DOKUZ EYLÜL UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCIES

IMPROVEMENT OF DEWATERING CAPACITY OF OILY SLUDGES

by

Emrah KÜÇÜKSELEK

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İZMİR

IMPROVEMENT OF DEWATERING CAPACITY OF OILY SLUDGES

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"IMPROVEMENT OF DEWATERING CAPACITY OF OILY SLUDGES"** completed by **EMRAH KÜÇÜKSELEK** under supervision of **Assoc.Prof.Dr. NURDAN BÜYÜKKAMACI** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Assoc.Prof.Dr. Nurdan BÜYÜKKAMACI

Supervisor

Prof.Dr. Ayşe FİLİBELİ

(Jury Member)

Assoc.Prof.Dr. Günseli ÖZDEMİR

(Jury Member)

Prof.Dr. Cahit HELVACI

Director

Graduate School of Natural and Applied Sciences

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IMPROVEMENT OF DEWATERING CAPACITY OF OILY SLUDGES

ABSTRACT

Oily sludge is generated to a vast amount in a wastewater treatment plant of a petroleum refinery plant, food processors, and metals manufacture and machining, and it is difficult to dewater this type of sludge.

Dewatering process is a process that separates large amounts of water (~99%) from sludge. A lot of benefits should be achieved in final disposal of sludges with dewatering process, such as easy to transport, reducing odor and fly problem and leachate production in landfill areas.

Sludge conditioning is applied to improve its dewatering characteristics. The main purpose of any sludge conditioning process is to enhance the effectiveness of a solid-liquid separation process with floculation that will follow.

The aim of this study was to improve the dewatering capacity of oily sludges by using chemical conditioning. In the experimental studies, sludge samples taken from a central wastewater treatment plant of an organized industrial district, a wastewater treatment plant of a leather industry, a meat processing industry, and a petrochemical industry. All sludge samples were thickened sludge.

In raw sludge characterization studies, pH, electrical conductivity, dry solid, suspended solid, oil ratio, capillary suction time (CST) and specific resistance to filter (SRF) values were analysed. In conditioning studies, both conventional conditioners, such as alum, lime and cationic polyelectrolyte, and less conventional conditioners, such as bentonite, fly ash and gypsum, were examined as chemical conditioners. In order to determine the optimum dosage of each conditioner, different dosages were applied. Classical Jar test method was used to condition the sludge samples. Capillary suction time and specific resistance to filter parameters were

taken into consideration to determine the best conditioner type and the optimum conditioner dosage for each sludge sample.

Keywords: Capillary suction time (CST), conditioning, dewatering, oily sludge, specific resistance to filter (SRF).

YAĞLI ÇAMURLARIN SU VERME KAPASİTELERİNİN ARTTIRILMASI

ÖZ

Yağlı çamurlar; petrol rafineleri, gıda sanayi ve metal işleme sanayi başta olmak üzere birçok endüstriyel kuruluştan kaynaklanan atık suların arıtımında oluşan, suyunu zor veren çamurlardır.

Çamur susuzlaştırma işlemi; çamurun içerdiği büyük orandaki suyun (~%99) çamurdan ayrılması işlemidir. Çamur susuzlaştırma işlemi ile, çamurun depolama gibi nihai çamur işleme tesislerine daha kolay, daha çabuk ve daha ekonomik bir şekilde ulaşımı, koku, sinek ve sızıntı suyu oluşumunun azalması ve benzeri birçok yarar sağlanır.

Çamur şartlandırma işlemi ise çamurun susuzlaştırılmasını kolaylaştırmak ve susuzlaştırma işlemi sonunda yüksek katı madde içeriğine sahip son ürün elde etmek amacıyla çamurun içindeki katı maddeleri yumaklar halinde bir araya getirme işlemidir.

Bu çalışmanın amacı; suyunu zor veren yağlı çamurların kimyasal şartlandırılma işlemi uygulanarak suyunu vermesinin geliştirilmesidir. Deneysel çalışmalarda bir organize sanayi bölgesi merkezi atıksu arıtma tesisi, bir deri sanayi, bir et kesim ve işleme sanayi ile bir petrokimya sanayi atıksu arıtma tesisi yoğunlaştırıcı çıkışından alınan çamur numuneleri kullanılmıştır.

Deneysel çalışmalarda öncelikle ham çamurun özelliklerini belirlemek amacıyla çamur numunelerinin pH, elektriksel iletkenlik, toplam katı madde, askıda katı madde, yağ içeriği, kapiler emme süresi ve özgül filtre direnci parametreleri analiz edilmiştir. Ham çamur karakterizasyonunu takiben çamur numunelerini şartlandırmak amacı ile alışılagelmiş kimyasallar olarak alum, kireç ve katyonik polielektrolit kullanılmış ve bunlara alternatif olarak bentonit, uçucu kül ve alçı taşı denenmiştir. Bu kimyasallar farklı dozlarda ilave edilerek her bir şartlandırıcı için en

uygun doz belirlemesi yapılmıştır. Şartlandırma işlemi Jar testi kullanılarak gerçekleştirilmiştir. En iyi şartlandırıcı tipi ve optimum şartlandırıcı dozunun belirlenmesinde kapiler emme süresi ile özgül filtre direnci parametreleri dikkate alınmıştır.

Anahtar sözcükler: Kapiler emme süresi, özgül filtre direnci, susuzlaştırma, şartlandırma, yağlı çamur.

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CHAPTER ONE
INTRODUCTION

"Oil and grease is the term given to the combination of fats, oils, waxes, and other related constituents found in wastewater" (Northern Arizona University, n.d.). "Fats are among the more stable of organic compounds and are not quickly broken down by bacteria" (Metcalf&Eddy, 1991, pp.66). The grease content of wastewater can cause many problems in sewers, wastewater treatment plant, and receiving environments. When large amounts of oils and greases are discharged to receiving waters, BOD levels increase, and they may float to the surface and harden, causing aesthetically unpleasing conditions. If grease is not treated before discharge, it may interfere with oxygen transfer within aquatic life. If the wastewater is warm and greasy, the grease cannot quickly separate from the water, so the grease flows through the septic tank and into the soil where it solidifies upon cooling. The grease can clog the gravel and soil pores ruining the drainage system. Excessive grease also adds to the septic tank scum layer, requiring more frequent tank pumping (Northern Arizona University, n.d.).

The requirements for oil and water separation prior to discharge are becoming tougher each day. Although the most part of oil float on the wastewater, a portion is carried into the sludge on settling solids. During oil production and processing, important quantities of oily sludges are generated, which represent a source of pollution for the environment and, at the same time, block important spaces in tanks or where they are stored. The oily sludges, frequently present in oil production or processing sites, contain different concentrations of waste oil (40–60%), wastewater (30–90%) and mineral particles (5–40%). After several treatments, from the initial oily sludge are recovered some quantities of oil which are transported to refineries. The remaining sediment still contains important quantities of waste oil, water/waste oil mix and solids mineral particles. This remaining sediment should be submitted to special treatments (Lazar, Dobrota, Voicu, Stefanescu, Sandulescu, & Petrisor, 1997).

“There are many industrial sources of oil wastes. Major industrial sources of oily waste include petroleum refineries, metals manufacture and machining, and food processors” (Patterson, 1985, pp. 274). Oily sludge was generated to a huge amount in a petroleum refinery plant, which cannot achieve safe disposal until its oil content has been reduced to less than some limit. The annual amount of oily sludge generated from a petroleum refinery plant in Taiwan is approximately 28,000 tons, whose average oil content is greater than 50% (Jean, & Lee, 1999). Many refineries have API (American Petroleum Institute) system or DAF (Dissolved Air Flotation) unit prior to the secondary treatment system with activated sludge or aeration basins. Separation of oil from the oily sludge would be beneficial for resource and recycling purpose. Refineries many times do not collect all the oils off the process side. Improved DAF or API can collect this clean oil and return it to the front end of the system thereby increasing barrel productivity. Waste oily sludge many times is hauled off as hazardous waste. With the right process, this can be re-used sometimes in the coker. Optimization upstream is always best, but still, optimizing the API and DAF can improve capture of oil and oily sludge that can be re-processed or reused. It also takes a tremendous loading off the activated sludge or biological system (Environmental Leverage, Inc., n.d.).

The oil component in oily sludge makes a challenge with respect to treatment. The oil sticks to the hot discs in the dryer; hence the oily sludge can not be dried in a traditional sludge drying equipment. The oily sludge is not suited for compost, since some oil components require years to decompose. In addition, a typical oily sludge from a refinery contains heavy metals which are not a very favorable content in soil. Moreover, a typical oily sludge from a refinery contains between 60-90% water and thus actually requires a supply of energy to burn.

Properties of oily sludge change depending on the type of industry, source of wastewater, and applied treatment units. Therefore the properties of oily sludge should be defined clearly before the determination of sludge handling and disposal methods. Dewatering properties of any sludge are very important and accumulation of oil in sludge creates difficulties in dewatering. Sludge conditioning operations

have been widely used to improve dewatering characteristics of sludge. There are a lot of conditioning methods, such as chemical conditioning, thermal conditioning, elutration, freezing – thawing. The most suitable conditioning process should be choosen before dewatering operations.

In this thesis focuses on the improvement of dewatering properties of the oily sludge samples taken from a meat industry, a leather industry, an organized industrial district, and a petrochemical industry wastewater treatment plant by using various chemical conditioners at different dosages. At the beginning of the study, less conventional conditioners, which were bentonite, fly ash, and gypsum, were used. Due to the fact that sufficient efficiency could not be obtained with these conditioners, conventional conditioners, which were alum, lime and cationic polyelectrolyte, were used together with less conventional conditioners at last two experiments. Specific Resistance to Filtration (SRF) and Capillary Suction Time (CST) parameters were taken into consideration to evaluate the conditioning performance.

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CHAPTER TWO
INTRODUCTION TO OIL

2.1 Types of Oil

Oil is a general term that describes a wide variety of natural substances of plant, animal, or mineral origin, as well as a range of synthetic compounds. The many different types of oil are made up of hundreds of major compounds and thousands of minor ones. As their composition varies, each type of oil or petroleum product has certain unique characteristics or properties. These properties influence how the oil behaves when it is spilled and determine the effects of the oil on living organisms in the environment. These properties also influence the efficiency of cleanup operations (Fingas, 2000).

"Lipids are hydrophobic biological compounds that are insoluble in water, but soluble in nonpolar solvents such as benzene, chloroform, and ether" (Shuler, & Kargi, 2002, p.39). Oil is a very complex mixture of indefinite number of compounds each of which has its own structure, characteristics and properties. These compounds can be classified in different classes or groups of compounds according to their chemical composition and structure (Türkman, 2005).

2.1.1 The Hydrocarbon Constituents

The major component in most lipids is fatty acids, which are made of straight chain of hydrocarbon (hydrophobic) groups, with a carboxyl (hydrophilic) group at the end. A typical fatty acid can be represented as (Shuler, & Kargi, 2002, p.39-40):

$$CH_3 - (CH_2)_n - COOH$$

The number of carbon atoms in each molecule may be one or up to 80. For example, petroleum origin oil has more than 200 hydrocarbons as well as trace

concentration of other compounds (C, H, O, N, P, S, heavy metals etc.). According to this number of carbon atoms they may be gasses, liquids or solids (Türkman, 2005).

2.1.1.1 Normal Paraffin

Paraffin (or called kerosene) is a mixture of hydrocarbons; it usually consists of about 10 different hydrocarbons, each containing from 10 to 16 carbon atoms per molecule; the constituents include n-dodecane, alkyl benzenes, and naphthalene and its derivatives. Kerosene is less volatile than gasoline; it boils between about 140 and 320 °C and have a relative density of 0.78 - 0.83. It is obtained from crude oil by distillation and is used as a fuel for heating and aircraft. Paraffins can be arranged either in straight chains (normal paraffins) or branched chains (isoparaffins). Most of the paraffin compounds in naturally occurring crude oils are normal paraffins. Crude oil refers to liquid petroleum as opposed to refined oil. The normal paraffins are uniquely poor as motor fuels. Longer-chain paraffins are major constituents of waxes. Normal-Paraffins are produced from selected kerosene and/or gas oil, feedstocks using molecular sieves extraction. After appropriate purification treatment of desulphurization, dearomatization, the n-paraffin stream is passed into the fractionation unit, and then the desired carbon cuts are obtained. Normal paraffins are used as a solvent; a basic material in the manufacture of surfactants; in the manufacture of metalworking compounds, lube oil components, plasticizers and chloroparaffins; production of oils for aluminum cold rolling; catalyst carrier for olefin polymerization; raw materials for a wide range of applications (Arokor Holding, Inc., n.d.).

