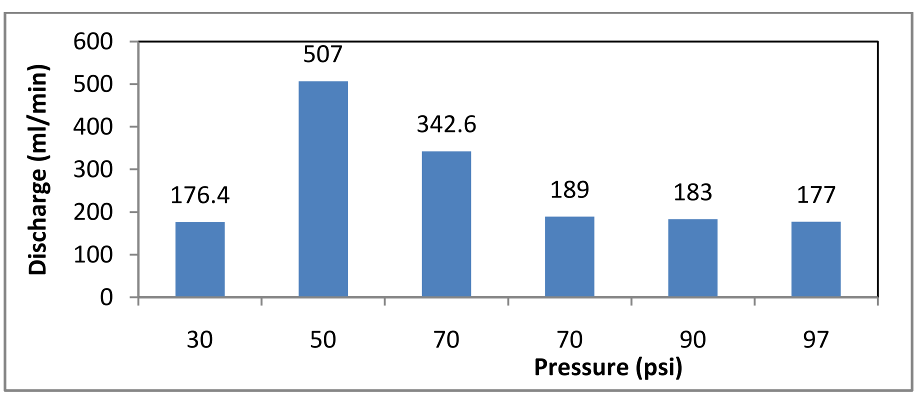


Figure 4.111 Discharge rate of 5 feet long grouted pipe with Grout-1 versus pressure

Grout-2

As it is seen in Figure 4.112 the foaming visible in the figure has two different colors that means at the first injection the section of the pipe was not completely blocked so that at the final stage (main) injection the foam could come out of the pipe.

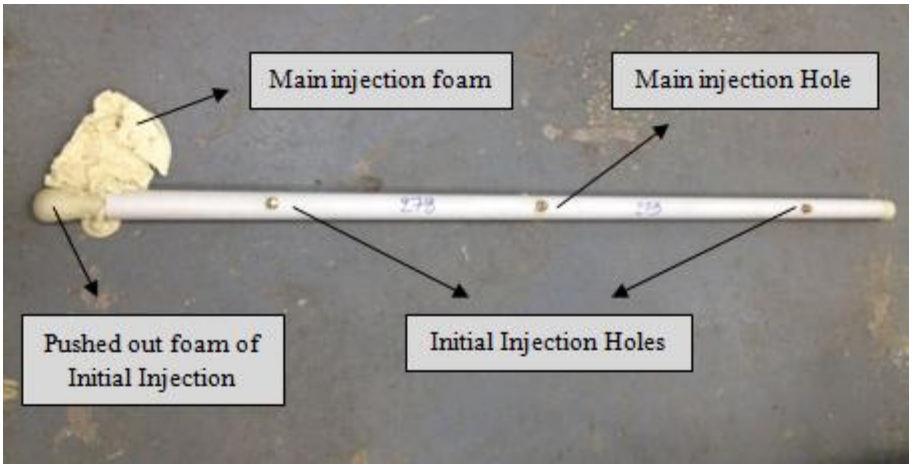


Figure 4.112 The status of the 5 feet long pipe after the injection with Grout-2

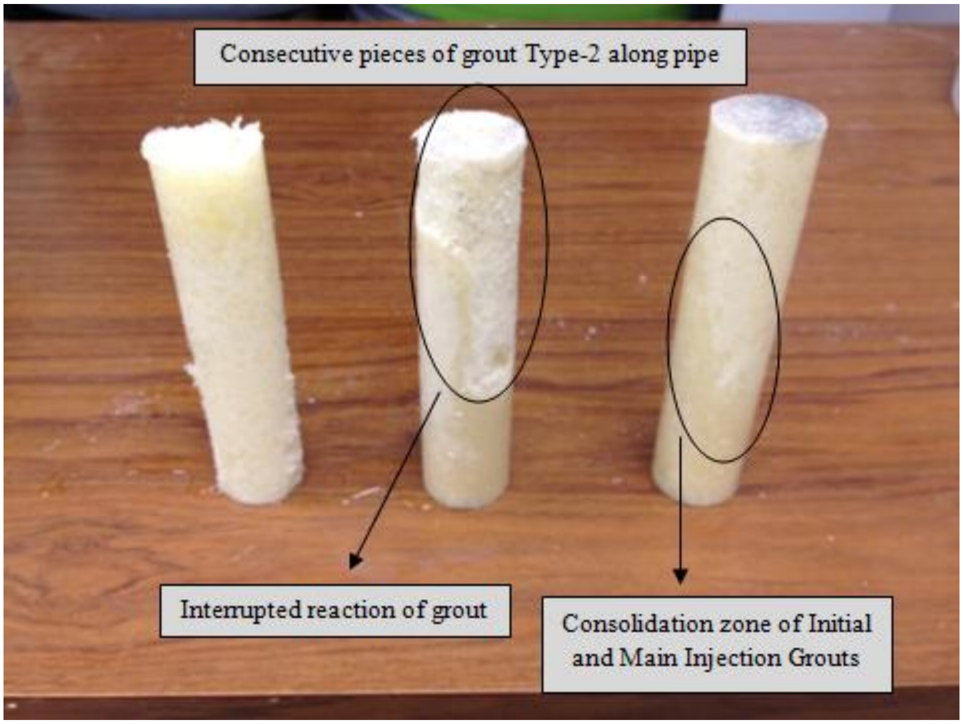


Figure 4.113 The structure of the Grout-2 along the pipe from one end to the centerline

On the other hand based on what is seen in Figure 4.114 left to right section from one end to the mid length of pipe. The variation in the color is indicative of the quality of foaming and final condition of the grout. Besides, the Discharge trend of grouted pipe with Grout-3 is shown Figure 4.114. As it seen the pipe was sealed up to pressure of 30 psi and above that pressure the discharge increases with a relatively high rate.

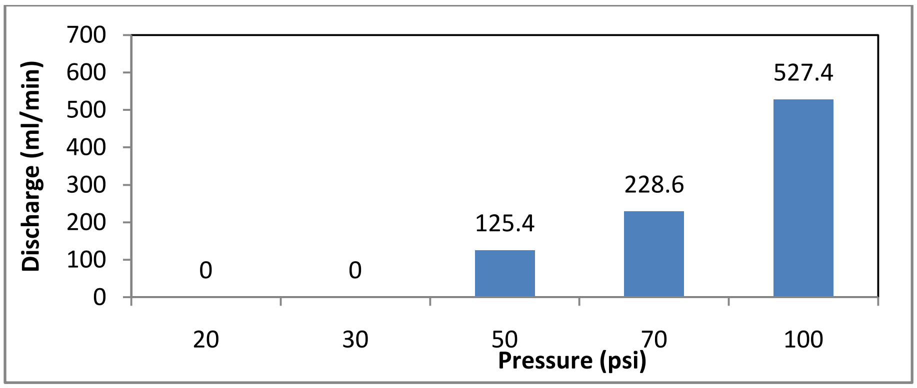


Figure 4.114 The discharge trend of 5 feet long pipe grouted with Grout-2

Grout-3

In Figure 4.115, from left to right we can see that the quality of grout is degrading, which is from the end to the mid-length of the pipe.

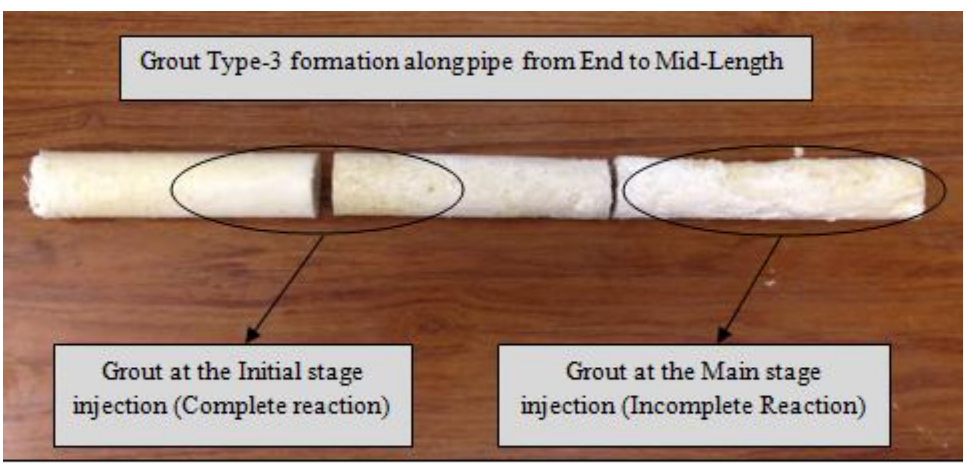


Figure 4.115 The structure of the grout along the 5 feet long pipe grouted with Grout-3

This fact is consistent with previous observation that this grout is very air sensitive and due to the blocked ends during the initial injections there was not enough air for reaction and the grout is not foamed well. Moreover, the discharge trend of the grouted pipe with Grout-3 is shown in Figure 4.116. As it is seen, in none of the pressure the sealing could not be achieved. Besides, the overall discharge rate was relatively high and the increase rate of discharge with Pressure is slightly lower than the corresponding rate in Grout-2.

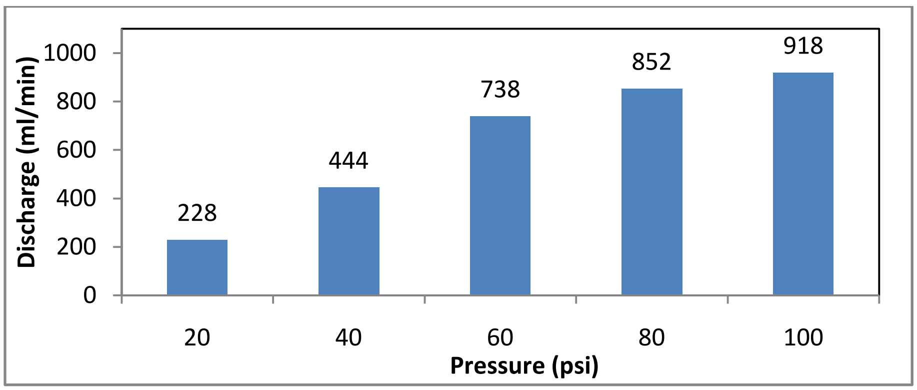


Figure 4.116 Discharge trend of the 5 feet long grouted pipe with Grout-3 versus pressure

Grout-5

As it is shown in Figure 4.117 from left to right we can see the grout from the center line of the pipe to one end. On the right side of foam we can see that the quality is higher and better and uniform foam is generated and his because of the access to enough air. And at the mid-length we can see that again the quality of foam is so good and also changing and it is again because of the lack of air that impairs the reaction of the grout at mid length of the pipe which is trapped by two grouted ends of pipe.

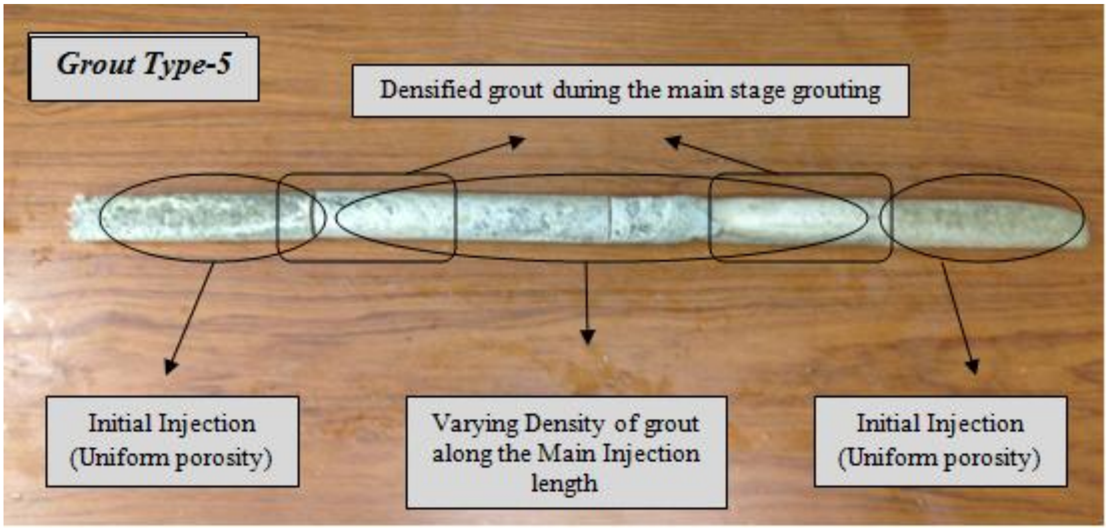


Figure 4.117 The structure of the grout along the 5 feet long pipe grouted with Grout-5

Figure 4.118 Close view of the Grout-5 structure along the main injection zone

In Figure 4.118 we have a closer view of grout at the point that the grouts injected at different stages reach each other. The right part is grout initial injection which is more uniform and the one at the left side is from the second stage of injection which is less uniform and more porous. In Figure 4.119 the discharge trend of the grouted pipe with Grout-5 is shown. It was seen up to 80 psi the discharge has an increasing trend with pressure. However, from 80 to 100 psi the discharge showed a remarkable drop. The phenomenon that was explained for the case with Grout-1 could be considered for this pipe too.

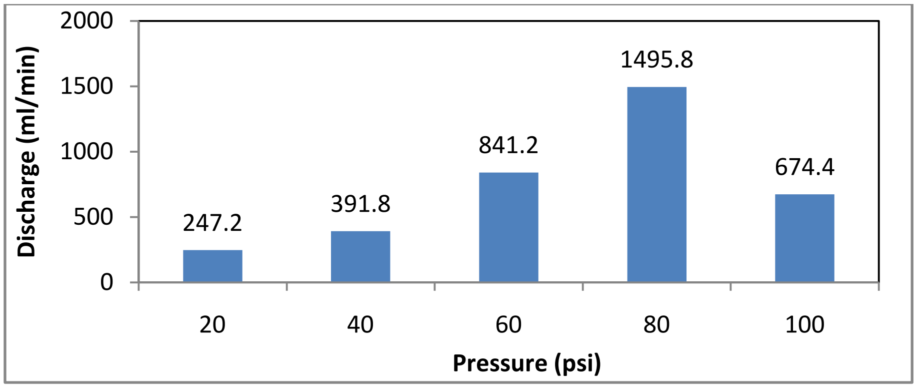


Figure 4.119 Discharge trend of the 5 feet long grouted pipe with Grout-5 versus pressure

10 feet long

Due to not having satisfactory results in 5 feet long pipes, it was decided to increase the length of the pipes to 10 feet. So, in (f) to (f) the result of Water leak test on the 10 feet long PVC pipes could be seen. As it is seen, the Grout-1 performed the best and up to 100 psi no leakage was noticed in the pips. On the other hand, pipe grouted with Grout-2 complete sealing up to 20 psi could be achieved and this grout performed as the worst case. Also, with Grout-3 the pipe was sealed only up to 40 psi and gradually the water permeation started and increased. For Grout-5 we had completely sealed pipe up to 60 psi and suddenly the bond between grout and pipe failed and the flow started so high. The trends and results of permeability are shown Figure 4.121 to Figure 4.124

Figure 4.120 shows the setup for testing 10 feet long pipes. In the left picture we can see that due to the pressure inside and resulting, movement of the end caps the pipe stated to buckle. To prevent this buckling a stiffener was provided at the mid-length of the pipe to work as the lateral support and prevent the buckling of the pipe and avoid the skidding of the caps on the end plates.