2.1.1.2 Isoparaffin

Isoparaffins are frequently produced in refinery processes and they have good engine-combustion characteristics. Isoparaffin is ideal for diluting and dissolving all oil containing products such as conventional gloss and eggshell paints and varnishes. It can be used for cleaning tools and brushes as well as dissolving tar, grease, wax and natural and synthetic resins (Earth Born, n.d.).

2.1.1.3 Cycloparaffins "Naphthenes"

Cycloparaffins are alicyclic hydrocarbons in which three or more of the carbon atoms in each molecule are united in a ring structure and each of the ring carbon atoms is joined to two hydrogen atoms or alkyl groups. The simplest members are cyclopropane (C_3H_6), cyclobutane (C_4H_8), cyclohexane (C_6H_{12}), and derivatives of these such as methylcyclohexane ($C_6H_{11}CH_3$) (Pennstate College of Medicine, n.d.).

2.1.1.4 Aromatic Hydrocarbons

Aromatic hydrocarbons are those which contain one or more benzene rings. The name of the class comes from the fact that many of them have strong, pungent aromas. They contain smaller amounts of hydrogen atoms as compared with cycloparaffins. All aromatic hydrocarbons both benzenoid and non-benzenoid are resonance stabilized. They are water insoluble. They are also carcinogenic (cancer forming) if exposed with sufficient concentration and exposure time (Georgia State University, 2005).

2.1.1.5 Oxygen Compounds

Oxygen is the third major impurity found in petroleum. Oxygen compounds in crude oil form acids while such compounds in natural gas are in the form of carbon dioxide (CO_2). The latter is, in itself, a natural gas, but it is non-combustible. Concentrations of oxygen vary widely. The oxygen content depends on the type of crude oil and is usually not higher than 2%. Excess oxygen must be removed during processing and refining (Leeric, n.d.).

2.1.1.6 Sulphur Compounds

Petroleum, a mixture of carbon, hydrogen and oxygen (called hydrocarbons), is seldom found in nature in a pure form without impurities. Of the three major impurities, sulfur, nitrogen, and oxygen, sulfur is seldom absent from crude oil and

can be found even in minute amounts. However, crude oil seldom has sulfur concentrations greater than 3% with the higher concentrations restricted to heavy crude. Some sulfur may be in elemental form in solution or as H_2S (hydrogen sulfide). Crude containing H_2S is referred to as sour crude. High sulfur crude oil costs more to refine which means that future oil supply costs will increase the price paid for gasoline at the pump. Moreover, compounding this problem, most refineries are not able to process the higher sulfur crude oil without major refinery modifications. Sweet crude is crude oil that contains less than 0.1% sulfur but such deposits have declined significantly since 1960's. Sour gas refers to natural gas containing H_2S. Similar restrictions apply to this type of natural gas as well. The H_2S must be extracted during processing of gas before the gas can be utilized by both industrial and domestic users. Sour gas is typically found in carbonate reservoirs; concentrations greater than 100 ppm are considered destructive because of the corrosive nature of H_2S (Leeric, n.d.).

2.1.1.7 Nitrogen Compounds

Nitrogen (N) is another major impurity in petroleum, though it is related primarily to asphalt content. These are present in very small quantities. Concentrations greater than 0.02% N are considered high, but in petroleum removed from some areas of the world such as in parts of Europe, it can exceed 90%. Nitrogen must also be removed during refining process; this requires low temperatures. The nitrogen can be recovered, and often is used as an inject ant in the secondary recovery of light oils (Leeric, n.d.).

2.1.1.8 Asphaltic Components

These are polycyclic compounds containing in addition to carbonate hydrogen 0.8 - 7% sulphur and less than 1% nitrogen. They may contain also oxygen. The main asphaltic components are resins or asphaltenes (Türkman, 2005).

2.1.1.9 Petroleum Oil Products

In refineries oil products are separated mainly by distillation. According to their boiling ranges the different cuts obtained are classified as in Table 2.1. These cuts may vary slightly according to the type of crude oil. Diesel fuel may be derived from high boiling kerosene or low boiling gas oil. Other fuel and heating oils are blends off residual oil with other distillates. Lubricating oils are made up mainly from isoparaffins and naphthenes with a small proportion of higher aromatics. Sludge containing up to 37% wax (higher normal paraffins) may separate from crude oils during transit, forming deposits in tanks which are dislodged and may be discharged during deballasting or tank-washing.

Table 2.1 Petroleum oil products

Cuts	**Boiling Ranges (^{o}C)**	**Carbon Numbers**
Refinery Gases	Up to 25	$C_3 - C_4$
Gasoline	40 – 150	$C_4 - C_{10}$
Naphtha	150 – 200	$C_{10} - C_{12}$
Kerosene	200 – 300	$C_{12} - C_{16}$
Gas Oils	300 – 400	$C_{16} - C_{25}$
Residual Oils	Above 400	Above C_{25}

2.1.1.10 Toxicity

The toxicity increases along the series paraffines, naphthenes and to aromatics. Within each hydrocarbon type the smaller molecules (with smaller number of carbon atoms) are more toxic than larger ones (Türkman, 2005).

2.2 Properties of Oil

The properties of oil discussed here are viscosity, density, specific gravity, solubility, flash point, pour point, distillation fractions, interfacial tension, and vapor pressure. These properties of oils are listed in Table 2.2 (Fingas, 2000).

2.2.1 Viscosity

Viscosity is the resistance to flow in a liquid. The lower the viscosity, the more readily the liquid flows. The viscosity of the oil is largely determined by the amount of lighter and heavier fractions that it contains. The greater the percentage of light components such as saturates and the lesser the amount of asphaltenes, the lower the viscosity. As with other physical properties, viscosity is affected by temperature, with a lower temperature giving a higher viscosity. For most oils, the viscosity varies as the logarithm of the temperature, which is a very significant variation. Oils that flow readily at high temperatures can become a slow-moving, viscous mass at low temperatures (Fingas, 2000).

2.2.2 Density

Density is the mass (weight) of a given volume of oil and is typically expressed in grams per cubic centimeter (g/cm^3). It is the property used by the petroleum industry to define light or heavy crude oils. Density is also important because it indicates whether particular oil will float or sink in water. As the density of water is 1.0 g/cm^3 at 15°C and the density of most oils ranges from 0.7 to 0.99 g/cm^3, most oils will float on water. As the density of seawater is 1.03 g/cm^3, even heavier oils will usually float on it. The density of oil increases with time, as the light fractions evaporate. Occasionally, when the density of oil becomes greater than the density of fresh or seawater, the oil will sink. Sinking is rare, however, and happens only with a few oils, usually residual oils such as Bunker C. Significant amounts of oil have sunk in only about 25 incidents out of thousands (Fingas, 2000; Jokuty et al., n.d.).

Table 2.2 Typical oil properties

Property	**Units**	**Gasoline**	**Diesel**	**Light Crude**	**Heavy Crude**	**Intermediate Fuel Oil**	**Bunker C**	**Crude Oil Emulsion**
Viscosity	mPa.s at 15°C	0.5	2.0	5 to 50	50 to 50000	10000 to 15000	10000 to 50000	20000 to 100000
Density	g/ml at 15°C	0.72	0.84	0.78 to 0.88	0.88 to 1.00	0.94 to 0.99	0.96 to 1.04	0.95 to 1.00
Flash Point	°C	-35	45	-30 to 30	-30 to 60	80 to 100	>100	>80
Solubility in Water	ppm	200	40	10 to 50	5 to 30	10 to 30	1 to 5	-
Pour Point	°C	NR	-35 to -1	-40 to 30	-40 to 30	-10 to 10	5 to 20	>50
API Gravity		65	35	30 to 50	10 to 30	10 to 20	5 to 15	10 to 15
Interfacial Tension	mN/m at 15°C	27	27	10 to 30	15 to 30	25 to 30	25 to 35	NR
Distillation Fractions	% distilled at 100°C	70	1	2 to 15	1 to 10	-	-	NR
	200°C	100	30	15 to 40	2 to 25	2 to 5	2 to 5	
	300°C		85	30 to 60	15 to 45	15 to 25	5 to 15	
	400°C		100	45 to 85	25 to 75	30 to 40	15 to 25	
	residual			15 to 55	25 to 75	60 to 70	75 to 85	

2.2.3 Specific Gravity

Specific gravity is the heaviness of a substance compared to that of water, and it is expressed without units. Another measure of density is specific gravity, which is an oil's relative density compared with that of water at 15°C. It is the same value as density at the same temperature. Another gravity scale is that of the American Petroleum Institute (API). The API gravity is based on the density of pure water, which has an arbitrarily assigned API gravity value of 10° (10 degrees). Oils with progressively lower specific gravities have higher API gravities. The following is the formula for calculating API gravity:

API gravity = [141.5 ÷ (density at 15.5°C)] – 131.5 (Fingas, 2000)

2.2.4 Solubility

Solubility in water is the measure of how much of oil will dissolve in the water column on a molecular basis. Solubility is important in that the soluble fractions of the oil are sometimes toxic to aquatic life, especially at higher concentrations. As the amount of oil lost to solubility is always small, this is not as great a loss mechanism as evaporation. In fact, the solubility of oil in water is so low (generally less than 100 parts per million) that it would be the equivalent of approximately one grain of sugar dissolving in a cup of water (Fingas, 2000).

2.2.5 Flash Point

The flash point of oil is the temperature at which the liquid gives off sufficient vapors to ignite upon exposure to an open flame. The lower the flash point is the greater tendency for the oil to suffer vaporization loss at high temperatures and to burn off on hot cylinder walls and pistons. The flash point can be an indicator of the quality of the base stock used. The higher the flash point is the better. A liquid is considered to be flammable if its flash point is less than 60°C. There is a broad range of flash points for oils and petroleum products, many of which are considered

flammable, especially when fresh. Gasoline, which is flammable under all ambient conditions, poses a serious hazard when spilled. Many fresh crude oils have an abundance of volatile components and may be flammable for as long as 1 day until the more volatile components have evaporated. On the other hand, Bunker C and heavy crude oils generally are not flammable when spilled (Fingas, 2000; Hackett, 1996).

2.2.6 Pour Point

The pour point is the lowest temperature at which oil will flow. The pour point of oil is the temperature at which it takes longer than a specified time to pour from a standard measuring vessel. As oils are made up of hundreds of, compounds, some of which may still be liquid at the pour point, the pour point is not the temperature at which the oil will no longer pour. The pour point represents a consistent temperature at which oil will pour very slowly and therefore has limited use as an indicator of the state of the oil. In fact, pour point has been used too much in the past to predict how oils will behave in the environment. For example, waxy oils can have very low pour points, but may continue to spread slowly at that temperature and can evaporate to a significant degree (Engineers Edge, n.d.; Fingas, 2000).

2.2.7 Distillation Fractions

Distillation fractions of an oil represent the fraction (generally measured by volume) of an oil that is boiled off at a given temperature. This data is obtained on most crude oils so that oil companies can adjust parameters in their refineries to handle the oil. This data also provides environmentalists with useful insights into the chemical composition of oils. For example, while 70% of gasoline will boil off at 100°C, only about 5% of a crude oil will boil off at that temperature and an even smaller amount of a typical Bunker C. The distillation fractions correlate strongly to the composition as well as to other physical properties of the oil (Fingas, 2000).

2.2.8 Interfacial Tension

The oil/water interfacial tension is the force of attraction or repulsion between the surface molecules of oil and water. Together with viscosity, tension is an indication of how rapidly and to what extent oil will spread on water. The lower the interfacial tensions with water, the greater the extent of spreading. In actual practice, the interfacial tension must be considered, along with the viscosity because it has been found that interfacial tension alone does not account for spreading behavior (Fingas, 2000).

2.2.9 Vapor Pressure

The vapor pressure of oil is a measure of how the oil partitions between the liquid and gas phases, or how much vapor is in the space above a given amount of liquid oil at a fixed temperature. Because oils are a mixture of many compounds, the vapor pressure changes as the oil weathers. Vapor pressure is difficult to measure and is not frequently used to assess oil spills (Fingas, 2000).

2.2.10 Toxicity

Oils with high properties of aromatics are actually toxic to marine life; others are harmful largely due to their smothering effect when disposed on shellfish, etc. In general terms, however, only sea birds diving through floating oil on the water surface are likely to be killed. Toxicity increases along the series paraffins, napthenes to aromatics. Smaller molecules are more toxic than larger ones (Türkman, 2005).

CHAPTER THREE
OIL IN WASTEWATER TREATMENT PLANTS

3.1. Definition of Oil Types in Wastewater

Fats and oils are contributed to domestic wastewater in butter, lard, margarine, and vegetable oils and fats. Fats are also commonly found in meats, in the germinal area of cereals, in seeds, in nuts, and in certain fruits (….) The term grease includes the fats, oils, waxes, and other related constituents found in wastewater (Metcalf&Eddy, 1991, p.66).

Kerosene, lubricating and road oils are derived from petroleum and coal tar and contain essentially carbon and hydrogen. These oils sometimes reach the sewers in considerable volume from shops, garages, and streets. For the most part, they float on the wastewater, although a portion is carried into the sludge on settling solids. To an even greater extent than fats, oils, and soaps, the mineral oils tend to coat surfaces. The particles interfere with biological action and cause maintenance problems (Metcalf&Eddy, 1991, p.66).

Oily waste materials are often measured in terms of their hexane and freon extractability, for purposes of pollution evaluation. Analytical results for oil and grease in wastewater may vary, depending upon the specific extraction technique, particular extraction solvent used and final analytical technique employed (Patterson, 1985, p.273).

Oil appears in wastewater in a number of different forms including free oil and grease, mechanically emulsified oil, chemically emulsified oil, dissolved oil, and oil wet solids.

- **Free Oil:** Oil which can rise to the surface under quiescent conditions. Free oils are commonly separated by gravity. In most situations the oil is lighter than water and can be separated by physical operations such as skimming or

flotation. The principles governing gravity separation of oil are expressed by Stoke's Law:

$$V = g (d_w - d_o) D^2 / 18 \mu$$

Where:

V = oil droplet rise rate

g = acceleration due to gravity

d_w = water density

d_o = oil density

D = oil droplet diameter

μ = water viscosity

As defined by Stoke's Law, the rise rate of the oil droplet can be varied by changing the oil density, water viscosity, water density or the oil droplet size. Temperature controls the first three variables, while the addition of chemical coagulants will alter the last variable, oil droplet size (Tramfloc, Inc., 2005).

- **Mechanically Emulsified Oil:** "Mechanically emulsified oil is fine droplets ranging in size from microns to a few millimeters (20-150 microns) in diameter, which are stabilized by electrical charges or other forces but not through the influence of surface active agents" (Patterson, 1985, p.273). "Such oils mix with water due to shear that can result from the wastewater traveling through a pump, wastewater splashing into a tank and anything that will break up and disperse larger oil droplets" (Scranton Gillette Communications, Inc., n.d.).

- **Chemically Emulsified Oil:** "This type of oil droplets similar to mechanical dispersions but with enhanced stability resulting from surface active agents at the oil/water interface" (Patterson, 1985, p.273). Oil is chemically emulsified in water when emulsifiers such as surfactants or soaps are present. The surfactants have hydrocarbon chains. The simplest ones are sodium laurel

sulfate or stearic acid, which have a hydrophilic (water loving) and a lipophilic (oil loving) end. The lipophilic end enters the oil droplet, while the hydrophilic end remains in the water. Since this creates a charge on the otherwise neutral oil droplet, the droplets will repel each other and disperse. This is called a chemically stabilized emulsion. The droplets are less then 20 microns, while the color of the water is white. The white color is an indicator that the emulsion must be split to allow removal of the oil. The source of such oils is metal working fluids, coolants, lubricants, motor oil, hydraulic fluids, etc (Scranton Gillette Communications, Inc., n.d.).

- **Dissolved Oil:** These are oils from the light end of the oil spectrum such as benzene, toluene and xylene. These are truly soluble species in the chemical sense and the molecules are less than five microns in size. They are removed very effectively by activated carbon (Patterson, 1985, p.273; Scranton Gillette Communications, Inc., n.d.).

- **Oil Wet Solids:** This category includes oil that adheres to sediments and other particulate matter such as metal chafing that are common in industrial wastewater. Such oily solids are removed with sand filters, bag filters, flocculants and oil/water separators. These processes are followed by polishing with organoclay (Scranton Gillette Communications, Inc., n.d.).

There are many industrial sources of oily wastes, such as baking, diary, oil extraction (e.g. olive, soybean, cotton seed oil), fish processing, and meat and poultry industries as well as manufacturers of oil-containing foods (e.g. margarine and salad dressing). Furthermore, mineral oils and hydrocarbons from oil refinery plants, petrochemical products plants, oil stocking, from off-shore platforms of petroleum exploitations and from harbor activities are other main sources of oily wastes.

Petroleum refineries produce large quantities of oil and oily emulsion wastes. In the metal industry two major sources of oily wastes, which are both emulsified and free oils, are steel manufacture and metal working. Metal working produces shaped

metal pieces and wastewater produced from these processes contain grinding oils, cutting oils, and lubrication fluids. Coolant oil-water emulsions are also employed in many metal-working processes. Soluble and emulsified oil content of wastewaters may vary from 100 to 5,000 mg/L (Patterson, 1985, p.274).

In the processing of meat, fish, and poultry, oily and fatty materials are produced primarily during slaughtering, cleaning, and by-product processing. The major grease source is the rendering area. Grease content in meat packinghouse waste streams may run several thousand mg/L, and waste from one fish-processing plant has been reported to contain up to 13,700 mg/l fish oil (Patterson, 1985, p.274).

3.2. The Effect of Oil in Sewer System and Wastewater Treatment Plants

Oil in water waste streams can coat and damage equipment, contaminate process water and escape treatment in biological systems. The grease content of wastewater can cause many problems in both sewers and waste treatment plants. “If grease is not removed before discharge of the waste, it can interfere with the biological life in the surface waters and create unsightly floating matter and films” (Metcalf&Eddy, 1991, p.66).

When Fats, Oils and Grease (FOG) are disposed of improperly they can cause sewer backups (Figure 3.1). Backups expose the city to costly environmental penalties, and cause health hazards. FOG leads to increased costs for maintaining sewers and wastewater treatment plants and cleaning grease clogs out of private and public property. Most pretreatment ordinances forbid the discharge of excessive amounts of FOG into the sewer system. FOG discharge can damage collection system equipment and treatment plants, and also is a primary cause of sewer line blockages that result in sewer overflows. Most pretreatment programs require FOG producing industries (food preparation and food processing facilities) to install a pretreatment device like a grease trap or grease removal system. Some pretreatment authorities sample and test water exiting the pretreatment device to ensure that the establishment is properly caring for the unit (DPV, 2004).



Figure 3.1. The effect of grease in sewer systems

Wastewater carrying oil with it creates treatment problems in the aerobic treatment as well as in the anaerobic digestion, and subsequently in the sludge dewatering processes (Hwa, & Jeyaseelan, 1997).

3.3. Treatment Alternatives of Oil

Treatment of oily waste streams can result in:

- Improved oil/water separation
- Improved water clarity
- Oil recovery
- Water reuse
- Protection of downstream facilities
- Environmental permit compliance

Emulsions are stable mixtures of two immiscible liquids. Emulsions are stabilized by an emulsifying agent which is a film of surface active agents that reduces the interfacial tension between the oil and water. The film of emulsifiers can be altered by heat, chemicals, mechanical devices or a combination of the three.

- Oil/Water Separators

The design of basic oil/water separators is based on Stoke's Law. The lighter oil droplets impact on the slant ribs of the media, coagulate and rise to the surface. The

principle of air flotation is that oil droplets will adhere to air and gas bubbles and rise to the surface of the tank. Chemically emulsified oil can be removed by heating the water from 150 to 220° F. However, this can become expensive.

Evaporators remove the water and leave the oil. This process also is expensive and results in difficult clean ups of the elements of the evaporator. The addition of salts, polymers, bentonite powders and pH adjustment are the most difficult but most successful methods of breaking emulsions and removing the oil.

Polymers are used to destabilize oily wastewaters on many types of equipment, such as: the American Petroleum Institute (API) separator, Corrugated Plate Interceptor (CPI) separator, Induced Air Flotation (IAF) and Dissolved Air Flotation (DAF). Figure 3.2 is a schematic of a DAF.

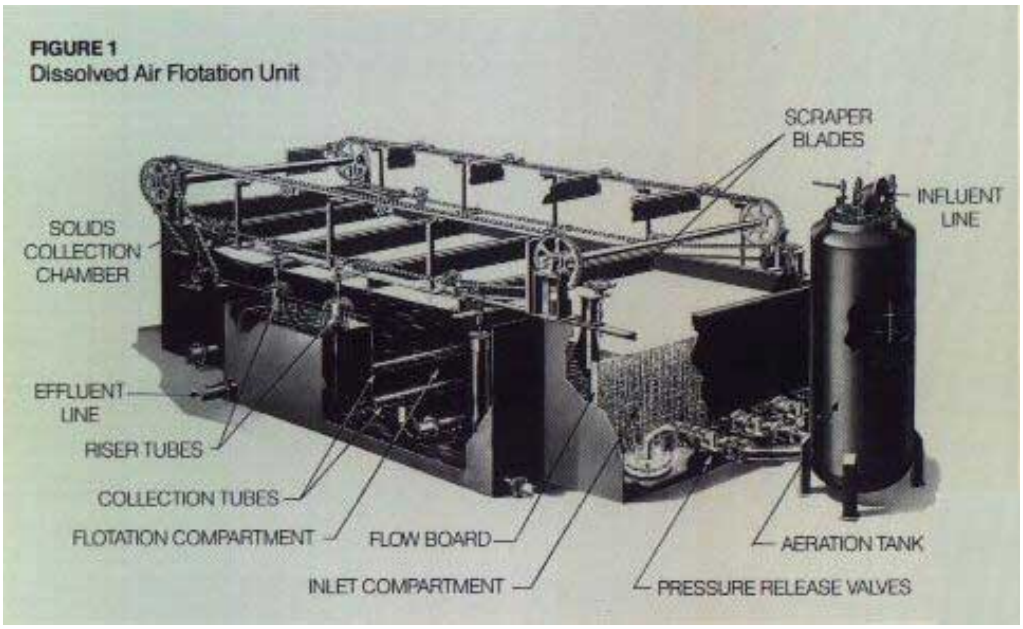


Figure 3.2 Schematic of DAF (Thramfloc, Inc., 2005)

When chemical treatment is applied, prior bench testing is required. The first step is the addition of an inorganic salt such as magnesium or aluminum sulfate. This may be sufficient to break emulsions, or deemulsify the oil, if sodium soaps are the emulsifier. If this process is not successful, a cationic coagulant may be added. The purpose is to neutralize the charges on the oil droplet caused by the emulsifier (i.e.,

drive the zeta potential towards zero). If this does not work, the pH may have to be adjusted downward to 3.5 with sulfuric acid to break up the surfactant. Coagulants and flocculants then may be added to remove the oil. This step is followed by passing the water through a bed of organoclay to remove the last traces of oil (polymers are not economical below 330 ppm), adjustment of the pH to 5 or higher and a pass through an activated carbon bed. The water now can be reused (Scranton Gillette Communications, Inc., n.d.).

- Emulsion Breaking

Emulsion breaking can be done by using acid or coagulant. Both sulfuric (H_2SO_4) and hydrochloric (HCl) acids are used to break emulsions; however, hydrochloric acid often seems to be superior.

At acid breaking process, after the pH is measured, acid is added until the pH reaches a level of 4 or 5. If the oil does not already rise to the surface, pH is adjusted as 3. If the oil content still is relatively high, 10-50 ppm of a non-ionic coagulant may be added to help coalesce the remaining oil droplets.

At coagulant breaking process, two methods are possible. Firstly, for emulsions that break at a pH of 7 or 6, addition of poly aluminum chloride (PAC), aluminum sulfate or ferric chloride at 50-200 ppm or more as needed is employed. Second possibility is the addition of cationic (or nonionic) polymer. 50 ppm (mg/l) to 1000 ppm or more, if needed, is added. Either inorganic or organic coagulants in combination may be used. Inorganic coagulants generate a gel-like sludge, but are much cheaper than organic coagulants. Sometime better results are achieved by combining the inorganic and organic coagulants (Scranton Gillette Communications, Inc., n.d.).