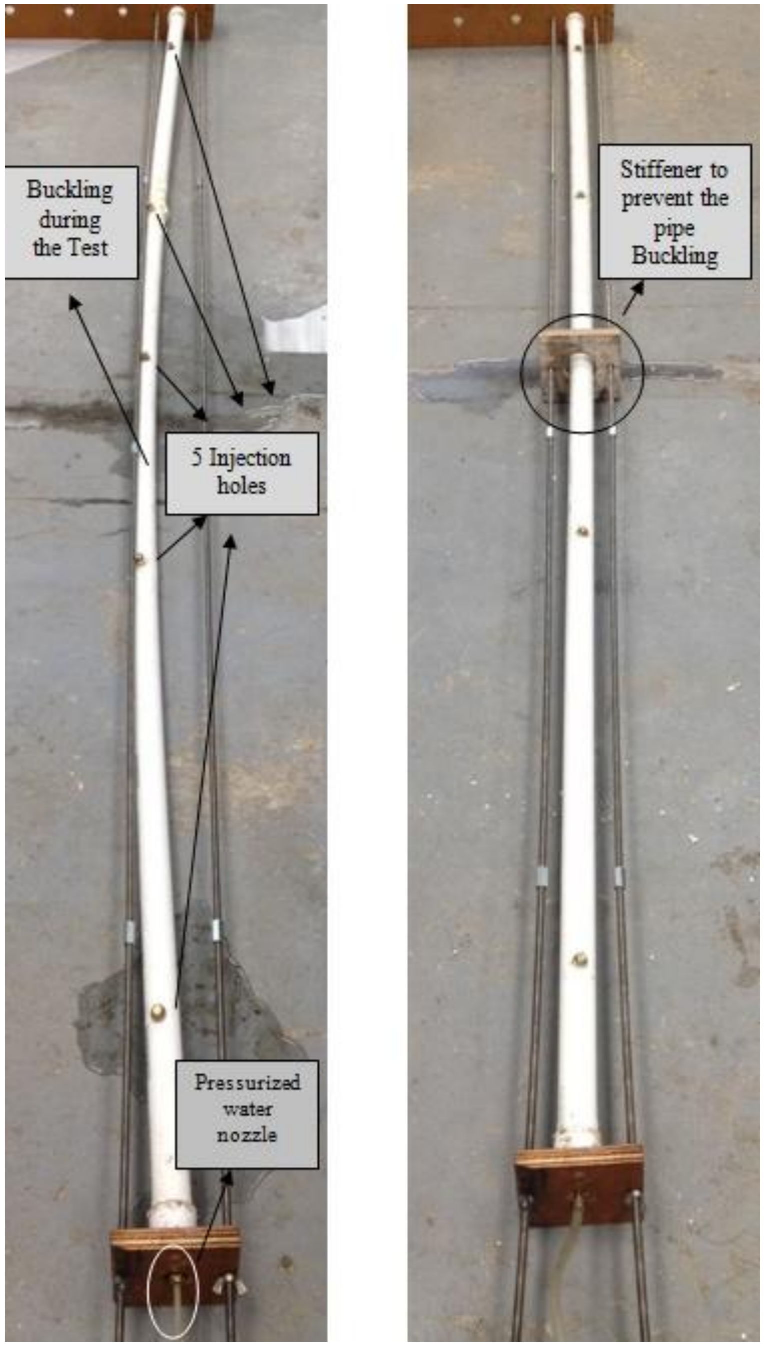


Figure 4.120 10 feet long grouted pipe under water leak test

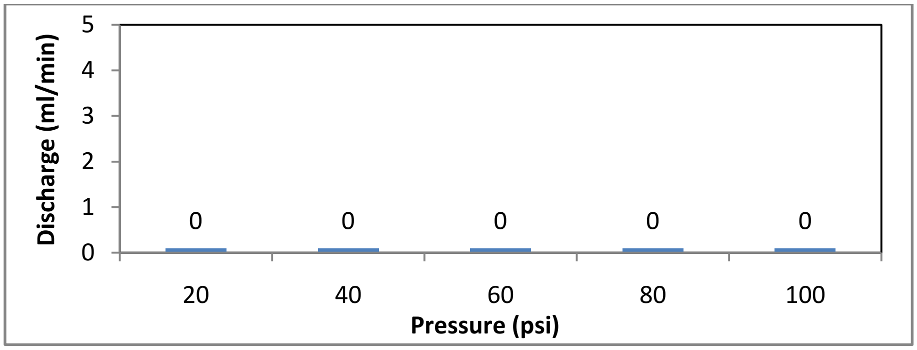


Figure 4.121 Discharge trend of the 10 feet long grouted pipe with Grout-1 versus pressure

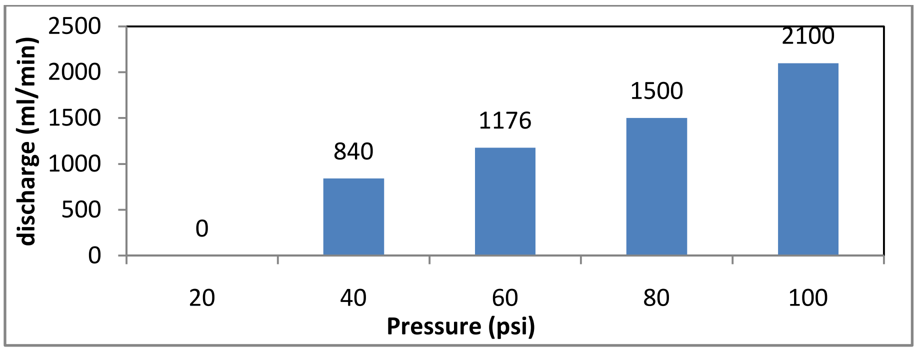


Figure 4.122 Discharge trend of the 10 feet long grouted pipe with Grout-2 versus pressure

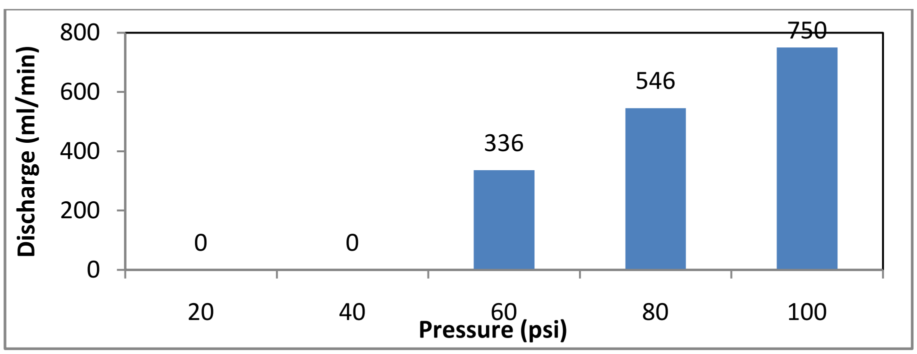


Figure 4.123 Discharge trend of the 10 feet long grouted pipe with Grout-3 versus pressure

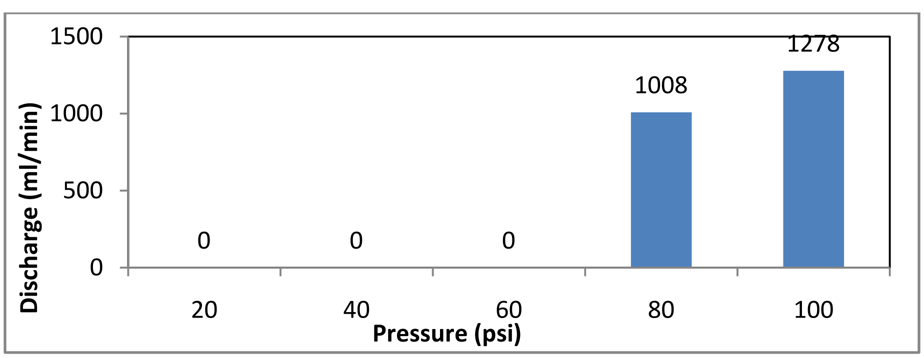


Figure 4.124 Discharge trend of the 10 feet long grouted pipe with Grout-5 versus pressure

4.3.5 Abandoned Steel Pipes

Based on an earlier study, the best performing grouts were selected to grout the four abandoned steel pipes. These four pipes are named as (case-1) to (case-4) It is aimed to duplicate each grout to make sure about the obtained results. Therefore Grout-1 and Grout-5 were chosen. The method of injection was the same as stage injection discussed in previous reports. The pipes are 10 feet long and the injection was done in 5 stages as shown in Fig.4.126. After the injection the pipes were tested for permeability. And in the cases that the results were not satisfactory it was tried to improve the sealing by further injections. After that the pipes were tested the pipes with higher leaks were selected to be crushed and cut into half and then do the permeability test on 5 feet length (half length) of grouted pipe to see the performance of the half length. Also, those pipes with lower permeability were also cut into half but without being crushed. In the two latter cases it was tried to check the performance of the half length of grouted pipe. Also, since the grout injection was symmetric and the pipes were cut at the centerline, it was possible to check the efficiency of grouting with shorter length of pipes.

Grout Injection

As it was mentioned before the grout was injected in five stages. The optimized amount of grout was obtained from previous studies done in this project. Since the initial studies were done with 5 feet long pipes, it was decided to follow the same pattern of injection for each 5 feet of pipe. So, we can repeat this pattern in consecutive sections of pipe based on the occurring pressure on the pipe for example for every 50 psi of pressure we should grout 5 feet of pipe. The pattern for 5 feet length is shown in Figure 4.125 and for 10 feet is shown in Figure 4.126. On the other hand, the optimized amount of grout is for the pipes with diameter of 1.25 inches, but our pipes are3 inch in diameter.

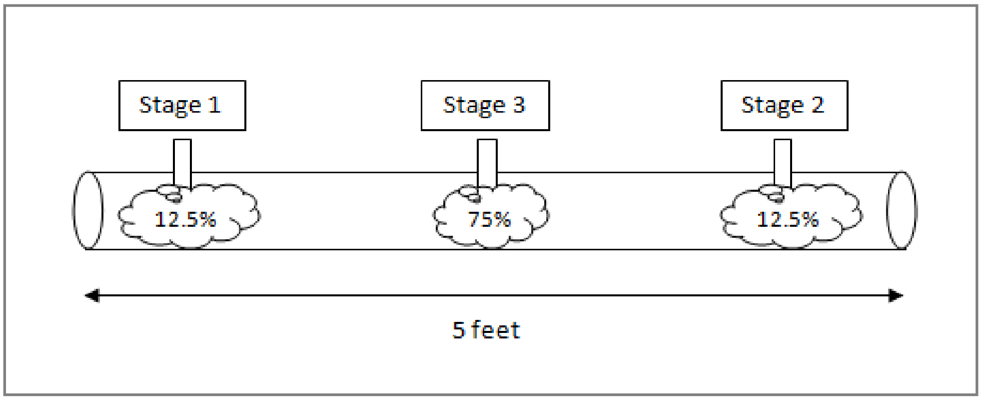


Figure 4.125 Typical stage injection of grout in a 5 feet long pipe

In the abandoned steel the pipes the wax was deposited all around the section of the pipe and hence the open space diameter was decreased to 1.25 to 1.5 inch, roughly speaking. Typical section of the pipe with wax is shown in Figure 4.127. Hence, it was decided to use the same amounts of grouts used in previous studies with 1.25 inch diameter pipes.

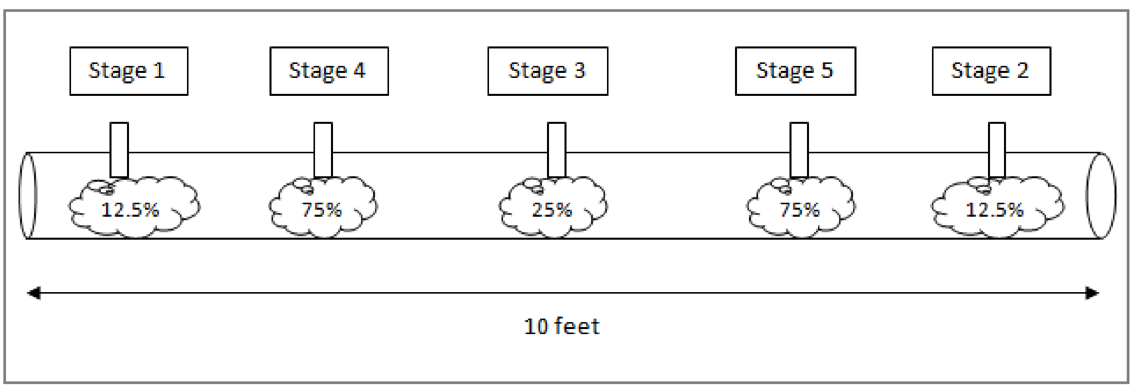


Figure 4.126 Stages of grouting along the 10 feet long pipe

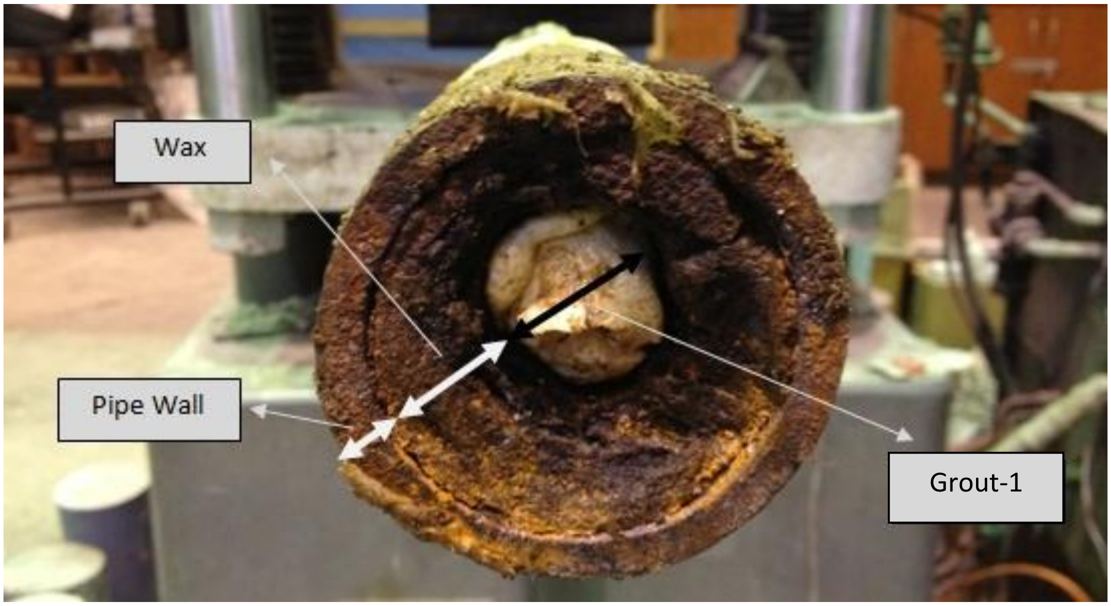


Figure 4.127 Typical cross section of an abandoned pipe

Test Methods

Permeability test on 10 feet long pipe

After that grouting the pipes, the caps were installed at both ends of pipe for performing the permeability test. The caps were sealed with silicon sealant. Since the silicon sealant had to be cured for 1 hour we can say that the permeability test was done within 2 hour after the grout was injected. Hence, it could be considered this test can give us ideas of these grouts performance in the field right after being injected. For the permeability test we had 5 pressures from 20 psi to 100 psi in 20 psi increments. And, after each increase in applied pressure we waited for 5 minutes to measure the amount of leaking water.

Pipe Crushing and cutting

In this part two grouted pipes with Grout-1 and Grout-5 with higher water leaking were crushed and cut and 2 other pies with lower water leak were only cut into half and then tested for leak. The crushing procedure and the pipes after cutting are shown in Figure 4.128 and Figure 4.129 respectively.

Figure 4.128 Initial stage of crushing the grouted abandoned pipe

Figure 4.129 Final stage of crushing of the grouted steel pipe

Figure 4.130 Cut grouted pipes with and without crushing

Figure 4.131 Capping and sealing the pipes

Permeability test on 5 feet crushed and cut pipes

After crushing and then cutting the pipes, the caps were put on for permeability testing. Also the injection holes were sealed. So, the caps were installed and were sealed with silicon glue. Also, the injection holes were patched with plastic sheet and epoxy glue. Since the epoxy needed at least 24 hours to cure, pipes were tested after one day. The prepared pipes for leakage and permeability are shown in Figure 4.131. For the permeability test the procedure is similar to the 10 feet pipes that already have been explained and the permeability setup is shown in Figure 4.132.