3.4. Bioremediation

"Remediate" means to solve a problem, and "bio-remediate" means to use biological organisms to solve an environmental problem such as contaminated soil or groundwater. In a non-polluted environment, bacteria, fungi, protists, and other microorganisms are constantly at work breaking down organic matter. What would occur if an organic pollutant such as oil contaminated this environment? Some of the microorganisms would die, while others capable of eating the organic pollution would survive. Bioremediation works by providing these pollution-eating organisms with fertilizer, oxygen, and other conditions that encourage their rapid growth. These organisms would then be able to break down the organic pollutant at a correspondingly faster rate. In fact, bioremediation is often used to help clean up oil spills.

Bioremediation of a contaminated site typically works in one of two ways. In the case described above, ways are found to enhance the growth of whatever pollution-eating microbes might already be living at the contaminated site. In the second, less common case, specialized microbes are added to degrade the contaminants.

Nonetheless, bioremediation provides a technique for cleaning up pollution by enhancing the same biodegradation processes that occur in nature. Depending on the site and its contaminants, bioremediation may be safer and less expensive than alternative solutions such as incineration or landfilling of the contaminated materials. It also has the advantage of treating the contamination in place so that large quantities of soil, sediment or water do not have to be dug up or pumped out of the ground for treatment (Cornell University, n.d.).

Bioremediation has become an important method for the restoration of oil-polluted environments by the use of indigenous or selected microbial flora. Several factors such as aeration, use of inorganic nutrients or fertilizers and the type of microbial species play a major role in the remediation of oil-contaminated sites. Experiments were undertaken for bioremediation of oil sludge-contaminated soil in

the presence of a bacterial consortium, inorganic nutrients, compost and a bulking agent. Addition of the bacterial consortium in different amendments significantly enhanced the removal of oil from the petroleum sludge from different treatment units (Vasudevan, & Rajaram, 2001).

CHAPTER FOUR
OILY SLUDGE CONDITIONING

Waste sludges from wastewater treatment plants have about 98-99% water. “Dewatering reduces the volume and quantity of sludge that needs to be disposed of or subsequently treated” (Spinosa, & Vesilind, 2001, pp.23). Thickening is a procedure used to increase the solids content of sludge by removing a portion of the liquid fraction. For example, if waste activated sludge, which is typically pumped from secondary settling tanks with a content of 0.8% solids, can be thickened to a content of 4% solids, then a five-fold decrease in sludge volume is achieved (Metcalf&Eddy, 1991, pp.801). A further reduction of the sludge amount is usually necessary after the thickening. The liquid sludge has to be dewatered and has to conform to a dry and porous form. Dewatering can be done naturally (dry beds, solar drying), however this is only possible during a long period of time and appropriate climate conditions. Therefore mechanical dewatering equipments, such as belt filter, centrifuges, filter press, etc., are usually preferred to obtain as high percentages dry solids (DS) content as possible. Using common centrifuges or belt presses, 20-25% DS can be obtained.

The difficulty in sludge dewatering is mainly attributed to presence of extra cellular polymer (ECP). ECP is thought to aid the survival of the bacterial cell by preventing desiccation and acting as an ion-exchange resin, controlling the ionic movement from solution into the cell. Polysaccharide, protein and DNA, which entraps the water and causes a high viscosity, are the main components of ECP but also humic-like substances, lipids and heteropolymers are present (Neyens & Baeyens, 2003).

“Sludge conditioning is applied to improve its dewatering characteristics. The main purpose of any sludge conditioning process is to enhance the effectiveness of a solid-liquid separation process that will follow” (Spinosa, & Vesilind, 2001, pp.278).

Two types of conditioning methods are commonly used: chemical conditioning, in which chemicals are added to change sludge properties, and physical conditioning, in which physical properties like temperature are used to alter sludge properties. Chemical conditioning is the more common process and prepares the sludge for better and more economical treatment with vacuum filters or centrifuges. Other conditioning methods such as freezing, irradiation, solvent extraction, and elutriation have also been used.

Only free water can be separated during mechanical dewatering. "Water in sludge appears to be of four kinds; *free water*, which is not bound to the particles, *interstitial water*, which is bound by capillary forces between the sludge flocs, *surface water*, which is bound by adhesive forces and *intracellular water*" (Kopp, & Dichtl, 2001). "With conditioning processes, different forms of water in the sludge transforms to free form. Table 4.1 summarizes the effect of some sludge handling units on different types of water in sludge" (Civelekoğlu, 2003).

Table 4.1 Effect of some sludge handling units on different kinds of water in sludge

Process	**Free Water**	**Capillary Water**	**Colloidal Water**	**Particular Water**	**Energy Requirement (kwh/m^3)**
Thickening	+	-	-	-	< 1
Conditioning & Dewatering	+	+	+	-	1 ~ 100
Heat Drying	+	+	+	+	> 100

"Surface properties, like the concentration of ECP, are related to zeta-potential measurements with particle electrophoresis. The sludges with high zeta-potentials are sludges with high amounts of ECP" (Neyens & Baeyens, 2003). The behavior of solids in water is strongly influenced by their electro kinetic charge. The sludge particles are usually negatively charged. The chemical conditioners electrochemically change this negative charge (Civelekoğlu, 2003; Hach GLI International, n.d.). "The classical double layer model is an attempt to explain the change neutralization" (Vesilind, 1979).

4.1 Chemical Conditioning

"The use of chemicals to condition sludge and biosolids for dewatering is economical because of the increased yields and greater flexibility obtained" (Metcalf&Eddy, 2003, p.1555). Therefore, chemical conditioning is used as the more common method. Chemical conditioning can increase the 1 % dry solid to 15-35 % dry solid after dewatering process, depending on the nature of the solids to be treated and the applied dewatering process type. Coagulation of the solids and release of the absorbed water is possible with chemical conditioning.

4.1.1 Conditioners

Inorganic additives such as ferric salts and lime, and high molecular weight organic polymers are used as conditioners. Sludge conditioning began with the use of inorganic chemicals and has primarily involved the application of a ferric salt (ferric chloride [$FeCl_3$] or [$Fe_2(SO_4)_3$]). Alum salts have been used less commonly (Spinosa, & Vesilind, 2001, pp.281). Some properties of commonly used coagulants are given in Table 4.2 (Kızılkılıç, 2002). Addition of chemicals can raise the amount of dry solid. "Typical dosage of alum & ferric chloride and lime is 50 ~ 100 kg/ton dry solid and 250 ~ 500 kg/ton dry solid, respectively" (Civelekoğlu, 2003).

Table 4.2 Properties of commonly used coagulant

Name	**Formula**	**Equivalent Weight**	**pH at 1% Solution**
Alum	$Al_2(SO_4)_3$	100	3.4
Lime	$Ca(OH)_2$	40	12
Ferric (III) chloride	$FeCl_3.6H_2O$	91	3-4
Ferric (III) sulphate	$Fe_2(SO_4)_3.3H_2O$	51.5	3-4
Copperas	$FeSO_4.7H_2O$	139	3-4
Sodium aluminate	$Na_2Al_2O_4$	100	11-12

In addition to conditioning, stabilization can also be obtained with the addition of quicklime, since it increases both the temperature and pH of the sludge. These

changes cause pathogens and odor-causing organisms within the sludge to be killed by raising the temperature above 70 °C and giving the final product a pH above 11.5. However; the use of lime can increase the original dry weight of sludge.

Because the sludge particles are usually negatively charged, cationic polymers are the main form of organic additive. Anionic polymers are cheaper than cationic polymers, but before using, sludge must be made acidic with hydrogen ions. In general, anionic polymers are used in raw water treatment in flocculation process as a second coagulant (Civelekoğlu, 2003). Erden (2004) reported that considerably sludge cake productions were not obtained for both non-ionic and anionic polyelectrolytes (KWD-20 LT and KWD A-0055) applications whereas cationic polyelectrolyte gave the best conditioning results for the sludge samples taken from a municipal wastewater treatment plant's biological treatment process.

"Advantage of organic polymers over inorganics is that polymers don't greatly increase the amount of sludge production: 1 kg of inorganic chemicals added will produce 1 kg of extra sludge" (The Mcilvaine Company, n.d.). On the other hand, less polymer dosage is necessary than chemicals (5 ~ 10 kg/ton dry solid). Organic polymers can burn with sludge in incineration process if treatment plant has an incineration unit. The disadvantage of polymers is their high cost.

4.1.2 Mixing

There are four important steps in conditioning:

- Conditioner dispersal into the liquid phase of the suspension
- Conditioner adsorption on to the sludge particle surfaces
- Particle aggregation
- Particle breakage

The first step can be critical in sludge conditioning, because the adsorption step is essentially irreversible (Spinosa, & Vesilind, 2001, pp.300). Hence, sufficient mixing of sludge and coagulant is essential for proper conditioning. "The mixing must not

break the floc after it has formed, and the detention should be kept to a minimum so that sludge reaches the dewatering unit as soon after conditioning as possible" (Metcalf&Eddy, 2003, p.1556-1557).

The mixing is generally realized in the pipe which exists before the dewatering unit. In addition to these, mixing requirements vary depending on the dewatering method used.

4.1.3 Dosage Determination

"The chemical dosage required for any sludge is determined in the laboratory" (Metcalf&Eddy, 2003, p.1555). Tests used for selecting chemical dosage include: *Standard Jar Test*, the easiest method to use, consists of testing standard volumes of sludge samples (usually 1 liter) with different conditioner concentrations, followed by rapid mixing, flocculation, and settling using standard jar test apparatus. *Buchner Funnel Test* is a method of testing sludge drainability or dewatering characteristics using various conditioning agents. *Capillary Suction Time Test* relies on gravity and the capillary section of a piece of thick filter paper to draw out water from a small sample of conditioned sludge.

In general, it has been observed that the type of sludge has the greatest impact on the quantity of chemical required. Difficult-to-dewater sludges that require larger doses of chemicals, generally do not yield as dry a cake, and have poorer quality of filtrate or centrate. Sludge types, listed in the approximate order of increasing conditioning chemical requirements, are as follows;

1. Untreated (raw) primary sludge
2. Untreated mixed primary and trickling filter sludge
3. Untreated mixed primary and waste-activated sludge
4. Anaerobically digested primary sludge
5. Anaerobically digested mixed primary and waste-activated sludge
6. Untreated waste-activated sludge
7. Aerobically digested sludge (Metcalf&Eddy, 2003, p.1556)

Typical levels of polymer addition for various types of sludge for diverse methods of dewatering are in Table 4.3 (Civelekoğlu, 2003).

Table 4.3 Typical levels of polymer addition

Type of Sludge	**kg of Dry Polymer Added / Ton of Dry Solids**		
	Vacuum Filter	**Belt Filter Press**	**Solid Bowl Centrifuge**
Primary	1 – 10	1 – 4	0.5 – 2.5
Primary & Waste Activated	5 – 10	2 – 8	2 – 5
Primary & Trickling Filter	1.25 – 2.5	2 – 8	–
Waste Activated	7.5 - 15	4 – 10	5 – 8
Anaerobically Digested Primary	3.5 – 7	2 – 5	3 – 5
Anaerobically Digested Primary & Air Waste Activated	1.5 – 8.5	1.5 – 8.5	2 – 5
Aerobically Digested Primary & Air Waste Activated	7.5 – 10	2 – 8	–

Charge density of a polymer (i.e. mole percent of the cationic monomer) is relatively unimportant when conditioning a primary sludge, but becomes more important with secondary sludges or their mixtures with primary sludge. A secondary sludge generated with a longer sludge retention time may require a lower charge demand (Spinosa, & Vesilind, 2001, pp.296).

4.1.3.1 Jar Test

A simple jar test is perhaps the most widely used method to evaluate chemical conditioning. In the standard jar test mechanism different concentrations of various chemicals are added to one liter sludge sample. Following a short period of rapid mixing, the sludge is flocculated for a few minutes then allowed to settle. The clarity of the liquid and the appearance of the floc structure is an indication of the chemical's ability to condition the sludge. This test does not yield quantitative data,

but it does give enough qualitative information to allow quick screening of conditioning agents (EPA, 1987, p.48; Vesilind, 1979, p.212).

4.1.3.2 Buchner Funnel or Specific Resistance to Filtration (SRF) Test

The rate of water removed during filtration is based on Darcy's Law, where the sludge cake is assumed to be a bed of small particles and the resistance to the flow of water is caused by the surface friction of the particle surfaces as water passes (Spinosa, & Vesilind, 2001, pp.344).

Sludge dewatering is often characterized by the sludge filterability, expressed as the specific resistance to filtration (SRF). SRF Test is used to determine the optimum conditioner for conditioning a kind of sludge, and it is also used to compare filtration resistance of different types of sludge or different conditioner dosed sludge.

The SRF is usually determined from a laboratory filtration test. A laboratory test apparatus involves a volumetric cylinder (100 ml), a Buchner Funnel and a vacuum pump (Figure 4.1). The Buchner Funnel is mounted on the top of volumetric cylinder and surface of the funnel is fitted with a Whatman #2 paper. Then 100 ml of sludge sample is poured onto the paper. The vacuum pump is turned on (2 bar) after 2 minutes gravity drainage. At about 10-second intervals, the filtrate volume is measured and written out till additional water cannot be removed. After this period, total suspended solids of filtrate are determined. The coefficient b is measured as the slope of the curve obtained by plotting the time/filtrate volume (T/V) versus filtrate volume (V). The following equation is used to calculate the specific resistance (r):

$$r = (2PA^2b) / \mu w = SRF$$

Where:

r = SRF = specific resistance, m/kg

P = pressure of filtration, N/m^2

A = area of filter, m^2

b = slope of time/volume versus volume curve, s/m^6

μ = viscosity of filtrate, Ns/m^2

w = weight of dry solids / volume of filtrate, kg/m^3

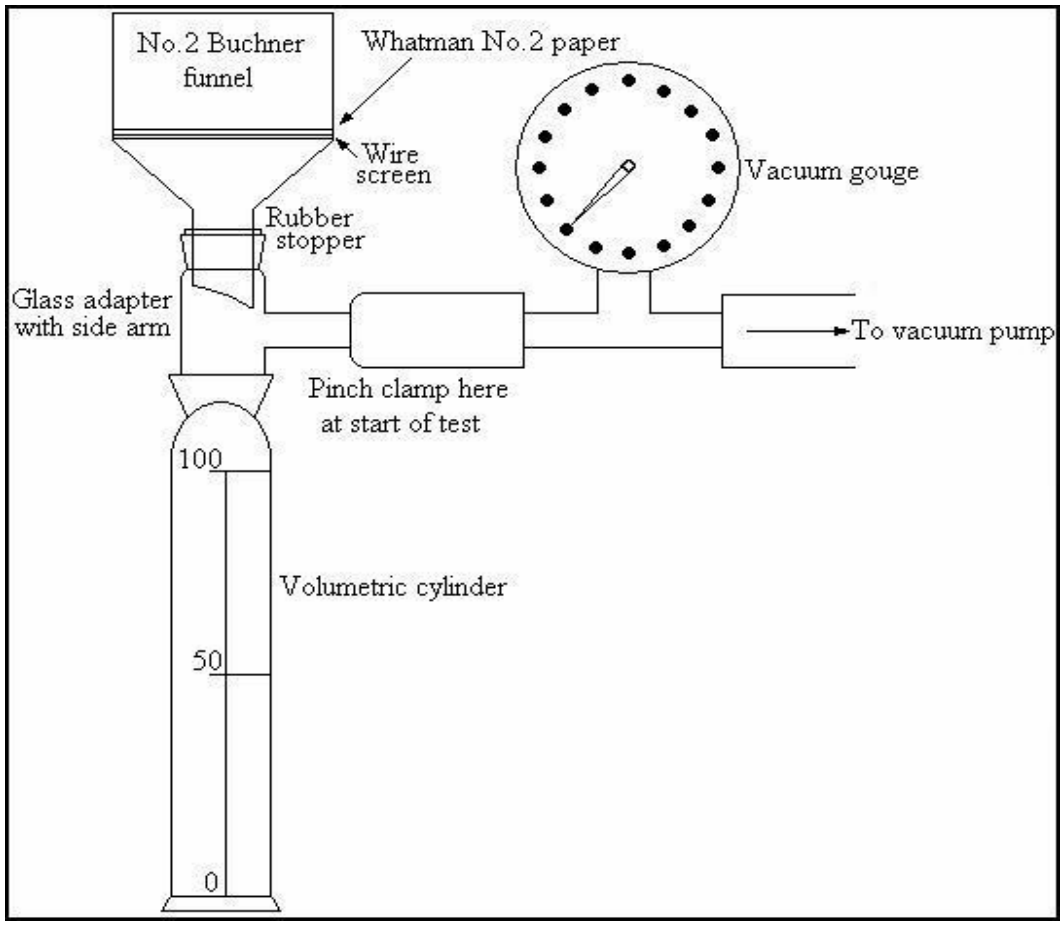


Figure 4.1 Buchner funnel apparatus (EPA, 1987)

"The SRF of activated sludge is normally in the range of 10 Tm/kg for unconditioned sludge, and a factor 5-10 less for conditioned sludge. Poor dewaterability is seen with sludge having an SRF above 50 Tm/kg" (Palmgren, n.d.).

4.1.3.3 Capillary Suction Time Test

The time of filtrate requires moving a fixed distance in the filter paper is referred to as capillary suction time (CST). The purpose of CST Test is to determine dewatering characteristics of a given sludge rapidly and easily. The advantages of this test are to be simple, inexpensive and easy. A large CST is usually indicator of

poor sludge dewaterability. (Eckenfelder, & Santhanam, 1981, p.77; EPA, 1987, p.50; Vesilind, 1988, p.216). “CST is usually in the range of 20-30 seconds for well dewatering sludge and above 50 s for poor dewatering sludge” (Palmgren, n.d.).

To optimize the operation of chemical sludge conditioning, CST parameter has been widely used by many researchers (Chitikela, & Dentel, 1998; Christensen, Sorensen, Christensen, & Hansen, 1993; Erden, 2004; Lin, & Shien, 2001; Palmgren, n.d.; Wu C. C., Wu, J. J., & Huang, 2003; Wu, Lee, Huang, 2000) and to measure CST of a sludge sample a CST apparatus (Figure 4.2) is necessary. This apparatus consist of a timer, an upper plate containing probes that activate and deactivate the timer and a lower plate that holds the filter paper and a metal sample container.

In order to measure capillary section time of a sludge sample firstly, a sample of sludge is placed in the sample container as water migrates through the filter paper and reaches the first probe, so the timer is activated. After the migrated water moves ahead 1 cm in the filter paper, it reaches the second probe, so the timer is deactivated. The time interval between timer activation and deactivation is the capillary suction time and is a measure of the dewaterability of the sludge.

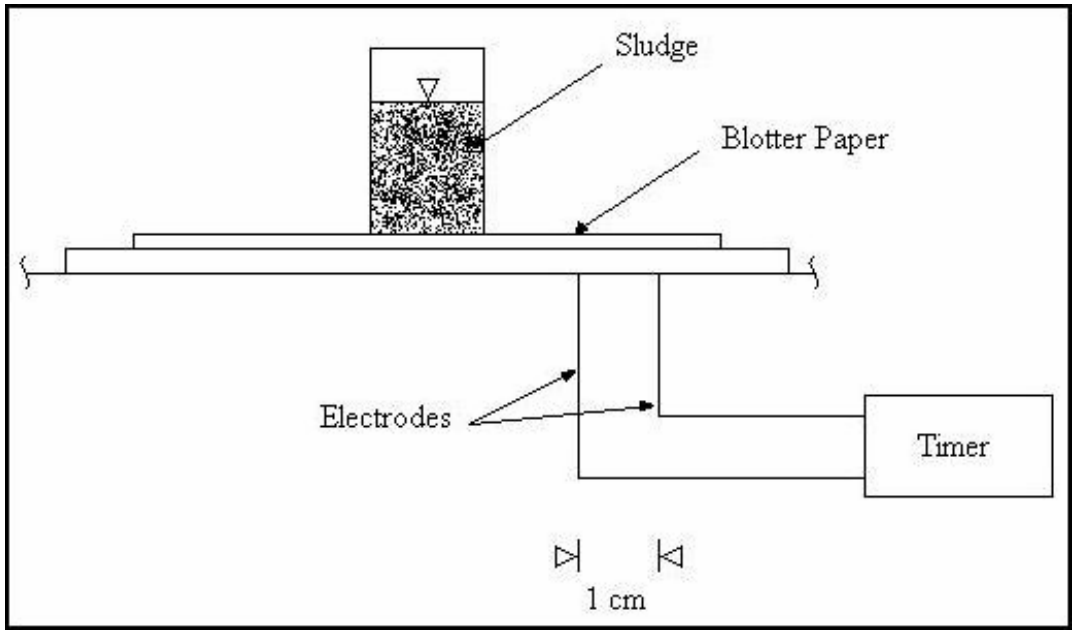


Figure 4.2 Capillary suction time apparatus (EPA, 1987)

CHAPTER FIVE
MATERIALS AND METHODS

5.1 Materials

5.1.1 Raw Sludge Samples Properties

In the experimental studies, chemical conditioning was applied to sludge samples taken from an organized industrial district (I), a leather industry (II), a meat processing industry (III), and a petrochemical industry (IV). Raw sludge samples were kept at 4°C during the experiments. The characteristics of the samples are given in Table 5.1.

Table 5.1 Properties of raw sludge samples

Parameter	**Units**	**Sample Numbers**			
		I	**II**	**III**	**IV**
pH	-	6.87	6.83	6.75	5.50
EC	µmhos/cm	4500	7200	2690	1880
DS	%	3.56	5.70	2.50	3.60
	mg/L	35.880	56.580	23.832	34.544
SS	mg/L	8860	55600	1352	9000
Oil	% (w/w)	12.83	10.52	40.04	15.34
CST	second	155.5	425.2	55.0	2000.0
SRF (r)	m/kg	2.615×10^{14}	1.601×10^{15}	1.010×10^{15}	5.528×10^{16}

5.1.2 Conditioners

Since lime, alum, and cationic polyelectrolyte are generally used for sludge conditioning purpose widely, it was aimed to use less conventional conditioners that are bentonite, gypsum ($CaSO_4$), and fly ash at the beginning of this study. The less conventional reagents were initially examined for two samples. Owing to the fact that unsatisfactorily results were obtained at these experiments, conventional

conditioners together with less conventional ones were also examined at last two experiments. The polyelectrolyte solutions were prepared as 0.1 % stock solution using distilled water. The properties of bentonite and fly ash used in the conditioning experiments are given in Table 5.2.

Table 5.2 The chemical compositions of bentonite and fly ash

Content (%)	**Bentonite**	**Fly Ash**
SiO_2	44.18	42.14
Al_2O_3	12.67	19.38
Fe_2O_3	1.28	4.64
CaO	8.88	26.96
MgO	6.64	1.78
K_2O	0.19	1.13
SO_3	-	2.43
Na_2O	2.56	-
Others	23.60	1.54

5.2 Methods

5.2.1 Analytical Methods

Dry solids content (DS, %), oil content (OC, %), suspended solids content (SS, %), pH, electrical conductivity (EC, µmhos/cm), capillary suction time (CST, s), and specific resistance to filtration (SRF, m/kg) parameters were analyzed for raw and conditioned sludge samples in laboratory studies. DS, OC, SS, pH, EC, CST, and SRF were measured according to procedures given in Standard Methods (APHA, 1995). pH measurements were carried out with a 890 MD pH meter, electrical conductivity was measured by using a YSI Model 33 conductivity-meter.

Correlation coefficients between SRF and CST parameters were calculated by using MicroSoft Excel correlation function.

5.2.2 Experimental Procedure

5.2.2.1 Oil Determination Method

The weight fraction of oil in the original sludge was determined by using Soxhlet Extraction Method. In this method the sample is dried at 103^{o}C, ground into small particles and placed in a porous cellulose thimble. The thimble is placed in an extraction chamber (2), which is suspended above a flask containing the solvent (1) and below a condenser (4). The flask is heated and the solvent (250 mL hexane) evaporates and moves up into the condenser where it is converted into a liquid that trickles into the extraction chamber containing the sample. The extraction chamber is designed so that when the solvent surrounding the sample exceeds a certain level it overflows and trickles back down into the boiling flask. At the end of the extraction process, which lasts about four hours, the flask containing the solvent and lipid is removed (in some device a funnel (3) allows to recover the solvent at the end of the extraction after closing a stopcock between the funnel and the extraction chamber). The solvent in the flask (1) is then evaporated and the mass of the remaining lipid is measured (Figure 5.1). The percentage of lipid in the initial sample can then be calculated (Cyberlipid Center, n.d.).