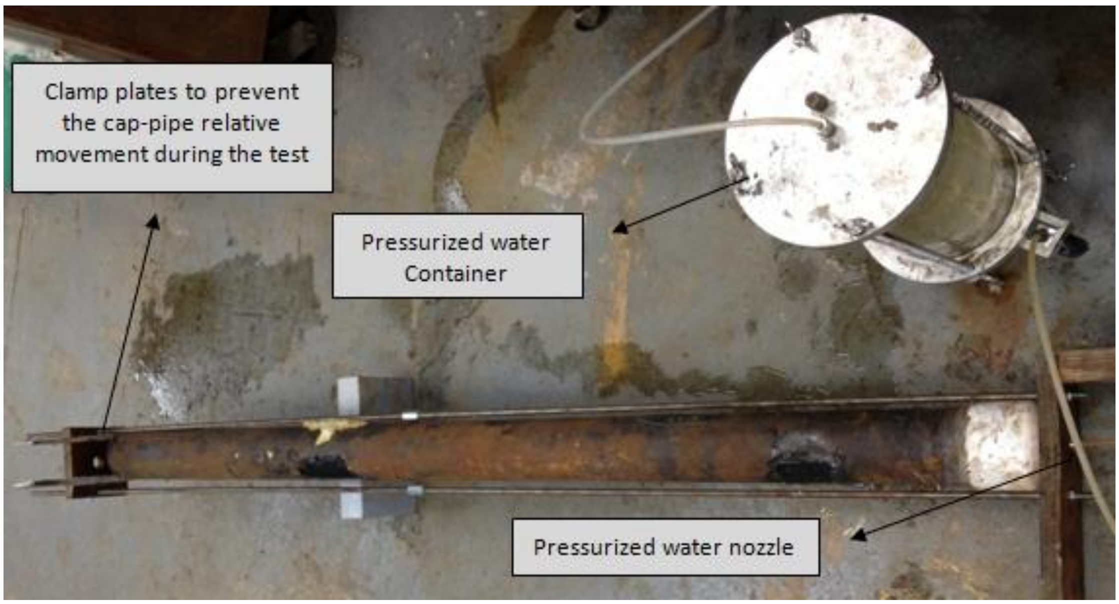


Figure 4.132 Testing setup for grouted pipe for leak.

Case1: Grout-5-Steel Pipe 1

Grout Injection (Primary)-10 ft long

As it already has been mentioned this grout is carried in 2 parts. The amounts of grout injected during each stage are summarized in Table 4.19. Two components were mixed for at least 20 seconds with pace of 80-100 rpm and then we waited for 10 seconds and after that the grout was injected into the pipe.

Table 4.19 Amounts of grout used in various stages of grouting

Stage	1	2	3	4	5	Total
Part B (g)	40	40	52	159	139	430
Part A (g)	40	40	52	159	139	430

Comments on the injection of the grouts are listed below:

Stage 1: Initially 50 grams of grout was injected. Since it did not build up completely, so, another 30 grams was injected at the same location.

Stage 2: At this stage injected the whole amount (80 grams) at once. The grout built was good and blocked the injection point.

Stage 3: This stage was done completely.

Stage 4: The reaction was done completely, but it did not build up completely. So, another complementary injection was done as much as (40g A + 40g B) and when 10% of it was injected it started to foam and the injection could not be proceeded.

Stage 5: For better foam generation the injection was done 10seconds later than the stage 4. Due to late injection the grout started to foam and only 90% of the whole amount of grout was injected.

Permeability/Leak test (after Primary injection)

After that the injection is done, the caps were put on and sealed and after one hour the Pressure test was done and the results are summarized in Figure 4.20.

Table 4.20 Permeability/Leak values of first leak test

Pressure (psi)	**20**	**40**	**60**	**80**	**100**
Time (seconds)	**10**	**10**	**10**	**10**	**10**
Leaking Water (cc)	**29**	**43**	**63**	**90**	**141**
Permeability (10^{-2} cm/sec)	**5.51**	**4.09**	**3.99**	**4.28**	**5.36**

Permeability test (Round 2) 1 days after first permeability test

In order to check the possibility of the shrinkage of the grout in the pipe, it was decided to do another permeability test one day after. The results collected are summarized in Table 4.21.

Table 4.21 Permeability/Leak values of second leak test

Pressure (psi)	**20**	**40**	**60**	**80**	**100**
Time (seconds)	**10**	**10**	**10**	**10**	**10**
LeakingWater (cc)	**22**	**35**	**54**	**79**	**128**
Permeability (10^{-2} cm/sec)	**4.18**	**3.33**	**3.42**	**3.76**	**4.87**

Grout Injection (Secondary) and Permeability test (After Secondary injection)

Now to improve the sealing of pipe we do another series of injections in the same holes. So, we drill the holes and remove the grout from it to provide some space for grout injection. The amounts presented in Table 4.22 were injected in the injection holes, named as stages from 1 to 5. Within 1 hour after the Secondary injection the permeability test was done and results are shown in Table 4.23

Table 4.22 Amounts of injected grout in secondary injection

Stage	**Part A (g)**	**Part B (g)**
1,2,3,4,5	15	15

Table 4.23 Permeability/Leak values after secondary injection

Pressure (psi)	**20**	**40**	**60**	**80**	**100**
Time (seconds)	**10**	**10**	**10**	**10**	**10**
LeakingWater (cc)	**0**	**0**	**16**	**24**	**35**
Permeability (10^{-2} cm/sec)	**0.00**	**0.00**	**1.01**	**1.14**	**1.33**

Observation:

The output cap was removed during the test to see the water flow. Actually the flow was through the interface of grout and the wax and fortunately the flow was not through the interface of wax and the pipe because, as long as the flow is through the interface of wax and grout we can work on it and improve it. However, if it is through the interface of grout and steel pipe we almost have no control over it.

Discussion

As it could be seen in Figure 4., the Discharge has a ascending trend. Also, the test that was done one day after, the discharge has decreased. This is opposite of what we expected to happen. Actually, based on previous observation of Grout-5, we can guess that due to the confined condition some grouts might have remained unreacted and during the permeability test those chemicals were mixed with water and second round foam generation took place. This new round provided more sealing and decreased water flow. On the other hand we can see that after the secondary injection series, great improvement is achieved, in the way that the pipe was sealed up to pressure of 40 psi. Furthermore, the peak discharge decreased to 25% of its initial value which remarkable. Totally based on what has been observed we can say that the more injection stages we have, the better sealing is obtained.

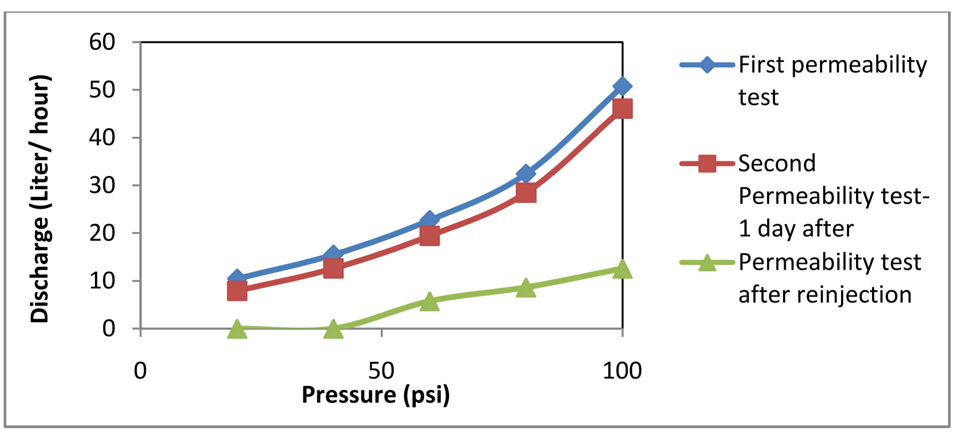


Figure 4.133 Water leaking performance of pipe after different injections with Grout-5

As we can see in Figure 4.133 the permeability of Grout-5 is to some extent dependant on the pressure. However, it does not follow a specific trend and at within the range of 20 to 60 psi it is virtually independent of pressure.

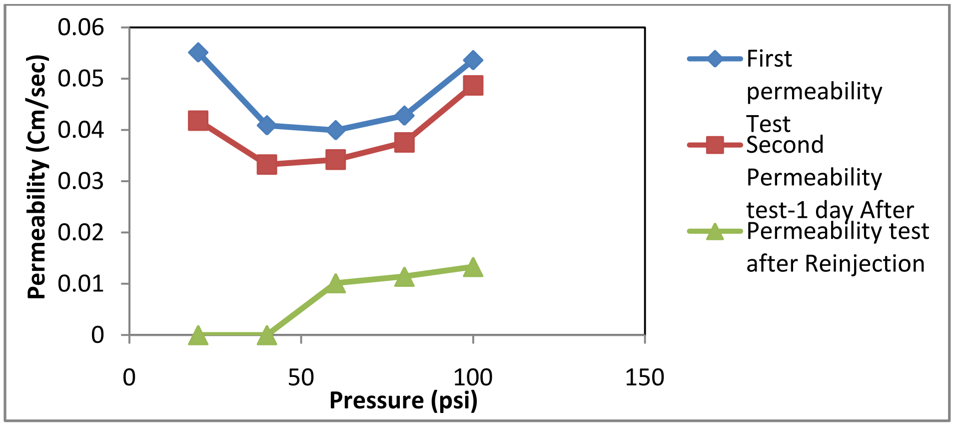


Figure 4.134 Permeability performance of pipe after different injections with Grout-5

Permeability test Crushed and Cut pipes – 5ft long

After doing the first round of permeability tests, it was decided to crush and cut the pipes into half and again do the permeability test on them to see the sealing quality of the half length of the pipe and also investigate the effect of crushing on permeability. Actually the crushing and cutting was done one month after the grouting operation. The Load-Deflection curve obtained during the crushing of pipe is shown in Figure 4.135. As it seen, we can say that at the load around 70 kips the crushing is completed, since the slope of the curve has sudden increase which indicates that the walls of pipe are touching each other and rigidity has sudden increase.

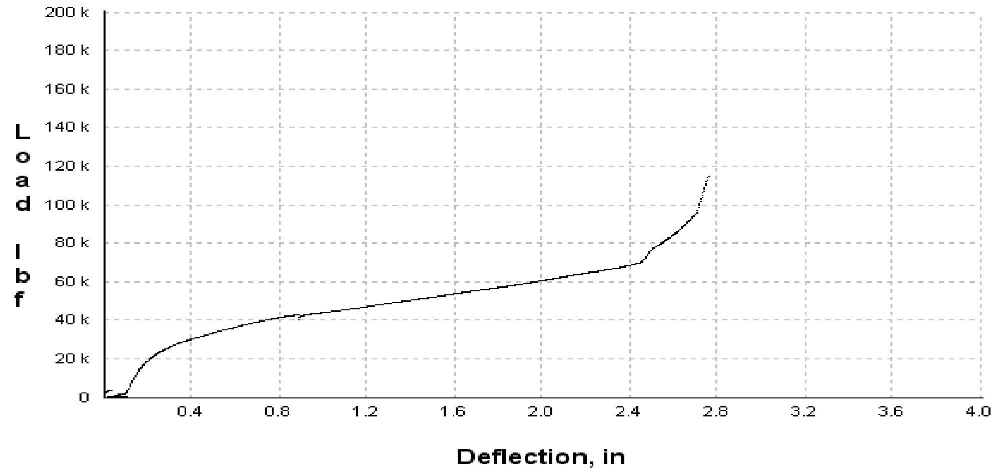


Figure 4.135 Load-Deflection curve of crushing of pipe grouted with Grout-5

After the crushing the pipe was cut into half and permeability test was done them. The results are shown in Table 4.24 for each piece of pipe.

Table 4.24 Permeability/Leak values of crushed 5 feet long pipe grouted with Grout-5

Piece 1					
Pressure (psi)	**20**	**40**	**60**	**80**	**100**
Time (seconds)	**10**	**10**	**10**	**10**	**10**
Leaking Water (cc)	**2.4**	**7.5**	**9.6**	**13.1**	**14.9**
Permeability (10^{-2} cm/sec)	**0.46**	**0.71**	**0.61**	**0.62**	**0.57**
Piece 2					
Pressure (psi)	**20**	**40**	**60**	**80**	**100**
Time (seconds)	**10**	**10**	**10**	**10**	**10**
Leaking Water (cc)	**8.4**	**15.94**	**23.9**	**28.1**	**32.5**
Permeability (10^{-2} cm/sec)	**1.60**	**1.52**	**1.51**	**1.34**	**1.24**

The trend and rate of discharge is shown in Figure 4.136.

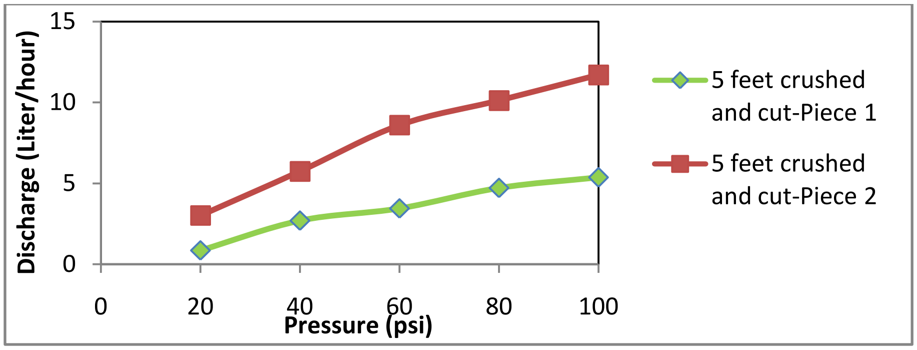


Figure 4.136 Water leaking performance of 5 feet long crushed pipe grouted with Grout-5

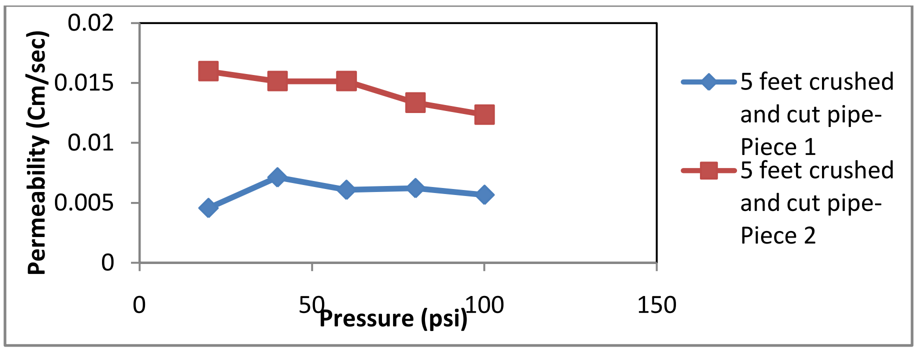


Figure 4.137 Permeability performance of 5 feet long crushed pipe grouted with Grout-5

In Figure 4.137 we can see that by changing the pressure the permeability does not change as much as the discharge rate changes. On the other hand we can see that; when the pressure is increased the permeability slightly decreases

As it seen the performance of two pieces are not similar, so, we can say that the grouting or maybe the section of the pipe in longitudinal direction is not symmetric. However, the promising point here is that the crushing has tremendous effect on permeability so that, in average the discharge decreased as much as 30%. On the other hand this length of pipe is 5 feet and when compared to 10 feet length, the discharge should have increased. We can conclude that this crushing compensated the decreased length of grouting and also provided even more sealing for us.

Summary

Generally in 10 feet long pipe testing when the pressure increased both the discharge and permeability increases, However the Discharge increases with higher rate than the Permeability. Moreover, in crushed 5 feet long pipes it was observed that; by increasing the pressure although the discharge increased but, the permeability showed a descending trend. In 10 feet long pipe after Secondary injection the discharge was decreased up to 12 (Liter/Hour) at 100 psi.

Case2: Grout-5-Steel Pipe 2

Grout Injection (Primary)

As it already has been mentioned this grout is carried in 2 parts. In Figure 4.21 the amounts of grout injected during each stage are presented. Two components were mixed for 20 seconds with pace of 80-100 rpm and then we waited for 10 seconds and after that the grout was injected.