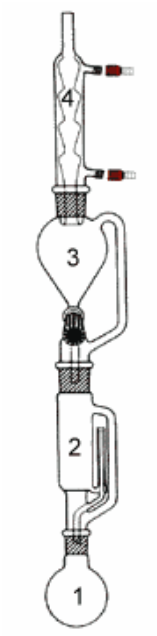


Figure 5.1 Soxhlet extraction apparatus

5.2.2.2 Chemical Conditioning Method

For conditioning studies, Jar Test Method was applied to sludge samples. The jar testing apparatus contains six paddles which stir the contents of six 1 liter beakers. Different amounts of conditioners were added to 500 mL of sludge samples in 1000 mL beakers. The mixture was stirred at 200 rpm for 2 minute. Then, the stirring speed was reduced to 25 rpm and mixing continued for 30 minutes.

5.2.2.3 Performance Evaluation of Chemical Conditioning

5.2.2.3.1 Specific Resistance to Filtration (Buncher Funnel) Test. Specific Resistance to Filtration (SRF) Test was applied to conditioned sludge samples for evaluation of dewatering characteristics. For this aim, SRF Test procedure was performed using a Buchner Funnel with a Whatman # 2 filter paper applying 2 bar of vacuum suction (see 4.1.3.2). Dry solids contents of sludge cake and filtrate samples obtained from Buchner Funnel Test applications were measured according to the procedures given in Standard Methods (APHA, 1995). Viscosities of filtrate samples were measured by using a Brookfield RVDV III Rheometer for calculation of SRF (r) value.

5.2.2.3.2 Capillary Suction Time Test. Capillary Suction Time (CST) Test was also used as another method for the evaluation of the dewatering performances of conditioned sludge samples. CST values were analyzed using a Triton A-304 M CST-meter. A standard CST sample cylinder of 1.8 cm diameter was used during experiments with Whatman # 17 filter paper (see 4.1.3.3). All CST measurements were conducted in triplicates and average of three values was taken into consideration.

CHAPTER SIX
RESULTS AND DISCUSSION

The results of experimental studies carried out with four different sludges and different conditioners are discussed below. In addition, filtration data of SRF analysis, SRF and CST results tables, and correlation coefficient determinations between SRF and CST results are also given at Appendix A, B, and C, respectively.

6.1 Results of Experimental Studies with Sludge I

Sludge I was taken from the central wastewater treatment plant of an Organized Industrial District, which is established in northwest of Izmir. There are 318 big industrial parcels and 177 small ones. In this Zone there is continuous production of almost every sector such as: textile dyeing and finishing; leather and ready made garments; cotton thread and fabrics; iron-steel products; metal; machinery for heavy industry and agriculture; steel constructions; spare parts and by-products for motorized vehicles; workbenches and presses; printing and publishing; plastic and rubber; hoses; pipes; medical and agricultural drugs; wood and wooden furniture; paper and cardboard packaging; electrics and electronics; cleaning products; chemicals; paints; varnishes; roofing and construction materials; glass; tobacco; canned foods; dried figs, raisins and other dried fruits; vegetable and olive oils; salt; floury, dairy and sweet foods and animal feeds.

The weight fraction of oil in the Sludge I was 12.8 % w/w. CST and SRF values of the raw sludge sample were found as 2.6×10^{14} m/kg and 156 s, respectively.

6.1.1 Bentonite

Bentonite was examined in the range of 0.1 to 4% dosage. The results shown in Figure 6.1 indicate that bentonite was not an effective conditioner for this type sludge conditioning. Since the CST analyses did not give appropriate results,

experimental studies have been stopped and SRF analysis was not carried out for this conditioner.

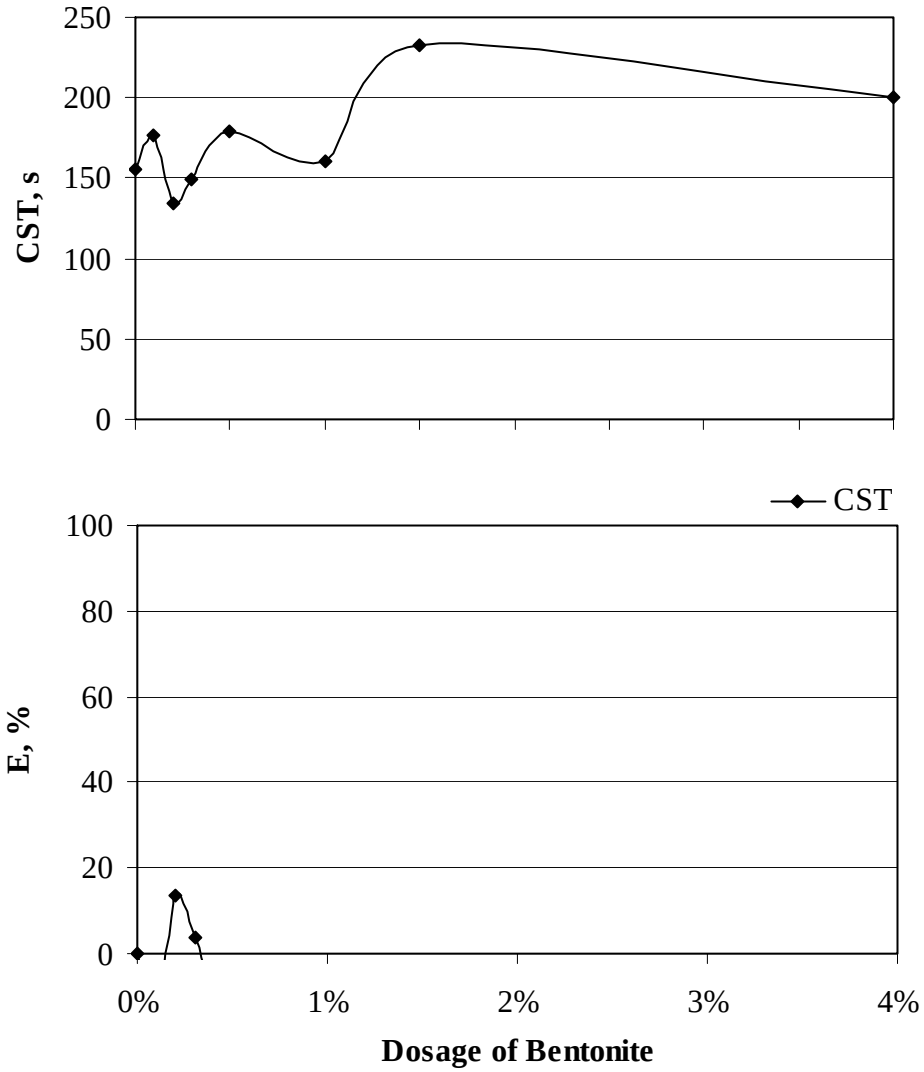


Figure 6.1 Bentonite performances for the Organized Industrial District sludge conditioning

6.1.2 Fly Ash

From 1.5% to 10.0% fly ash dosages were tested to investigate the effect of fly ash on the conditioning of the organized industrial district sludge. The best CST result was obtained as 85.8 s (E= 44.8%) at 4.0% dosage, and the best SRF result was 1.03022×10^{14} m/kg (E= 60.6%) at 6.0% fly ash dosage (Figure 6.2). Correlation between CST and SRF results was 0.53.

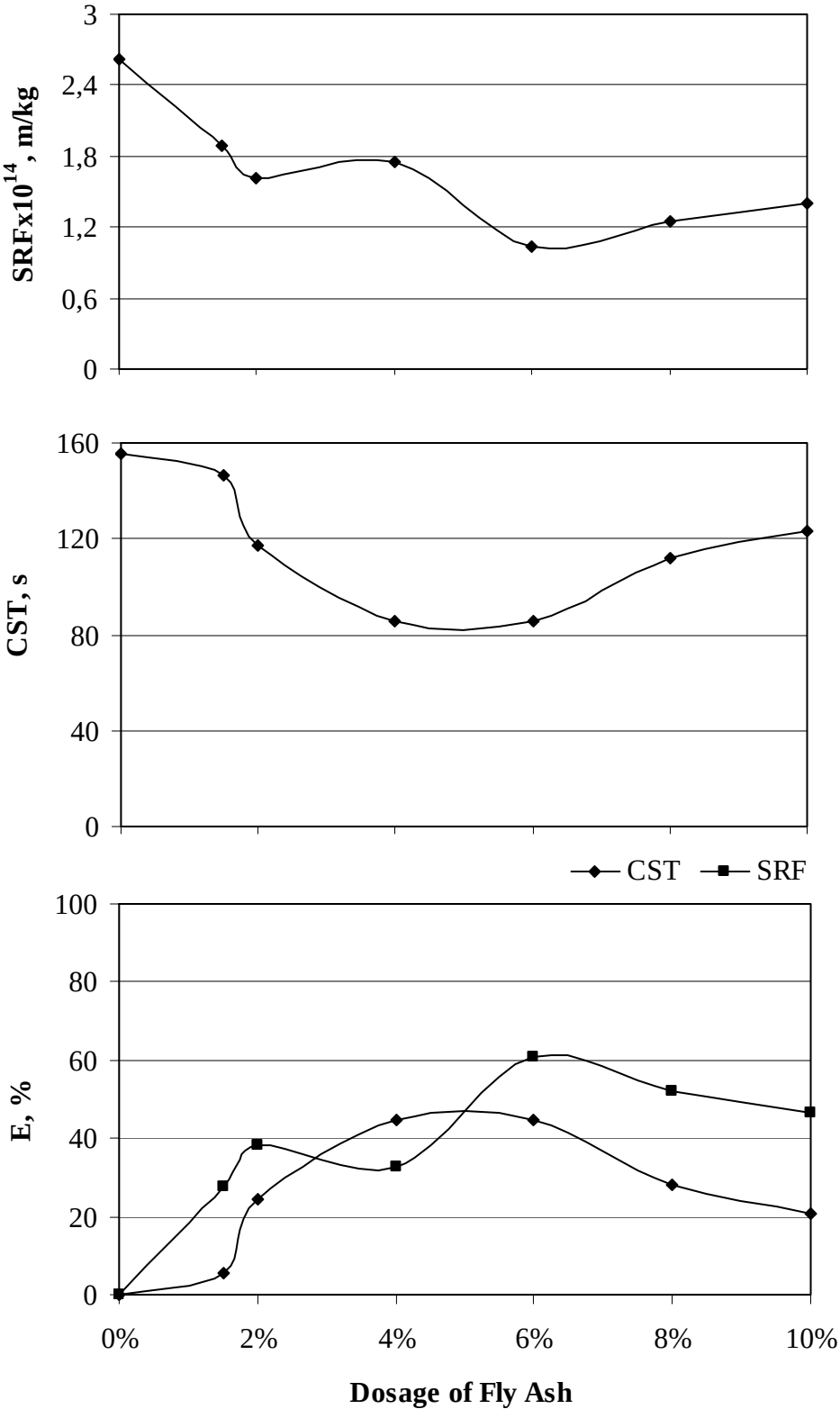


Figure 6.2 Fly ash performances for the Organized Industrial District sludge conditioning

6.1.3 Gypsum

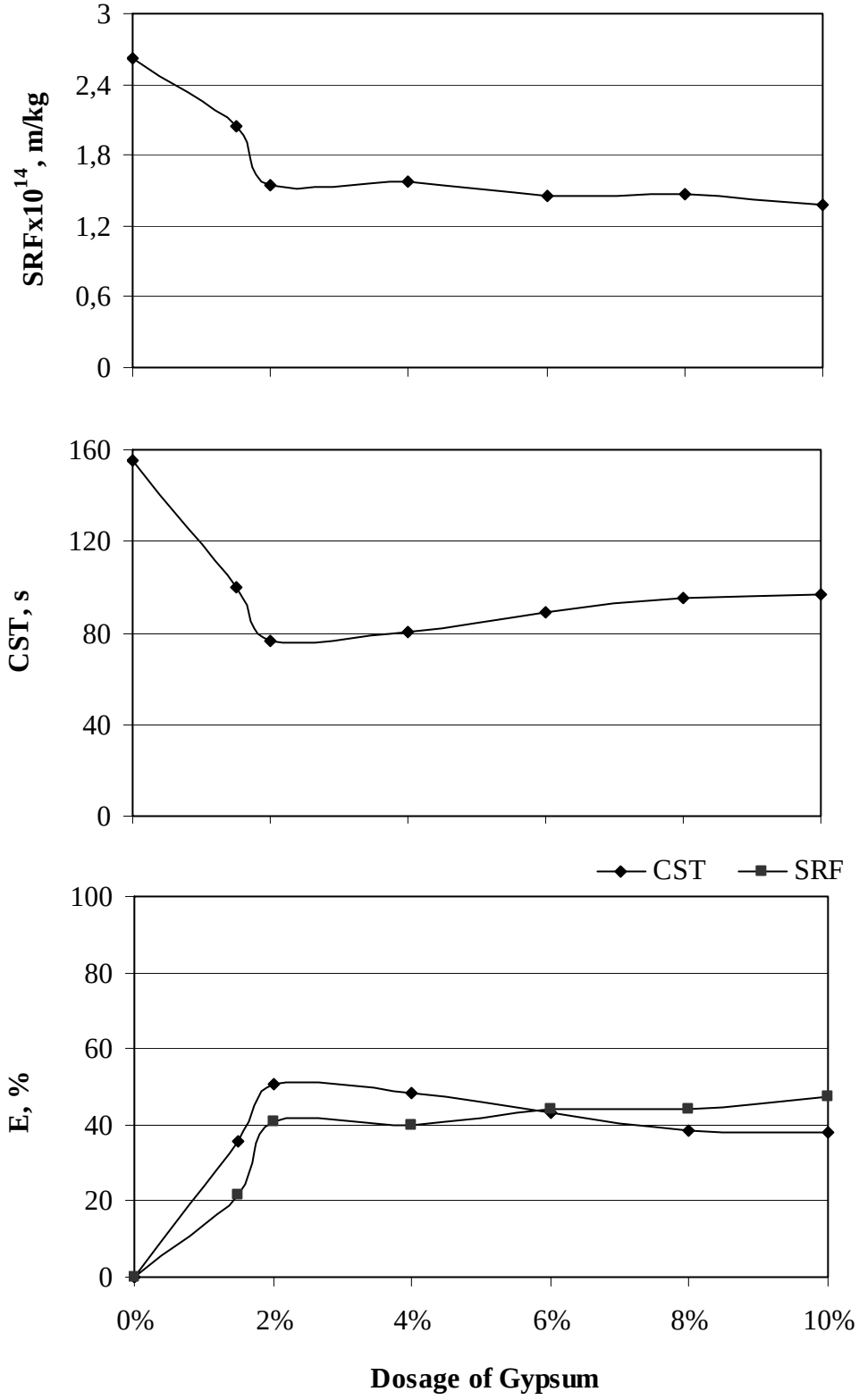


Figure 6.3 Gypsum performances for the Organized Industrial District sludge conditioning

Figure 6.3 shows the results of experiments carried out with gypsum. Gypsum dosages were applied from 1.5% to 10.0%. Although minimum SRF was calculated as $1.38x10^{14}$ m/kg (E = 47.23%) at 10% dosage, there was no huge difference between the results obtained at 2% and 10%; and minimum CST was also obtained at 2.0% dosage as 76.5 s (E = 50.8%). Therefore, 2% gypsum was determined as optimum dosage. Correlation coefficient between SRF and CST was 0.76.

6.2 Results of Experimental Studies with Sludge II

Sludge II was taken from the wastewater treatment plant of a Leather Industry. The company is placed in Torbali, Izmir. In this tannery complex, the raw materials are processed to shoe upper, lining, bag, belt and upholstery leathers. Sludge II contains 10.5 % w/w oil. CST and SRF values of the sludge were $1.6x10^{15}$ m/kg and 425 s, respectively. In order to condition the sludge, bentonite, fly ash, and gypsum were examined at different dosages.

6.2.1 Bentonite

Bentonite was examined in the range of 0.5 to 4.0% dosage (Figure 6.4). The lowest CST was obtained as 340 s (E = 20%) at 0.1% bentonite dosage. The best SRF result was $2.1x10^{15}$ m/kg at 1.5% bentonite dosage; so any SRF reduction performance was obtained with bentonite additions. However, correlation between SRF and CST results were very high ($R^2 = 0.82$).

6.2.2 Fly Ash

In the range of 2.0 to 12.0% dosage of fly ash was examined for the leather industry sludge conditioning (Figure 6.5). Almost similar results were achieved with bentonite applications. Any effects of fly ash additions on SRF reduction were detected at the applied dosages and minimum SRF value was obtained as $1.98x10^{15}$ m/kg at 2.0% dosage. Only 8.8% CST reduction was achieved at 6% dosage. Correlation between SRF and CST results was 0.64.