Table 4.25 Amounts of grout used in various stages of grouting of pipe-2 with Grout-5

Stage	1	2	3	4	5	Total
Part B (g)	50	90	80	185	110	515
Part A (g)	50	90	80	185	110	515

Notes during Injection

Stage 1: Built up completely and visually good sealing provided.

Stage 2: At one of the ends we did not have enough wax for a length of 8 inches so we had a larger volume to fill with grout and we increased the amount of grout and we injected (70 +70) instead of (50+50). Although we injected more grout, but it did not build up completely and we had to add more injection at the same hole. So we injected (20g A+20g B) grout and then the pipe was sealed at the desired length.

Stage 3) Injection was done completely.

Stage 4) Injection was done completely.

Stage 5) The foam generated during the stage 3 grouting occupied the space in the pipe more than what was expected. So, the expected available volume for stage 5 injection was less and we could not completely inject the whole amount. So, only 60% of mixed grout was injected.

Permeability test (after Primary injection)

After that the injection is done, the caps were put on and sealed and after one hour the permeability test was done and the results are shown in Table 4.26 In order to check the possibility of the shrinkage of the grout in the pipe, it was decided to do another permeability test one day after. The results collected are brought in Table 4.26.

Table 4.26 Permeability/Leak values of pipe-2 grouted with Grout-5 after primary injection

Permeability test (after Primary injection)					
Pressure (psi)	20	40	60	80	100
Time (seconds)	10	10	10	10	10
Leaking Water (cc)	0	0	24	39	56
Permeability (10^{-2} cm/sec)	0.00	0.00	1.52	1.85	2.13
Permeability test (Round 2) 1 days after first permeability test					
Pressure (psi)	20	40	60	80	100
Time (seconds)	10	10	10	10	10
Leaking Water (cc)	0	0	20	24	30
Permeability (10^{-2} cm/sec)	0.00	0.00	1.27	1.14	1.14

As it is seen, the flow rate decrease which proves the improvement of sealing. Here we can make one guess that; there might be some unreacted grout remaining in the pipe and during permeability test, since they were mixed with water and started to react again and the generated foam has filled the remaining voids.

Grout Injection (Secondary) and Permeability test (After Secondary injection)

Now to improve the sealing of pipe we do another series of injections in the same holes. So, we drill the holes and remove the grout from it to provide some space for grout injection. The amounts shown in Table 4.27 were injected in injection holes of Primary injection part, named as stages from 1 to 5.Within 1 hour after completion of injection the permeability test was done and the results are shown in Table 4.28.

Table 4.27 Amounts of injected grout during secondary injection of pipe-2 with Grout-5

Stage	1	2	3	4	5	Total
Part A (g)	12	14	16	12	14	68
Part B (g)	12	14	16	12	14	68

Table 4.28 Permeability/ Leak values of pipe-2 after secondary injection with Grout-5

Pressure (psi)	**20**	**40**	**60**	**80**	**100**
Time (seconds)	**10**	**10**	**10**	**10**	**10**
Leaking Water (cc)	**0**	**0**	**12**	**12**	**16**
Permeability (10^{-2} cm/sec)	**0.00**	**0.00**	**0.76**	**0.57**	**0.61**

As it is shown in Figure 4.138, in all the tests the pipe was sealed up to pressure of 40 psi. On the other hand during the second round, we see that the permeability has noticeable improvement. This improvement is more remarkable in comparison to the same change in (Case-1). Here again we can speculate that ;since we have more grout injected compared to (Case-1) more amount of grout is remained unreacted and during the permeability test and mixing of this chemicals with water more foam is generated in proportion to corresponding condition in (Case-1),So, more improvement is observed.

Also, the secondary injection has provided tremendous sealing, so that, the discharge decreased as much as 50%.

As it could be seen in Figure 4.139 the permeability is during the tests after 1 day and also after Secondary injection stabilizes. From 60 to 100 psi it could be concluded that permeability is virtually independent from pressure.

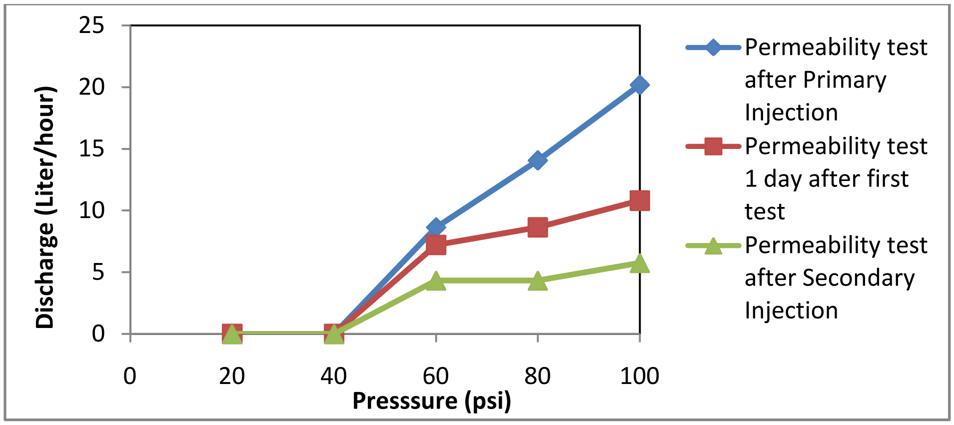


Figure 4.138 Water leaking performance of pipe after different injections with Grout-5

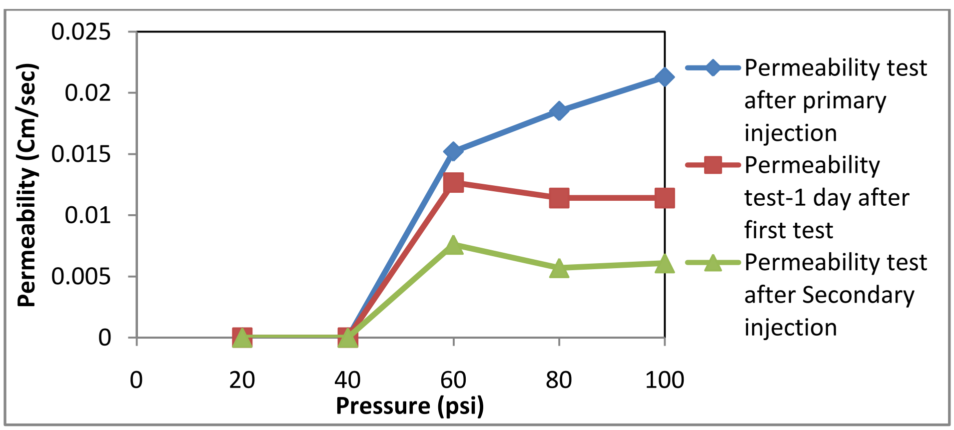


Figure 4.139 Permeability performance of pipe after different injections with Grout-5

Permeability test on Cut pipes – 5ft long

After the permeability test on 10 feet pipes it was aimed to check the performance of the half length of the pipe. Also, we interested to see whether the grouting was symmetric or not. On the other hand, the pipes was cut into half one month after the grouting process. So, the effect of long-term shrinkage could be to some extent investigated. The obtained results from the test for each piece of pipe are shown in Table 4.29. The trend and the discharge curve is presented in Figure 4.140. We can see from the graph that the two pieces did not perform similarly, so, the grouting and the performance was not symmetric. Moreover, although the grouted and tested length is decreased to half, the discharge increased 5 times more in average. This magnifies the effect of the length of grouting in the way that if we double the length of grouting in the field we will be able to have 5 times less water discharge.

Table 4.29 Permeability/leak values of 5 feet long cut pipes grouted with Grout-5

Piece 1					
Pressure (psi)	**20**	**40**	**60**	**80**	**100**
Time (seconds)	**10**	**10**	**10**	**10**	**10**
Leaking Water (cc)	**16.5**	**35.7**	**57.1**	**75.2**	**101.3**
Permeability (10^{-2} cm/sec)	**3.14**	**3.39**	**3.62**	**3.57**	**3.85**
Piece 2					
Pressure (psi)	**20**	**40**	**60**	**80**	**100**
Time (seconds)	**10**	**10**	**10**	**10**	**10**
Leaking Water (cc)	**3.6**	**10.2**	**18.4**	**27.3**	**43.2**
Permeability (10^{-2} cm/sec)	**0.68**	**0.97**	**1.17**	**1.30**	**1.64**

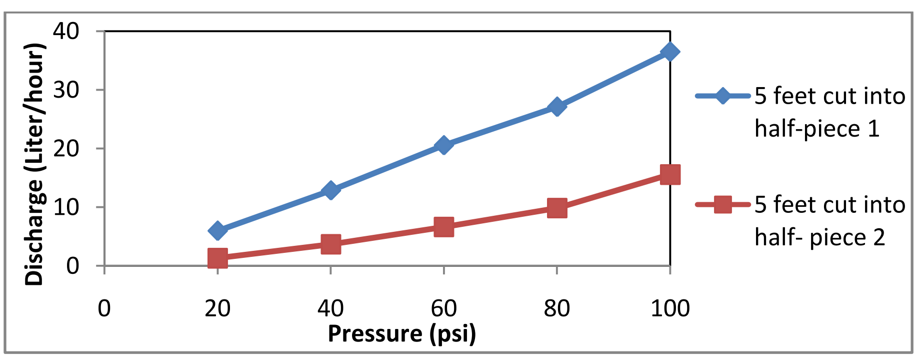


Figure 4.140 Water leaking performance of 5 feet long cut pipes grouted with Grout-5

In Figure 4.141 it is seen that the permeability has a slight increasing trend and from 20 to 100 psi the permeability increases as much as 25% of the initial value at 20 psi.

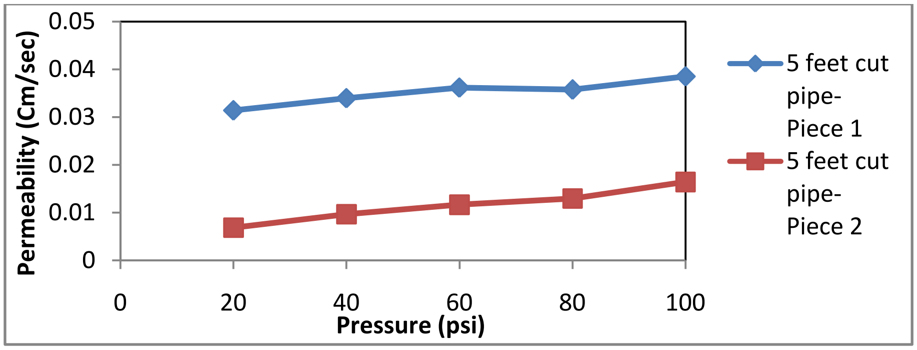


Figure 4.141 Permeability performance of 5 feet long cut pipes grouted with Grout-5

Summary

This pipe that was grouted with Grout-5 was sealed up to 40 psi. But during the second test the discharge decreased. On the other hand the Secondary injection did not have the tremendous effect in discharge the same as case-1 however, it decreased the permeability. In the case that the pipe was cut into half and then was tested for water leaking, it was observed that two pieces did not perform similarly and we can say that its foaming was not symmetric along the pipe.

Case 3: Grout-1-Steel Pipe-3

Primary Injection and Permeability Test

As it was mentioned, this grout is made of three parts. Grout-1 is base chemical, another component is carried as the catalyst and the water is added as the initiator. These components were mixed and blended for 20 seconds with speed of 80-100 rpm and then was injected. This grout is rather faster than Grout-5 so should be injected faster. The amount that was injected at each stage is brought in Table 4.30.

Table 4.30 Amount of injected grout during primary injection of pipe-3 with Grout-1

Stage	1	2	3	4	5	Total
Part-1 (g)	30	30	60	180	180	480
Part-2 (g)	1.2	1.2	3	9	9	23.4
Water (g)	0.8	0.8	1.6	4.8	4.8	12.8
Remarks	15% wasted	5% Wasted	-	15% Wasted	-	-

Notes during Injection

Stage 1: Grout built up completely and 15% could not be injected.

Stage 2: Grout built up completely and 5% could not be injected.

Stage 3: The stage was done completely.

Stage 4: The injection was delayed a little to aerate the grout, so, the grout started to foam and 15% of it could not be injected.

Stage 5: Done completely.

The selected amount to be injected is 1.25 times more than the grout that was injected in 1.25 inch diameter PVC pipes.

Permeability Test

After that the injection is done, the caps were put on and sealed and after one hour the permeability test was done and the results are shown in Table 4.31 In order to check the possibility of the shrinkage of the grout in the pipe, it was decided to do another permeability test one day after. The results collected are summarized in Table 4.31

Table 4.31 Permeability/Leak values after primary grouting of steel pipe-3 with Grout-1

Permeability test (after Primary injection)					
Pressure (psi)	**20**	**40**	**60**	**80**	**100**
Time (seconds)	**10**	**10**	**10**	**10**	**10**
Leaking Water (cc)	**0**	**0**	**10**	**13.5**	**20**
Permeability (10^{-2} cm/sec)	**0.000**	**0.000**	**0.634**	**0.642**	**0.761**
Permeability test (Round 2) 1 days after first permeability test					
Pressure (psi)	**20**	**40**	**60**	**80**	**100**
Time (seconds)	**10**	**10**	**10**	**10**	**10**
Leaking Water (cc)	**0**	**0**	**11.2**	**14.8**	**21.7**
Permeability (10^{-2} cm/sec)	**0.000**	**0.000**	**0.710**	**0.703**	**0.825**

Grout Injection (Secondary) and Permeability test (After Secondary injection)

Now to improve the sealing of pipe we do another series of injections in the same holes. So, we drill the holes and remove the grout from it to provide some space for grout injection. The following amounts were injected in the holes, named as stages from 1 to 5. The amounts of injected grout are shown in Table 4.32. Also, within one hour after the injection the permeability test was done and the obtained results are summarized in Table 4.33.

Table 4.32 Amounts injected during secondary injection of pipe-3 with Grout-1

Stage	1	2	3	4	5	Total
Part-1 (g)	30	30	30	30	30	150
Part-2 (g)	1.5	1.5	1.5	1.5	1.5	7.5
Water (g)	0.8	0.8	0.8	0.8	0.8	4.0
Remarks	20% wasted	40% Wasted	20% wasted	10% Wasted	50% wasted	-

Table 4.33 Permeability/Leak values after secondary injection of pipe-3 with Grout-1

Pressure (psi)	**20**	**40**	**60**	**80**	**100**
Time (seconds)	**10**	**10**	**10**	**10**	**10**
Leaking Water (cc)	**0**	**0**	**7**	**10**	**12**
Permeability (10^{-2} cm/sec)	**0.000**	**0.000**	**0.444**	**0.475**	**0.456**

As it could be seen in Figure 4.142 during the second round of permeability test the discharge increased, which indicates the shrinkage in the grout. Grout-1 has already shown shrinkage potential that is consistent with current observation. On the other hand, the performance of this grout in comparison with Grout-5 is much better and again this pipe is also sealed up to the pressure of 40 psi. In this case we also can see that the secondary injection improved the sealing and decreased the discharge as much as 40% which is also promising.

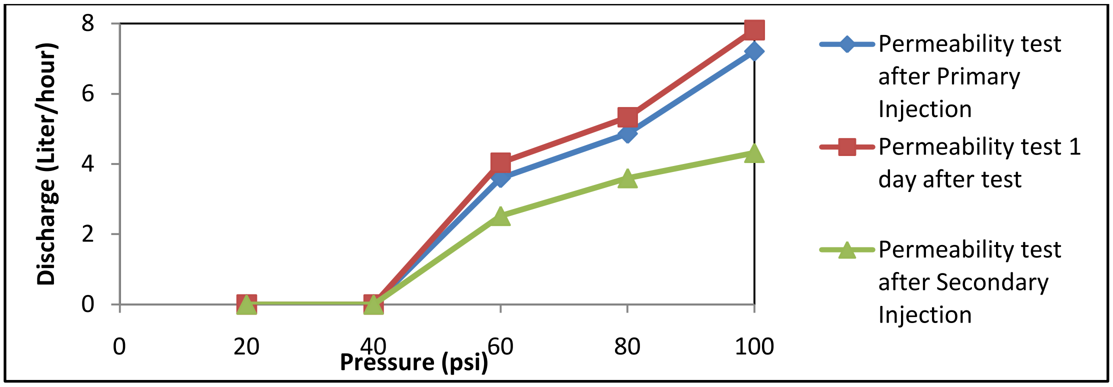


Figure 4.142 Water leak performance of pipe-3 after different injections with Grout-1

As we see in Figure 4.142 after the flow starts, the permeability becomes less sensitive against the pressure change. Furthermore, after the Secondary injection the Permeability turns to be almost independent of Pressure.

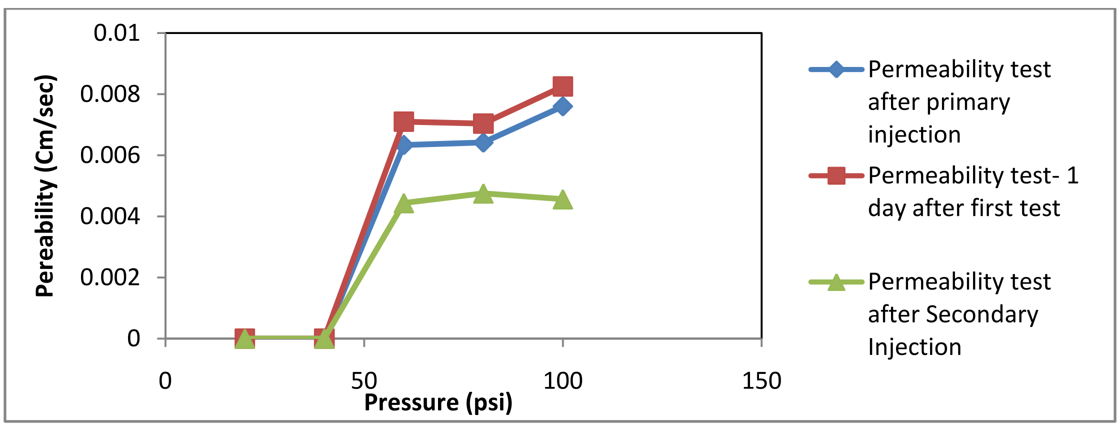


Figure 4.143 Permeability performance of pipe-3 after different injections with Grout-1

Permeability test on Crushed and Cut pipes – 5ft long

After doing the first round of permeability tests, it was decided to crush and cut the pipes into half and again do the permeability test on them to see the sealing quality of the half length of the pipe and also investigate the effect of crushing on permeability. Actually the crushing and cutting was done one month after the grouting operation. The Load-Deflection curve obtained during the crushing of pipe is shown in Figure 4.144. As it seen, we can say that at the load around 65 kips the crushing is completed, since the slope of the curve has sudden increase which indicates that the walls of pipe are touching each other and rigidity has sudden increase. The crushing and cutting was done one month after the grouting process and after cutting the pipes were tested for permeability and the results are shown in Table 4.34. As it could be seen in Figure 4.145 the two piece performed almost similarly. So, we can say that the Grout-1 has good symmetric performance. On the other hand the rate of discharge is remarkably low although these are 5 feet long pipes. So, we can say that the crushing has very good effect on decreasing the permeability so that with half grouted length we have half 50% less discharge compared to 10 feet steel pipes.

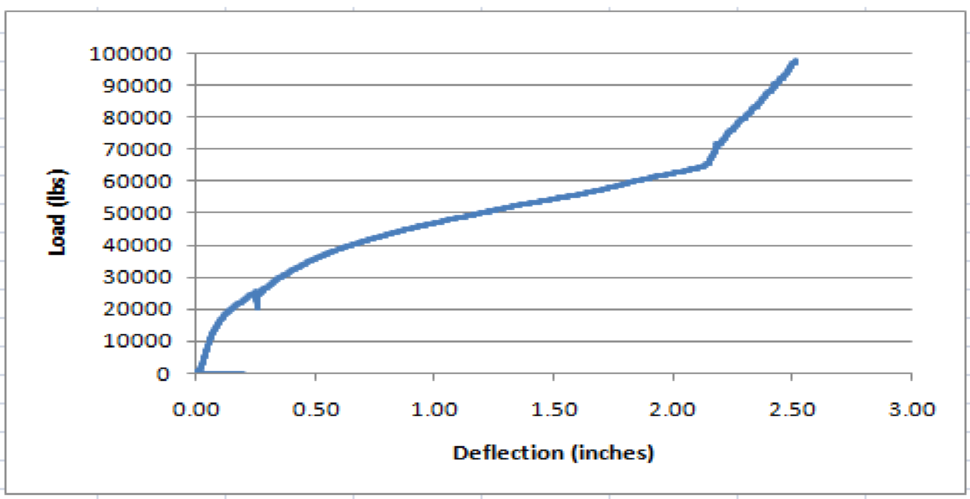


Figure 4.144 Load-Deflection curve of crushing of pipe-3

Table 4.34 Permeability/Leak values of 5 feet long crushed pipe grouted with Grout-1

Piece 1					
Pressure (psi)	**20**	**40**	**60**	**80**	**100**
Time (seconds)	**10**	**10**	**10**	**10**	**10**
Leaking Water (cc)	**1.6**	**2.6**	**3.3**	**3.9**	**5.9**
Permeability (10^{-2} cm/sec)	**0.304**	**0.247**	**0.209**	**0.185**	**0.224**
Piece 2					
Pressure (psi)	**20**	**40**	**60**	**80**	**100**
Time (seconds)	**10**	**10**	**10**	**10**	**10**
Leaking Water (cc)	**0**	**0.8**	**3.3**	**4.7**	**5.8**
Permeability (10^{-2} cm/sec)	**0.000**	**0.076**	**0.209**	**0.223**	**0.221**

In Figure 4.146 it is seen that as the pressure is increased the permeability starts to converge for both pieces of pipe. The point is that from 60 psi it could confirmatively said that the permeability becomes independent of Pressure.

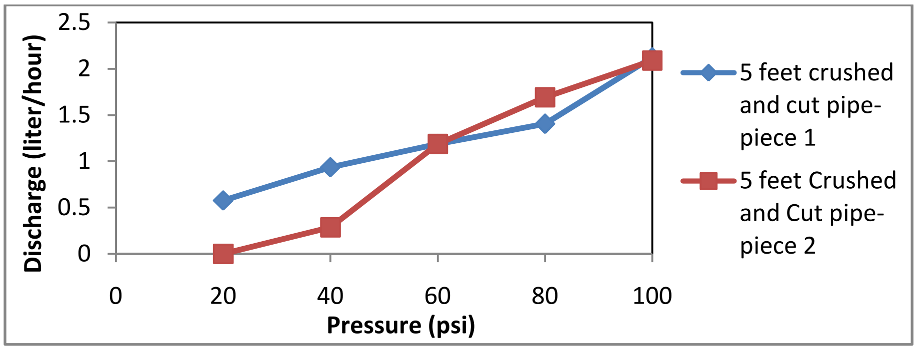


Figure 4.145 Water leaking test of 5 feet long crushed and cut pipes grouted with Grout-1

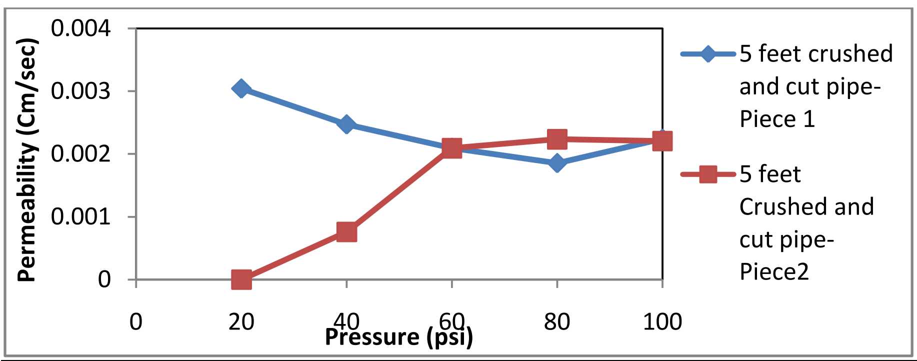


Figure 4.146 Permeability test of 5 feet long crushed and cut pipes grouted with Grout-1

Summary

Overall, this pipe that was grouted with Grout-1 has a very good and acceptable performance. Moreover, it was observed that at high pressures such as 60 psi and more the permeability in most of cases becomes virtually independent of pressure. Furthermore, as the performance of each 5 feet long piece of pipe was studied it was seem the performance were acceptably similar that confirms the good symmetric performance of the grout. The best performance was obtained after the secondary injection and the final discharge was about 4 liter/hour. On the other hand the crushing had a remarkable effect on the discharge and for 5 feet long pipe the discharge of 2 liter/hour was achieved.

Case4: Grout-1-Steel Pipe 4

Primary Injection and Permeability Test

The selected amount of grout for this pipe is 1.5 times the total amount injected in the (Case 3). When compared to the amount injected in the 10ft long 1.25 inch diameter PVC pipes, it is 1.875 times the total injected amount. The injected amounts are summarized in Table 4.35.

Table 4.35 Amounts of injected Grout-1 during primary injection of pipe-4

Stage	1	2	3	4	5	Total
Part-1(g)	45	45	90	270	270	720
Part-2(g)	2.25	2.25	4.5	13.5	13.5	36
Water (g)	1.2	1.2	2.4	7.2	7.2	19.2
Remarks	-	-	-	-	15% wasted	-

Notes during Injection

Stage 1, 2, 3 and 4: The injection was done completely and enough grout was built up.

Stage 5: Built up completely, but 85% could be injected.

After the injection the capes were installed and permeability test was done. The results are presented in Table 4.36. Also another test was done one day after to see the effect of short-term shrinkage and the results are brought in Table 4.36.

Table 4.36 Permeability/Leak values after primary grout injection pipe-4 with Grout-1

Permeability test (after Primary injection)						
Pressure (psi)	**20**	**40**	**60**	**80**	**100**	**120**
Time (seconds)	**10**	**10**	**10**	**10**	**10**	**10**
Leaking Water (cc)	**0**	**0**	**0**	**0**	**0**	**11**
Permeability (10^{-2} cm/sec)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.349**

Table 4.36 Permeability/Leak values after primary grout injection pipe-4 with Grout-1 (continued)

Permeability test (Round 2) 1 day after first permeability test						
Pressure (psi)	20	40	60	80	100	120
Time (seconds)	10	10	10	10	10	10
Leaking Water (cc)	0	0	0	0	0	11.9
Permeability (10^{-2} cm/sec)	0.000	0.000	0.000	0.000	0.000	0.377

As it is seen in Figure 4.147 the pipe is sealed completely up to 100 psi. However we increased the pressure up to 120 psi to see how far the pipe is sealed. At the pressure of around 113 psi some crushing sound was heard that might be attributed to the failure of the bond of the grout to the wax that led to the loss of interface and the flow started at a very low rate. Also, we can see that at the test one day after injection the pipe showed very similar performance which verifies the good performance of this grout.

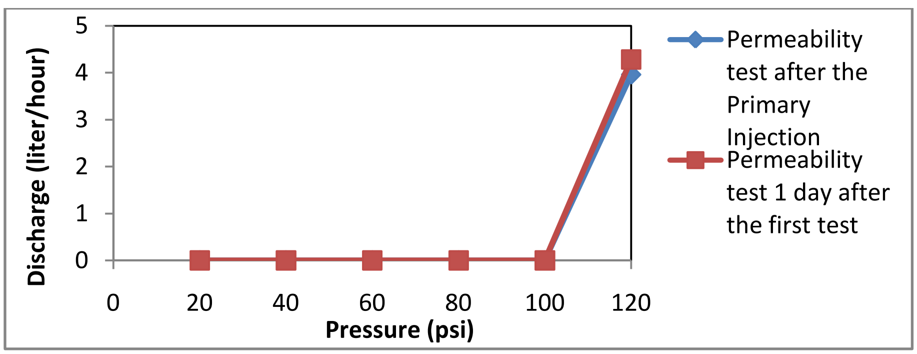


Figure 4.147 Water Leaking test performance of pipe-4 grouted with Grout-1

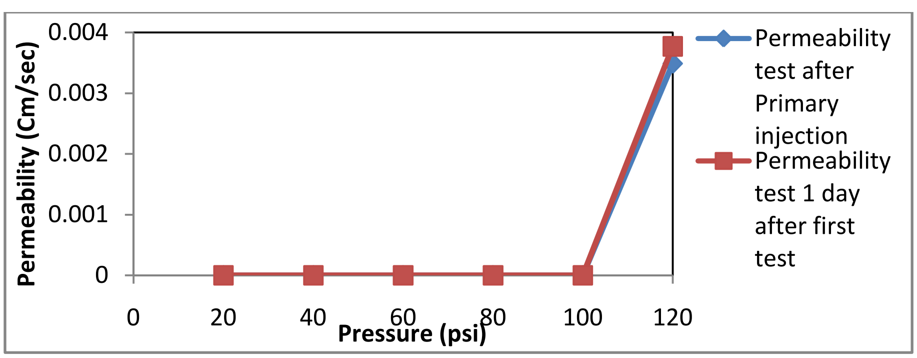


Figure 4.148 Permeability test performance of pipe-4 grouted with Grout-1

Permeability test on Cut pipes – 5ft long

Since this grout could completely seal the pipe, it was decided to check that whether half length of the pipe is sealed or not. Therefore, the pipe was cut into half and the permeability test was done on each piece. This round on permeability was done 1 month after in order to check the long-term shrinkage potentiality of the grout. The results of the permeability test are brought in Table 4.37.

Table 4.37 Permeability/Leak values after primary grouting of pipe-4 with Grout-1

Piece 1					
Pressure (psi)	**20**	**40**	**60**	**80**	**100**
Time (seconds)	**10**	**10**	**10**	**10**	**10**
Leaking Water (cc)	**0**	**3**	**8**	**14**	**20**
Permeability (10^{-2} cm/sec)	**0.000**	**0.285**	**0.507**	**0.665**	**0.761**
Piece 2					
Pressure (psi)	**20**	**40**	**60**	**80**	**100**
Time (seconds)	**10**	**10**	**10**	**10**	**10**
Leaking Water (cc)	**0**	**6.8**	**9.8**	**14.8**	**16.9**
Permeability (10^{-2} cm/sec)	**0.000**	**0.646**	**0.621**	**0.703**	**0.643**

Based on Figure 4.149 we can say that the two pieces performed similarly. Also, peak discharge is to some extent acceptable when compared with discharge rate of 10 feet pipe of (Case-3). We can guess that if the pipe of (Case-4) is crushed before cutting the 5 feet piece has the potential of being fully sealed.

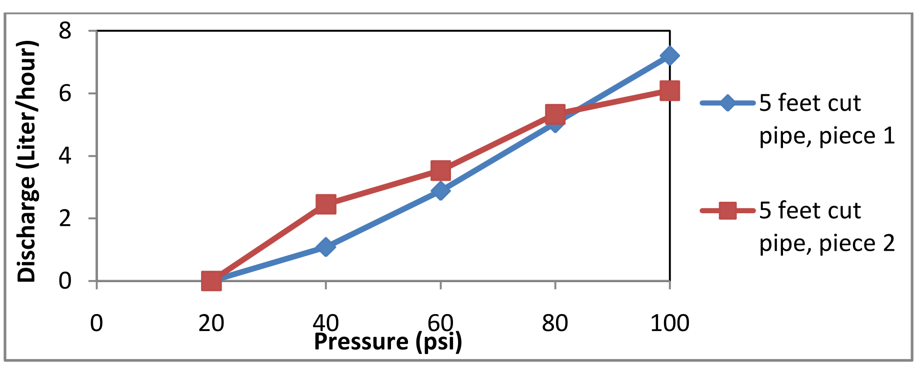


Figure 4.149 Water leaking test of each 5 feet long piece of cut pipe grouted with Grout-1

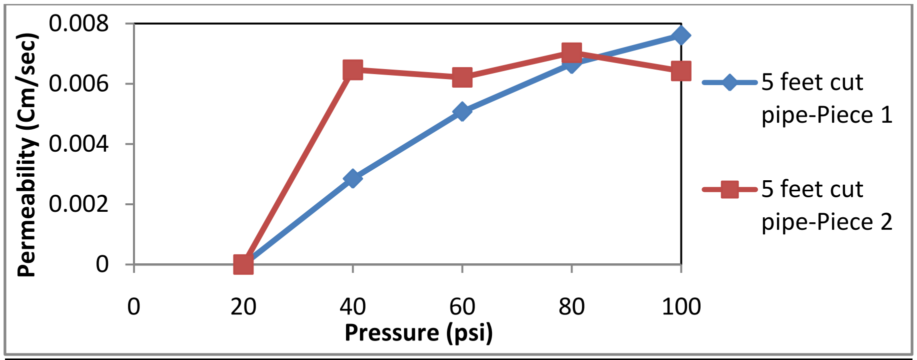


Figure 4.150 Permeability test of each 5 feet long piece of cut pipes grouted with Grout-1

As it is seen in Figure 4.150 the permeability is dependent on the pressure, however, from 80 to 100 psi the curves start to be flattened which gives the hint that the in high pressures the permeability gradually becomes independent of pressure.

4.4) Summary and Conclusion

In the case the complete sealing condition of the pipe at pressure of 100 psi was obtained. The test was run for 1 hour and the sealing condition was confirmed for one hour, however once we tried the 120 psi, the flow gradually started. In either cases of 10 feet or 5 feet cut pipe the permeability factor was dependant on the pressure in the way that as the pressure increased the permeability also increased.

Totally, after completion of all the tests we can come to the following conclusions:

1) Grout-5 is sensitive against air and if it is injected more than the optimized amount some percentage of that will remain unreacted.

2) Grout-1 has a more steady and uniform reaction in the way throughout the pipe it is generated uniformly.

3) Grout-5 has no shrinkage effect but also it has some improvements after the permeability test.

4) Grout-1 has very little shrinkage which could be neglected.

5) Only the Grout-1 could seal the pipe up to pressure of 100 psi.

6) In none of 5 feet long crushed pipes we could have complete sealing.

7) The crushing has tremendous effect on decreasing the discharge of water in the way that in one case the discharge decreased 5 times less.

8) During the secondary stage injection, although relatively little amount of grout was injected, but remarkable improvements in the permeability were obtained in all the cases.

9) In the case that we tested the 5 feet long cut pipes, those grouted with Grout-1 showed mostly performance and both half pieces have close performance. However, those grouted with Grout-5 did not exhibit symmetric performance and two half piece did not perform similarly.

Overall, we can conclude that Grout-1 is the best option regarding the steady and uniform performance and also resistance against shrinkage and strong sealing properties. On the other hand, in the case that the crushing is possible, it is highly recommended since it has tremendous effect on decreasing the permeability of grouted section.

CHAPTER 5

MODELING

In this chapter, a model for uni-axial pressure development in polyurethane grout during the curing was studied. The model was developed by Sunder and Vipulanandan, (2012) and basically it was applied for a hydrophilic PU grout. In this chapter a comparison is made between the experimental results and the model prediction. The results of the curing monitoring of four grouts are compared using this model. However, three of these grouts were hydrophobic and one was hydrophilic grout. Furthermore, parametric study was done on this model and effect of each parameter on the output of this model and its trend was studied.

5.1) Modeling the uni-axial pressure

As shown in Figure.5.1 shows the setup was used to measure the uniaxial stress developed and the variation in temperature with time during grout setting. Also, the thermocouple is inserted inside the cylindrical mold to capture the variation in temperature during the polymerization. Similarly a load cell is placed over the top cap of the mold which is used to capture the increase in the stress developed during the expansion of the grout.

The apparatus is set and sealed as soon as the grout components are poured and have been hand mixed. Care is taken to ensure that there was minimum leak of the expanding grout during the polymerization.

The polyurethane grouts expand during curing. This expansion is a critical issue as the stress associated with the expansion grout is extremely high and also change rapidly. Some polyurethane grouts expand more than 30 times their original volume;

however the rate and amount of expansion will be influenced by the grout constituents and the confined conditions in the field. The current model takes into account the gas production and hardening of the grout during the curing process.

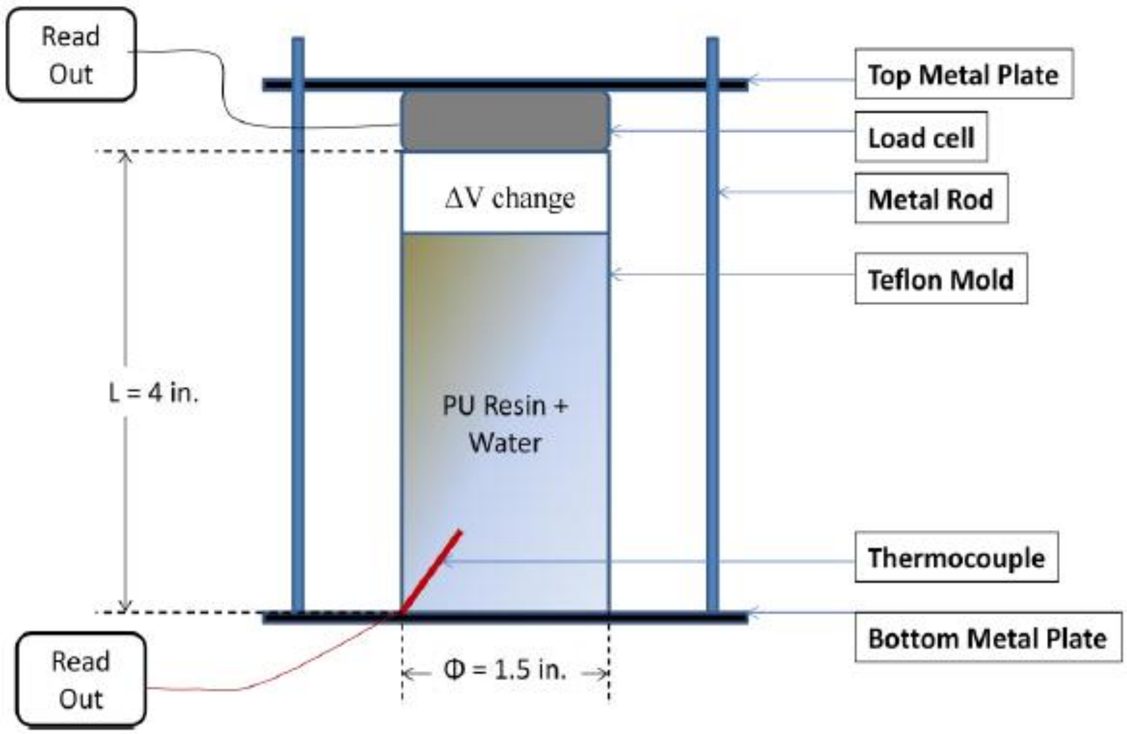


Figure 5.1 Experimental setup to determine the uniaxial expansion stress and the temperature variation

5.1.1) Model Development

The model has been developed to represent the curing of expansion of polyurethane grout. During the curing of grout mix, it expands and the chemical reaction produces gas and heat.

Figure 5-2 shows the physical model that describes the confined expansion (uniaxial) of the polyurethane grout. The expanding porous solid is a mixture of voids along with the strengthening semi-solid gel (grout). The shell represents the strengthening of the grout with time. The voids (bubbles) formed in the porous solid due to the evolution of carbon di oxide (CO_2) gas as a result of polymerization is lumped into a single void which is indicated in figure 5-2. P_T is the uniaxial pressure exerted by the curing grout under confined conditions. With time the grout will gain strength $\sigma_s(t)$ – tensile strength of the grout which increases with respect to time because of gelling of the grout till the uniaxial pressure (P_T) attains peak and the $P_g(t)$ which is attributed to the gas pressure. The increase in gas pressure is because of the gas produced during the polymerization reaction. It must be noted that the temperature also will influence the P_T.

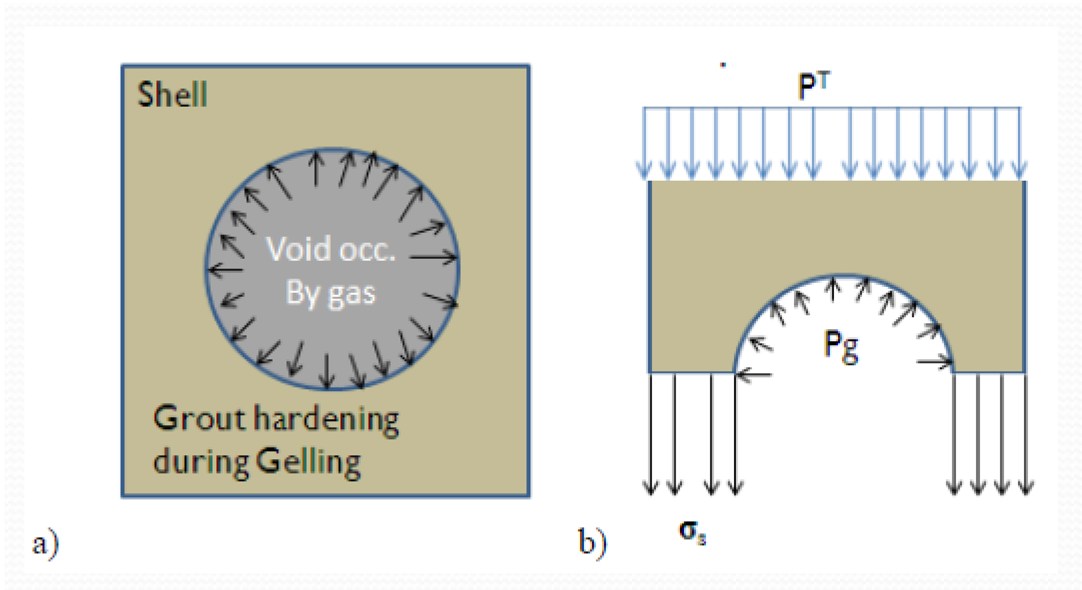


Figure 5.2 (a) Lumped model of porous solid, b) equilibrium condition of the lumped model.

5.1.2 Governing Equations and Assumptions

Groverning equations: In order to capture the uniaxial stress development during the curing of polyurethane grout, following governing equations were used,

1) Exothermic Chemical Reaction:

$$X + Y + (Z) \rightarrow CO_2 + PU + Heat\ , \qquad (5.1)$$

where, X and Y are the grout components and Z is the water, It is an exothermic chemical reaction which attributes to the increase in the temperature of the grout during its phase transformation.

2) Total uniaxial stress developed is a function of time dependent pressure applied due to gas formation and grout strengthening

$$P_T(t) = f(P_g(t), \sigma_s(t)), \quad (5.2)$$

where, P_T = total uniaxial pressure developed by the curing grout,

P_g= Pressure developed by the gas formation in the void

σ_s = tensile strength of curing PU.

3) Modified ideal Gas law equation for gas,

$$P.V = n.R.T. \quad (5\text{-}3)$$

In the case of grout hardening,

$P = P_g(t)$ which is pressure exerted by the gas trapped in the void.

$N = n_g(t)$ which is number of moles of the gas produced during the chemical reaction

T – T(t) which is change in the temperature with time during the setting of the grout.

Therefore,

$$p_{gas}(t) = (n_g(t)/V). R. T(t). \quad (5\text{-}4)$$

This gives,

$$p_{gas}(t) = M(t).R.T(t), \quad (5\text{-}5)$$

where, R = universal gas constant = 8.314 J/K/mol and

$$M(t) = n_g(t)/V \text{ moles/m}^3. \quad (5\text{-}6)$$

Assumptions:

The following are the assumptions considered in developing this model:

1) The produced CO_2 obeys the ideal gas law equation and M(t) represent the mass of CO_2 produced per unit volume of the gas.

2) The tensile strength of the curing grout increases with time during the process of setting of the grout.

5.1.3 Modeling Procedure

Consider a system of curing grout (semi liquid and gas phase) where gas is formed in the voids while grout is gelling. (lumped system shown in Figure 5-1).

Considering the equilibrium condition,

$$p_T(t).A_T = p_{gas}(t).A_g - \sigma_s(t).A_s\,, \qquad (5\text{-}7)$$

where,

A_T = total cross-sectional area of the lumped system,

A_g = area occupied the gas occupied lumped void,

A_s = area occupied by the shell (curing grout).

So,

$$A_T = A_g + A_s, \qquad (5\text{-}8)$$

dividing (Eqn.5-7) by the total area, A_T, we get,

$$p_T(t) = p_{gas}(t)(A_g/A_T) - \sigma_s(t).(1-(A_g/A_T)). \qquad (5\text{-}9)$$

Substituting $A_g/A_T = \alpha$, which is defined as the area ratio,

$$p_T(t) = p_{gas}(t).\ \alpha - \sigma_s(t).(1-\alpha). \qquad (5\text{-}10)$$

Gas Production

From Equation 5-5 and 5-6,

$$p_{gas}(t) = M(t).R.T(t), \qquad (5\text{-}5)$$

where,

$$M(t) = n_{gas}(t)/V \text{ moles/m}^3. \qquad (5\text{-}6)$$

The pressure exerted by the gas production during the chemical reaction on the strengthening grout can be represented as shown in equation 6-5. It is important to note that, M(t) and T(t) are variables which are time dependent and needs to be modeled. Bikard et al. (2007) studied the polymerization reaction of a two component polyurethane chemical. On investigating the expansion of the grout during setting, it was found that, the evolution of gas was following the exponential decay path. It is to be noted that, the main factor that contributes to the variation of $p_{gas}(t)$ with respect to time is the production of CO_2 during the chemical reaction and hence it was observed that $P_g(t)$ follows an exponential decay path also. The rate of production of gas in this model is represented as follows,

$$\frac{dM}{dt} = B.(t) + C.D.e^{-Dt} , \quad (5\text{-}11)$$

where, t = time B, C and D are the model parameters which are related to the production of CO_2 that impacts in the exponential increase of $p_{gas}(t)$. From (Eqn.5-11), the mass of gas produced M(t) varying with respect to time as follows,

$$M(t) = B(t-t_0)+C.e^{-Dt0} (1-e^{-D(t-t0)}), \quad (5\text{-}12)$$

where, t_0 = initial time used for mixing the grout component.

Temperature Variation

Mattey (2001) proposed the Temperature model to predict the variation of the temperature of the polyurethane grout material during the process of gelling. Where (Eqn.5-13) gives the time temperature relationship of polyurethane grout,

$$T = Tr + Tc(t/tc)/[q + (1-p-q)(t/tc) + p(t/tc)\hat{}((p+q)/p)] \quad (5\text{-}13)$$

Where p and q are the material parameters to be determined, T_r is the initial grout mix temperature, T_c is the peak temperature during the chemical reaction and t_c is the time corresponding to the peak temperature. The parameter q is the ratio between the secant and the initial tangent moduli. Parameter p is obtained by minimizing the error to predict the time-temperature relationship. It is to be noted that q varies between 0 and 1 and $(p+q)/p \geq 0$.

Substituting (Eqn.5-13) and (Eqn.5-12) for T(t), and M(t) in (Eqn.5-5), following relationship is obtained:

$$P_g(t) = B(t-t_0)+C.e^{-Dt_0}(1-e^{-D(t-t_0)}).R.$$

$$. \quad Tr + Tc(t/tc)/[q+(1-p-q)(t/tc)+p(t/tc)^\wedge((p+q)/p)] \quad . \qquad (5\text{-}14)$$

Grout Strengthening Phase

In addition to the pressure exerted by the gas which results in the expansion of the grout, there is also an opposing force which is the tensile force of the grout due to strengthening of the grout mix during its transformation from liquid to solid resulting because of the polymerization. It is assumed that this increase in tensile strength of the grout from zero and reaches the maximum value when the M(t) reaches a constant value indicating the completion of the chemical reaction. This increase is considered to be at an exponential rate in this study which can be represented as follows,

$$\sigma_s(t) = \sigma_{so}(1-e^{-F(t)}) \quad . \qquad (5\text{-}15)$$

5.1.4 Confined Expansion Model

Thus combining the equations, 5-14 and 5-15 and substituting it in equation 5-10 we get,

$$P_T(T) = [[B(t-to) + C.e^{-Dto}(1-e^{-D(t-to)})] .R.$$

$$[T_r + [(t/t_c)/ (q +(1-p-q).(t/t_c) + p.(t/t_c)^{((p+q)/q))}T_c]] .\alpha$$

$$- \sigma_{so}(1-e^{-F(t)}).(1-\alpha) \quad . \tag{5-16}$$

Equation 5-16 is the proposed model to predict the uni-axial stress developed during the polyurethane grout expansion.

5.2) Parametric Study on the Model

In this section the effect of each parameter will be studied. Here, the curve for the Grout-5 model is considered randomly as the basis model. In this model the value of each parameter will be varied to investigate the effect of each specific parameter on the final output of the model. However, there is chance of observing different behavior and trend if another model is selected as the basis for comparison. On the other hand, as it was tried the selected ranges for each parameter almost have the same effect in all other models also. So, observed trends and changes could be extended and expected for the other models and claim that these parameters will have the same effect on the model of all the studied grouts in this study.

5.2.1) Parameter (σ_0)

As seen the parameter (σ_0) almost has no effect on the output of model. Actually the selected values for (σ_0) are based on the common ranges in the literature. Here it could be claimed this parameter is taken to its extremes but no change is observed.

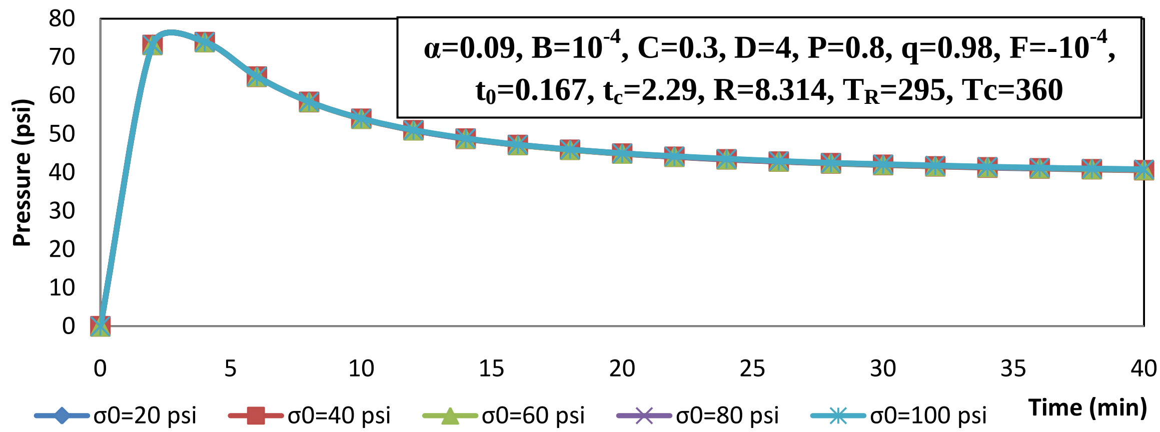


Figure 5.3 Effect of parameter (σ_0) on the model output

5.2.2) Parameter (α)

As shown, the parameter (α) has a direct effect on the magnitude of the model output values. Also it increases the peak area of the curve becomes more sloped as the (α) increases. It could be said that this parameters provides the exponential trend for model.

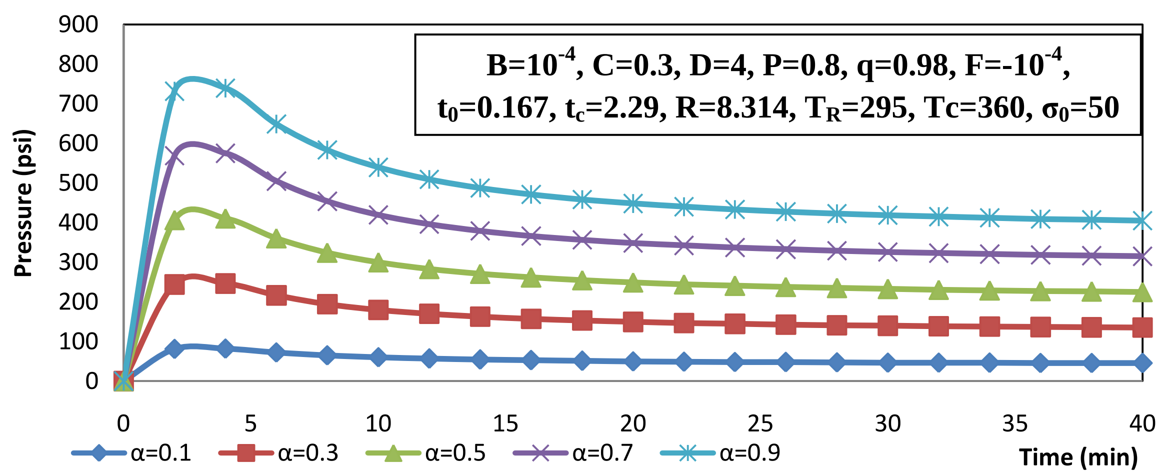


Figure 5.4 Effect of parameter (α) on the model output

5.2.3) Parameter (B)

Basically, this parameter controls the increasing trend of the pressure by time. However its growth trend is linear. On the other hand an approximate range of sensitivity could be defined as (B>0.0001) that within this range the output changes.

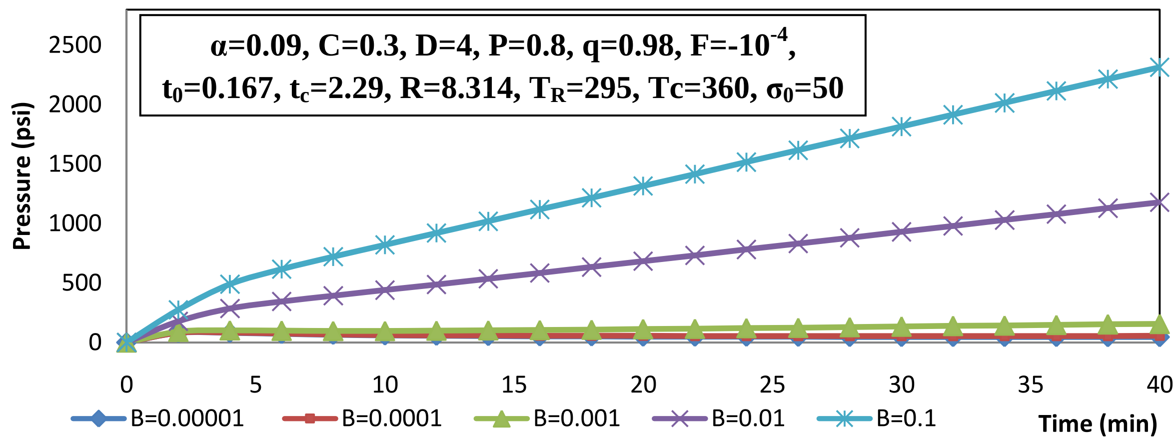


Figure 5.5 Effect of parameter (B) on the model output

5.2.4) Parameter (C)

Actually this parameter shows the same effect as the parameter (α). However, this parameter a wider range of meaningfulness and it can take more values. Besides, this parameter has less effect on the increase of value magnitude compared to (α).

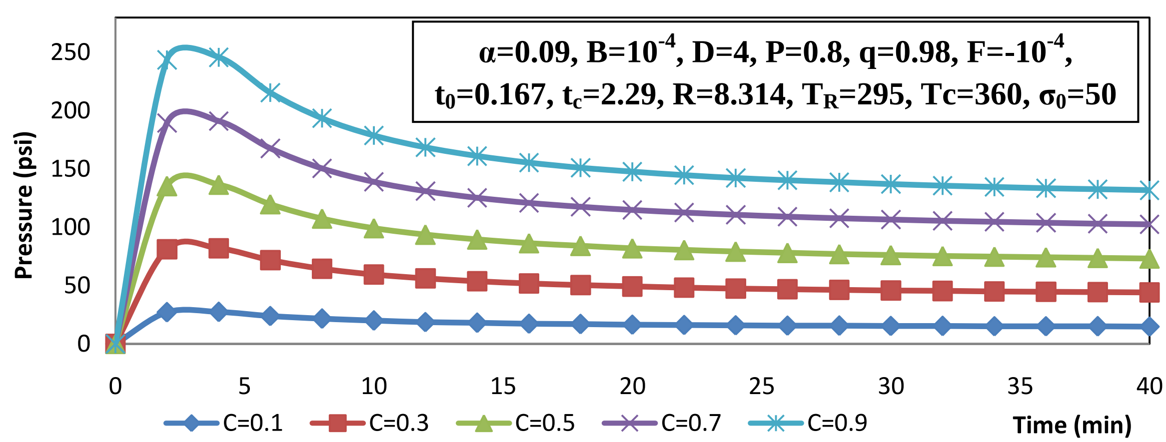


Figure 5.6 Effect of parameter (C) on the model output

5.2.5) Parameter (D)

For parameter (D) an approximate range of sensitivity could be defined as (0.01<D<100). From D=0.01 the increase in the values is seen and it reaches its peak approximately at D=1. Besides, the exponensial trend is seen only within narrow range of (1<D<10).

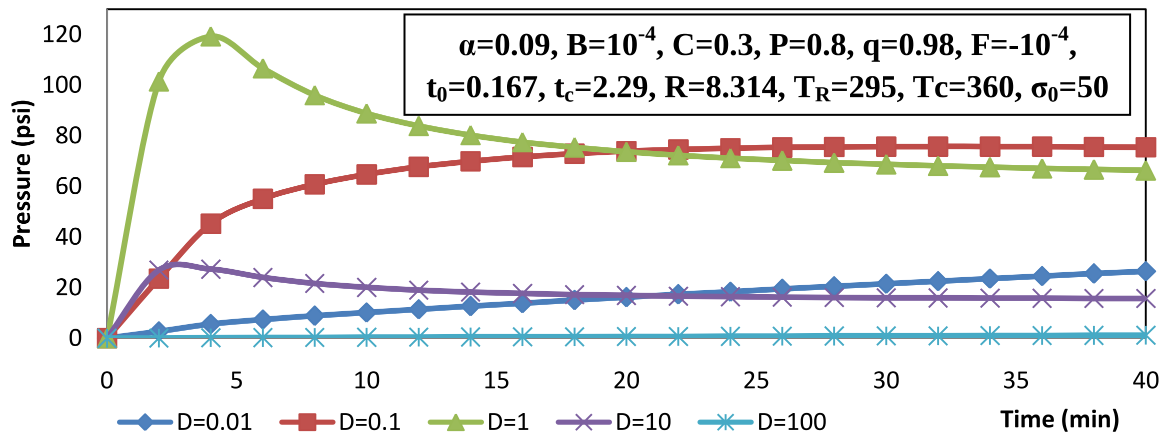


Figure 5.7 Effect of parameter (D) on the model output

5.2.6) Parameter (P)

Parameter (P) is effective within approximate range of (0.01<P<1). However, the exponential trend could be obtained only within a very narrow range of values. Besides as the magnitude of (P) increases the magnitude of the model output decreases.

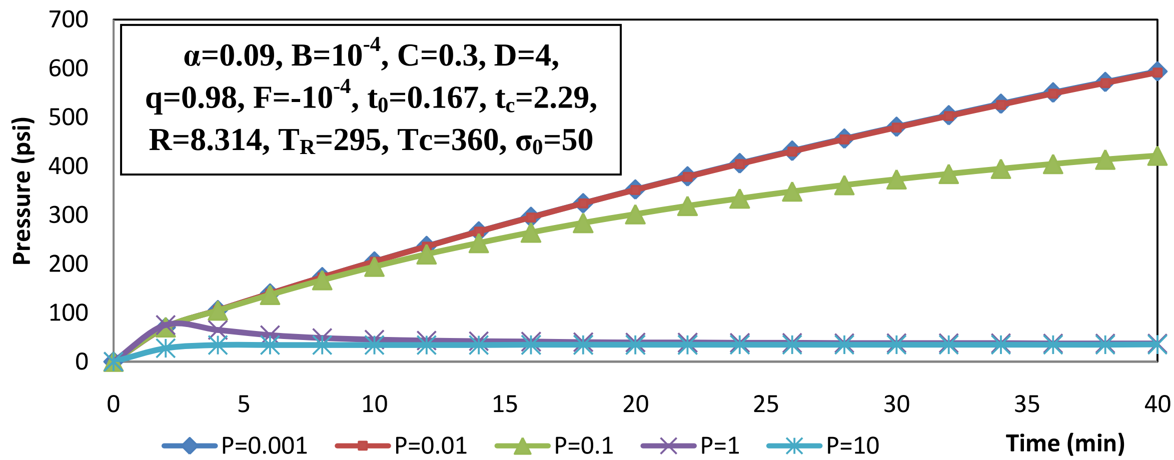


Figure 5.8 Effect of parameter (P) on the model output

5.2.7) Parameter (q)

Generally, this parameter controls the initial peak of the curve. Besides the exponensial decay that happens after the peak is remarkably affected by this parameter such that as the (q) increases, the slope becomes smoother.

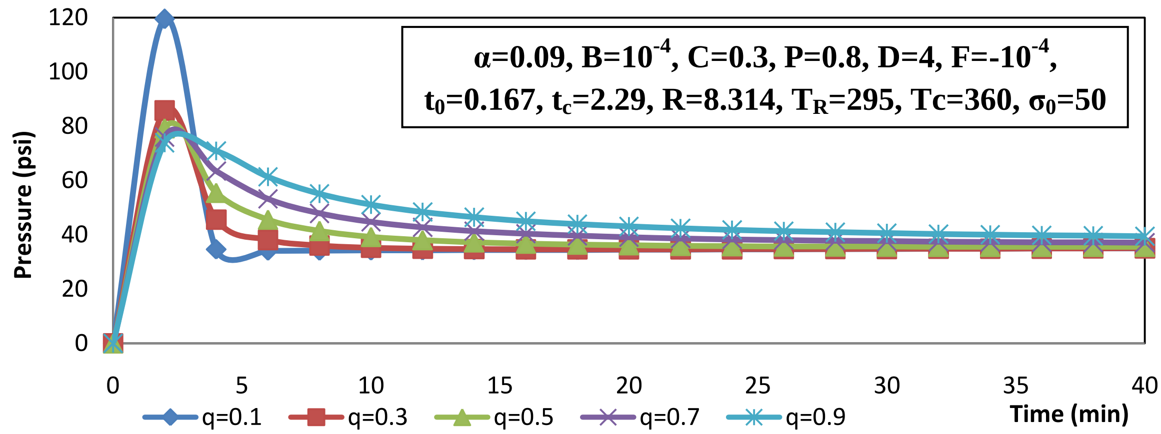


Figure 5.9 Effect of parameter (q) on the model output

5.2.8) Parameter (F)

Parameter (F) controls the tail of the curve and shows its sensitivity form the values of (F>-0.001) and as it increased the exponential decay gradually faded. Actually, this parameter affects the exponential decay and plateau of the model that the curve turns flat.

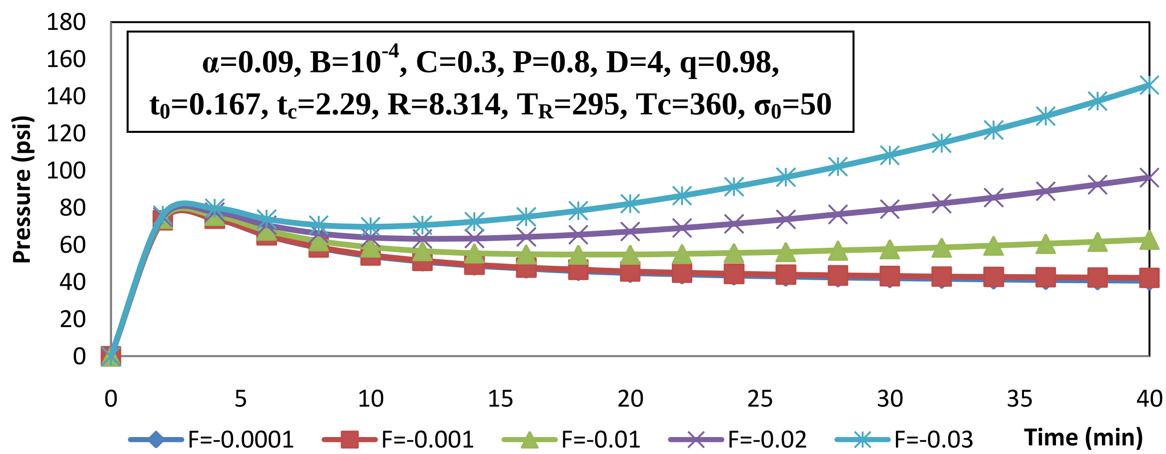


Figure 5.10 Effect of parameter (F) on the model output

5.3) Model Prediction

Grout-1, Grout-2, Grout-4 and Grout-5 experimental results are compared with corresponding Model outputs and all the Temperature-Pressure trend and behavior of the all these grouts are discussed in (Section 4.2.1). Figures (5.11) to (5.15) show the comparison of the modeled uniaxial stress curve with the experimental curve. It is to be noted that the model predicts the experimental observations for all the cases of the grout mix. Hence the proposed model is applicable for the expansive grouts with varying compositions. Besides in Tables (5.1) to (5.5) the model parameters for each grout are summarized. In the case with Grout-2 since the trend of the pressure development has a sharp increase, this model cannot predict its behavior well. However, by ignoring that pick two models are offered that one of them can predict the performance of the grout up to the pick and the other model predicts the overall trend of pressure development by ignoring the sudden increase and pick of the curve. The two mentioned models are shown in Figures (5.12) and (5.13). Overall it could be seen that this model has a good capability of modeling different types of Polyurethane grouts with pressure developments. Besides, it represents good prediction of the exponential trend of the grout behavior. In the following part the graphs are presented.

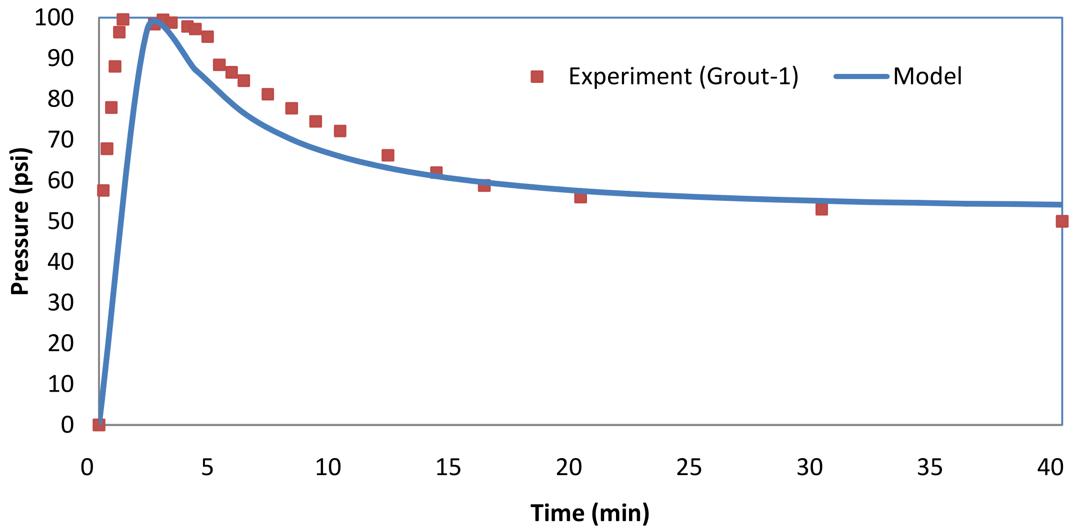


Figure 5.11 Comparison of model and experimental results of Grout-1

Table 5.1 Model parameter for Grout-1

σ_0	α	B	C	D	P	q	F	t_0	t_c	R	T_R	T_C
50	0.17	0.0001	0.2	4	0.7	0.95	-0.001	0.167	1.5	8.314	301	342

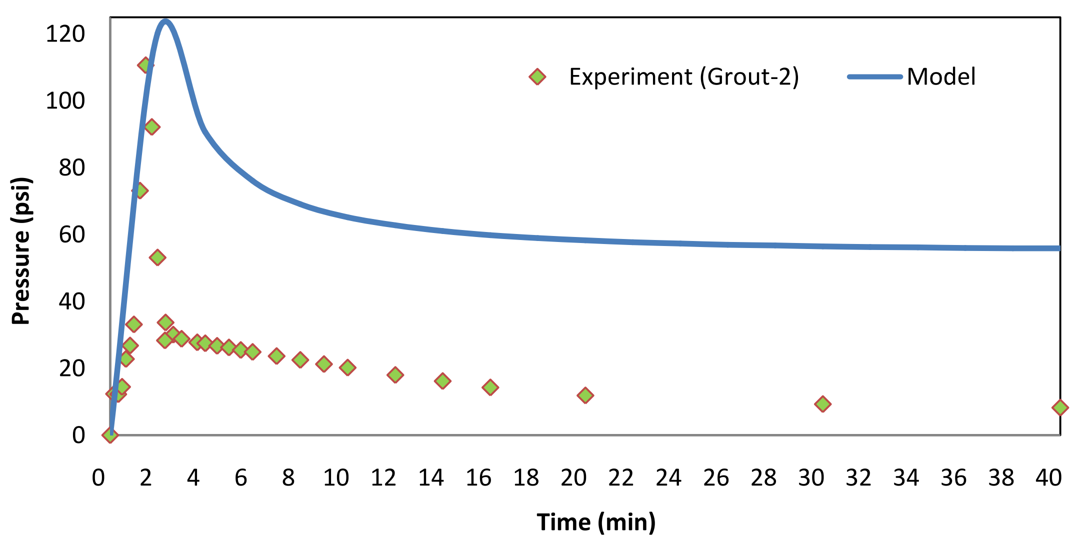


Figure 5.12 Comparison of model and experimental results of Grout-2-Model-1

Table 5.2 Model parameter for Grout-2-Model-1

σ_0	α	B	C	D	P	q	F	t_0	t_c	R	T_R	T_C
50	0.15	0.0001	0.6	11.3	0.95	0.9	-0.0001	0.167	1.75	8.314	295	408

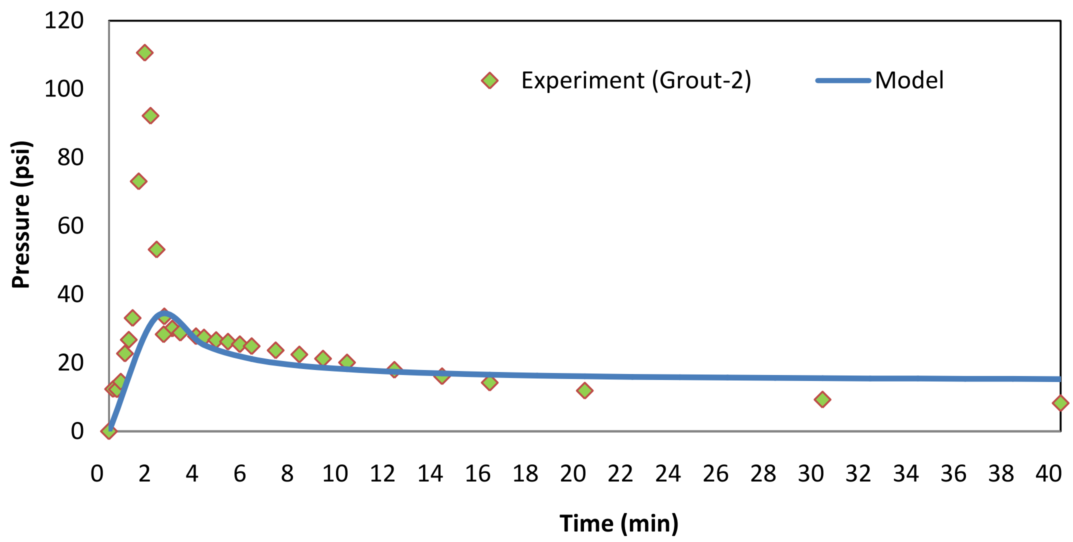


Figure 5.13 Comparison of model and experimental results of Grout-2-Model-2

Table 5.3 Model parameter for Grout-2-Model-2

σ_0	α	B	C	D	P	q	F	t_0	t_c	R	T_R	T_C
50	0.1	10^{-7}	0.13	4	0.95	0.9	-0.0001	0.2	1.75	8.314	295	408

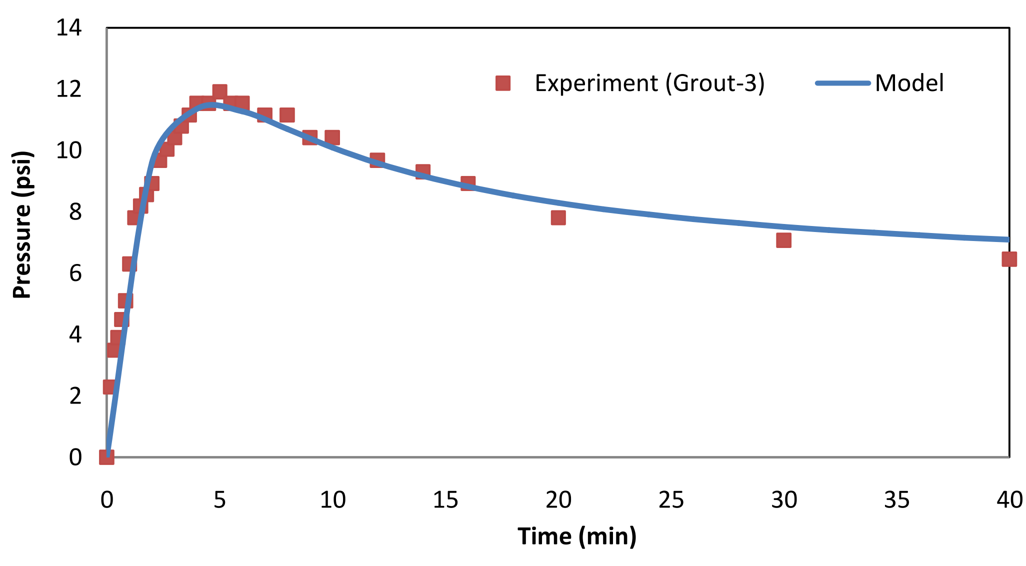


Figure 5.14 Comparison of Model and Experimental results of Grout-4

Table 5.4 Model parameter for Grout-4

σ_0	α	B	C	D	P	q	F	t_0	t_c	R	T_R	T_C
50	0.09	10^{-6}	0.3	15	0.6	0.82	-10^{-7}	0.167	3.3	8.314	50	0.09

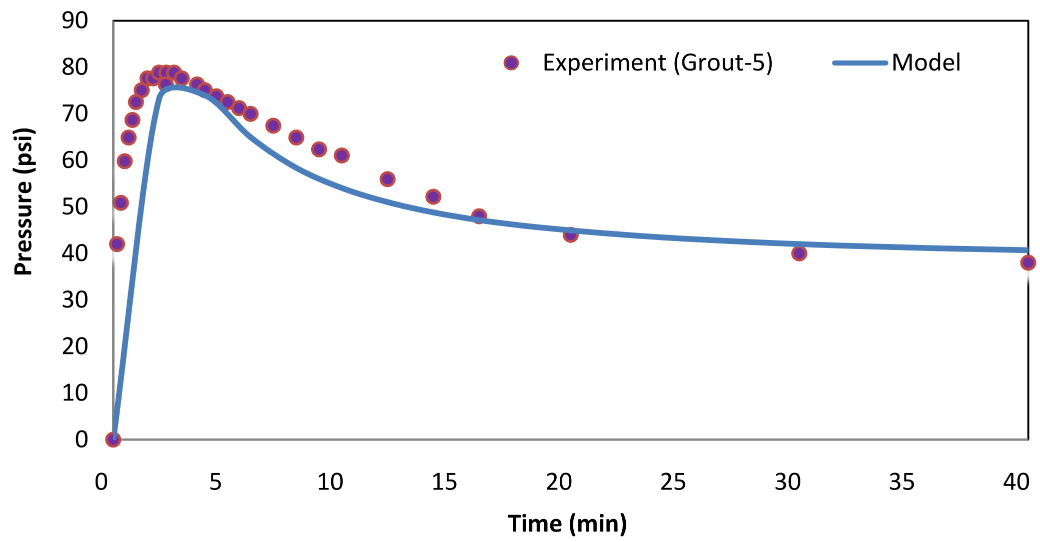


Figure 5.15 Comparison of model and experimental results of Grout-5

Table 5.5 Model parameter for Grout-5

σ_0	α	B	C	D	P	q	F	t_0	t_c	R	T_R	T_C
50	0.09	0.0001	0.3	4	0.8	0.98	-0.0001	0.167	2.29	8.314	295	360

5.4) Summary

In this study a previously developed model was used to predict the uniaxial pressure developed by the polyurethane grouts. The model was already verified by experimental results from the tests on hydrophilic polyurethane grouts. In this study the experimental results of hydrophilic, hydrophobic and two component grouts were modeled by this model to evaluate the capability of this model to predict the behavior of the polyurethane grouts with different compositions.

Based on the model and model predictions the following conclusions are determined:

1) The model has 7 parameters and it includes the gas production and grout strength development.

2) The model predicted the performance of most of the grouts. The peak pressure and the time to reach the peak pressure are two important parameters.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

There is a need to develop rapid methods to decommission abandoned oil pipelines offshore. In this study, test protocol was developed to evaluate various expanding grouts to seal up to 3-in diameter pipes. Several grouts and grouting methods were evaluated to fill the pipes with grouts. Grouted pipes were then tested for air and water leak. Based on the experimental and analytical study following conclusions are advanced:

1) For the initial screening, grouts were characterized based on the pressure and temperature increases and rising time during the confined curing of the grout.

2) The maximum pressure varied from 45 to 210 psi the rising time to reach the maximum pressure varied from 0':50'' to 3':00''.

3) One grout was sensitive to the amount of air not be in the confined space and hence curing was affected. Hence free expansion was not a good indicator of grout performance under confined condition.

4) Salt water and oil contaminations affect the curing of some of the grouts. The limits of the contaminations were up to 10% of the water in the hydrophilic grouts and grout in hydrophobic grouts.

5) The stage grout injection method variables were point and order of injection proved effective and by this method it could be assured that the reaction of grout is complete and provided the chance to complete the grouting step by step.

6) Plastic pipes of various diameters and lengths were used to characterize the filling effects of grouts. Grout filled pipes tested for water and air leaks up to 100 psi (700 kPa).Of the five grouts tested one was effective in meeting all the requirements.

7) Selected grouts were used to demonstrate the grout filling concept in abandoned 3 inch diameter steel pipes. Crushing the grout filled pipe before cutting also improved the performance of the pipes.

8) The model has 7 parameters and it includes the gas production and grout strength development.

9) The model predicted the performance of most of the grouts. The peak pressure and the time to reach the peak pressure are two important parameters.

6.2) Recommendations

Based on this study following recommendations are made.

1) For expanding grouts availability of air is a critical factor that should be investigated and test protocols for the simulation of the grouting should be developed.

2) If the requirement for free air is important during grout injection the air could also blown through a separate tube. However, this concept might have specific challenges and requires further study and research.

3) Air pressure test concept must be further developed to evaluate the grout filled pipes.

4) Development of stage grouting concept is important and to extend this concept to larger diameter pipes.

5) This study was limited to 3-in (75 mm) diameter pipes with the length of 10 feet. The potential of grouting longer pipes for higher pressure application must be investigated.

6) Various methods of crushing and cutting the grouted pipes must be investigated.

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