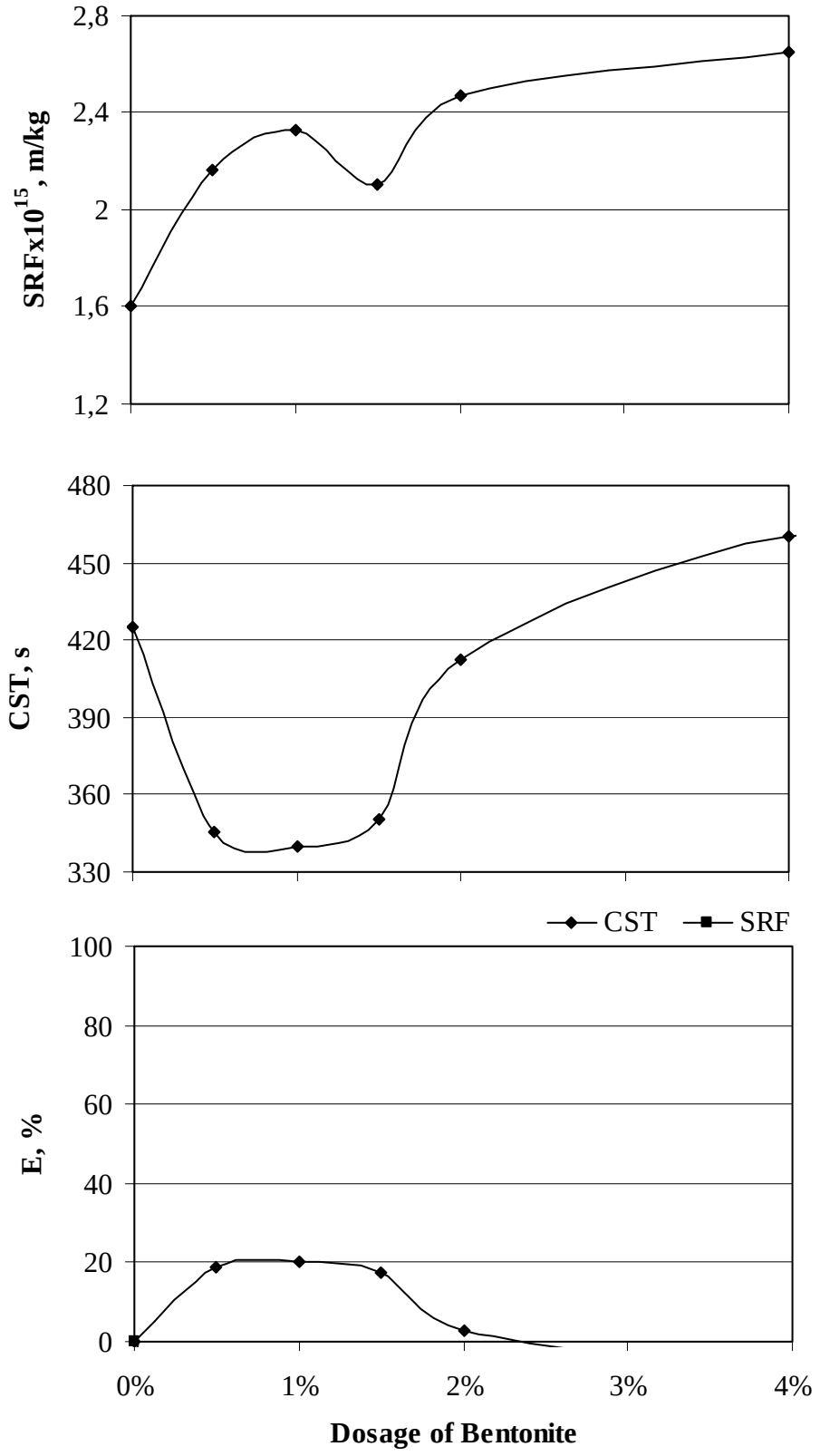


Figure 6.4 Bentonite performances for the Leather Industry sludge conditioning

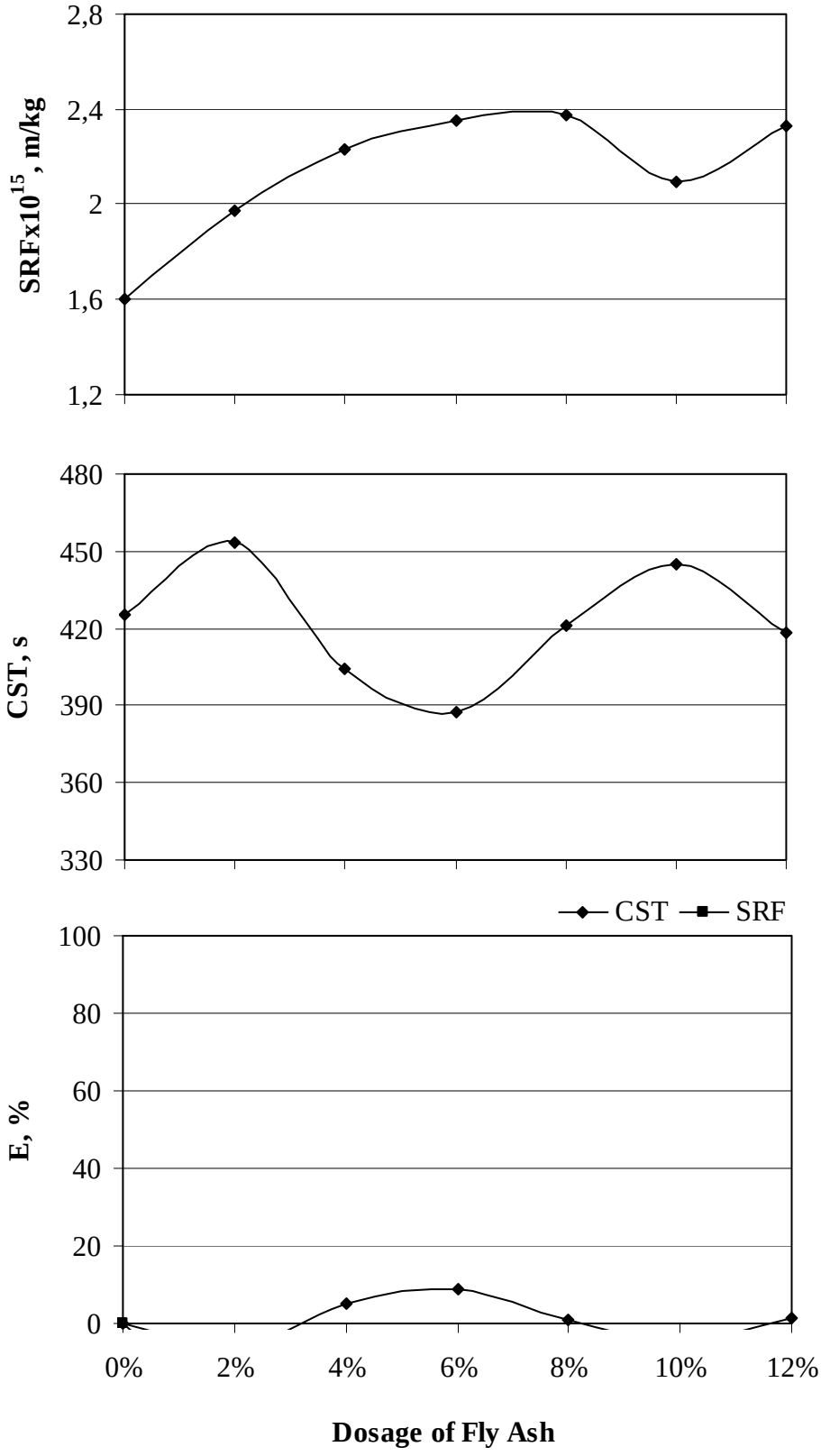


Figure 6.5 Fly ash performances for the Leather Industry sludge conditioning

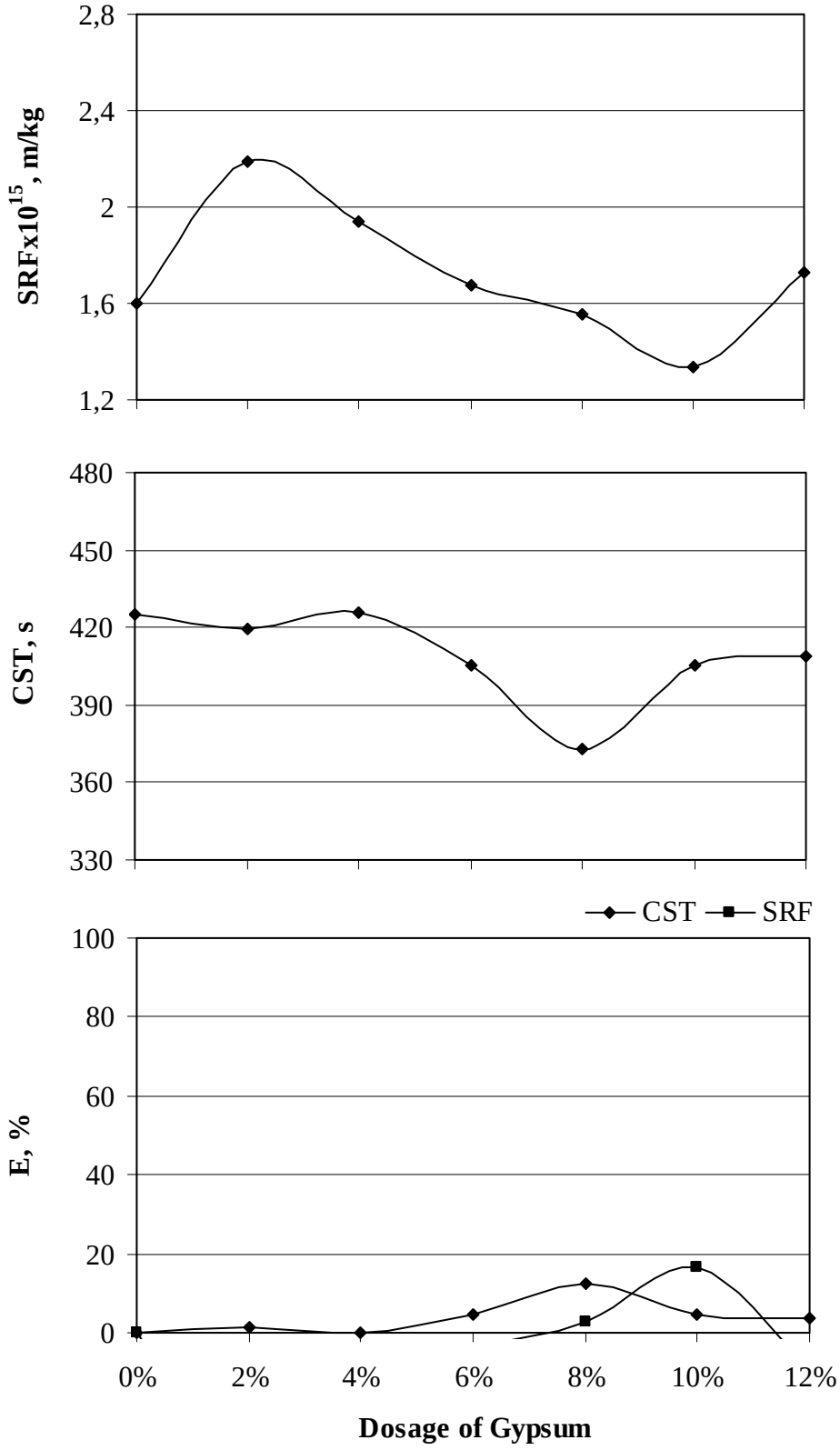


Figure 6.6 Gypsum performances for the Leather Industry sludge conditioning

6.2.3 Gypsum

The examined dosages of gypsum were between 2.0% to 12.0% for Sludge II (Figure 6.6). CST decreased to 373 s at 8.0% gypsum application and SRF reduced to $1.34x10^{15}$ m/kg at 10.0%. CST and SRF reduction efficiency was only 12.28% and 16.53%, respectively. So, the addition of gypsum for the conditioning of Sludge II is not a reasonable solution. Correlation coefficient between SRF and CST was 0.22.

6.3 Results of Experimental Studies with Sludge III

Sludge III was taken from a wastewater treatment plant of a Meat Processing Industry located in Kaynaklar, Izmir. Since the wastewater plant has oil removal units, thickened sludge contain only 8% w/w. Therefore, oil scraped from oil separator was added to the sludge and oil content of the sludge was increased to 40% w/w. CST and SRF values of the sludge sample were found as $1.0x10^{15}$ m/kg and 55 s, respectively. Bentonite, fly ash, gypsum, lime, alum, and polyelectrolyte were examined with this sludge.

6.3.1 Bentonite

Bentonite dosages were varied between 0.5% - 3.0% (Figure 6.7). As in previous studies, bentonite gave unsatisfactory results for Sludge III. Since only about 10% CST reduction was obtained, SRF analyses were not carried out.

6.3.2 Fly Ash

The results obtained with fly ash application for meat processing industry sludge conditioning are depicted in Figure 6.8. Fly ash was dosed to the sludge in the range of 2.0% to 18.0%. As seen from the figure, this conditioner did not give high conditioning efficiency. Maximum CST reduction efficiency was 8.7% (CST_{min} = 50.2 s).

6.3.3 Gypsum

Figure 6.9 shows the gypsum applications results for Sludge III. It was examined in the range of 2.0% to 14.0% dosage. As in bentonite and fly ash applications, insufficient conditioning performances were obtained with gypsum. Maximum CST reduction efficiency was achieved as 9.5% at 12% dosage (CST_{min} = 51.4 s). Hence, SRF measurements were not performed.

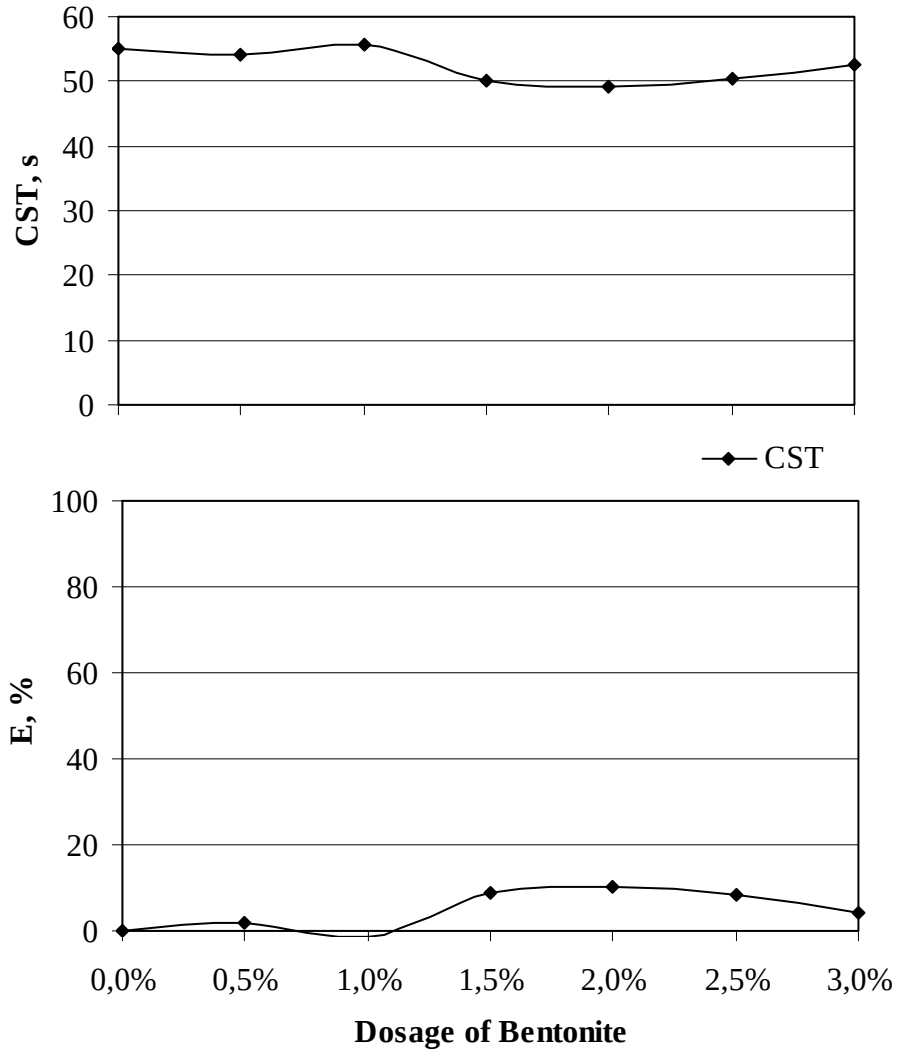


Figure 6.7 Bentonite performances for the Meat Processing Industry sludge conditioning

6.3.4 Alum

Alum was examined in the range of 4.0 to 22.0% dosages (Figure 6.10). Alum gave better results than previously applied conditioners. Maximum CST reduction was 71.8% (CST_{min}= 15.5 s) and it was obtained at 16.0% dosage. However, 22.0% was the best dosage for SRF. At this application, 59.3% SRF reduction (SRF_{min}= $0.41x10^{15}$ m/kg) was obtained. Correlation between SRF and CST results was 0.85.

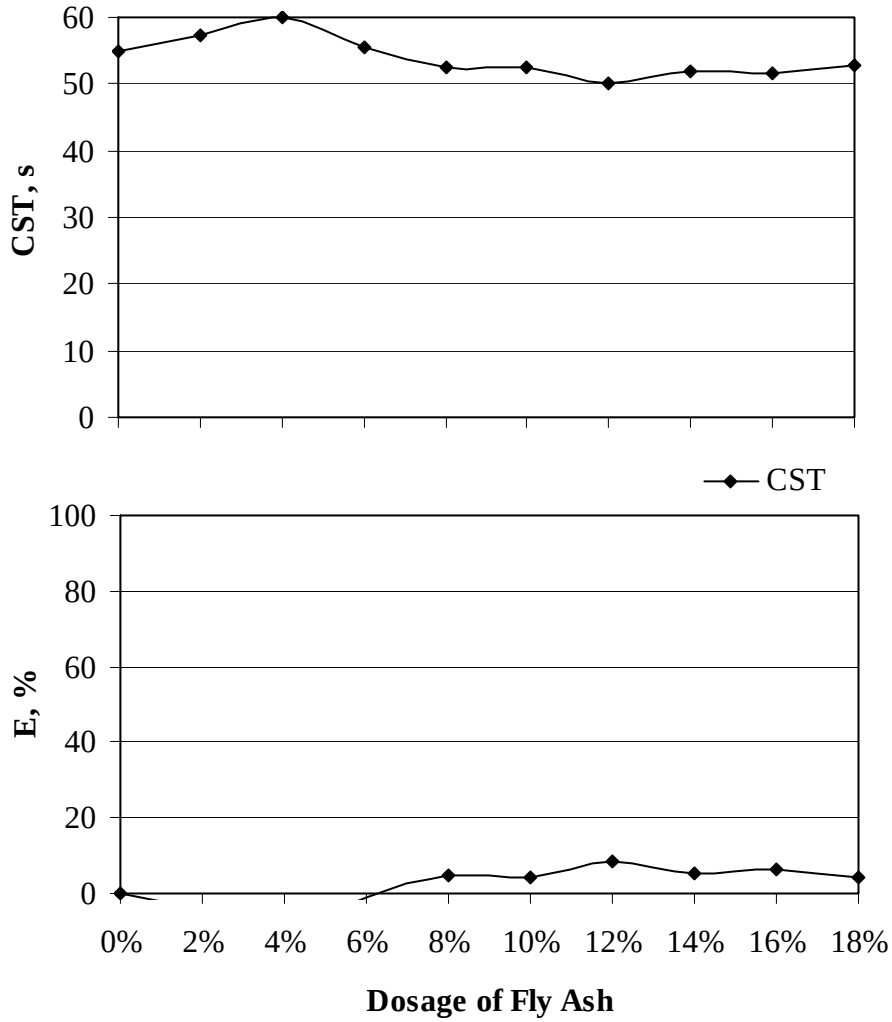


Figure 6.8 Fly ash performances for the Meat Processing Industry sludge conditioning

6.3.5 Lime

Figure 6.11 depicts the lime application results. It was applied between 2.0% and 26% dosages. Minimum CST value was observed as 23.2 s (E = 57.8%) at 26% lime

dosage and minimum SRF value was calculated as $0.41x10^{15}$ m/kg (E = 59.1%) at 14% dosage. Correlation between CST and SRF was very low (R^2= 0.18).

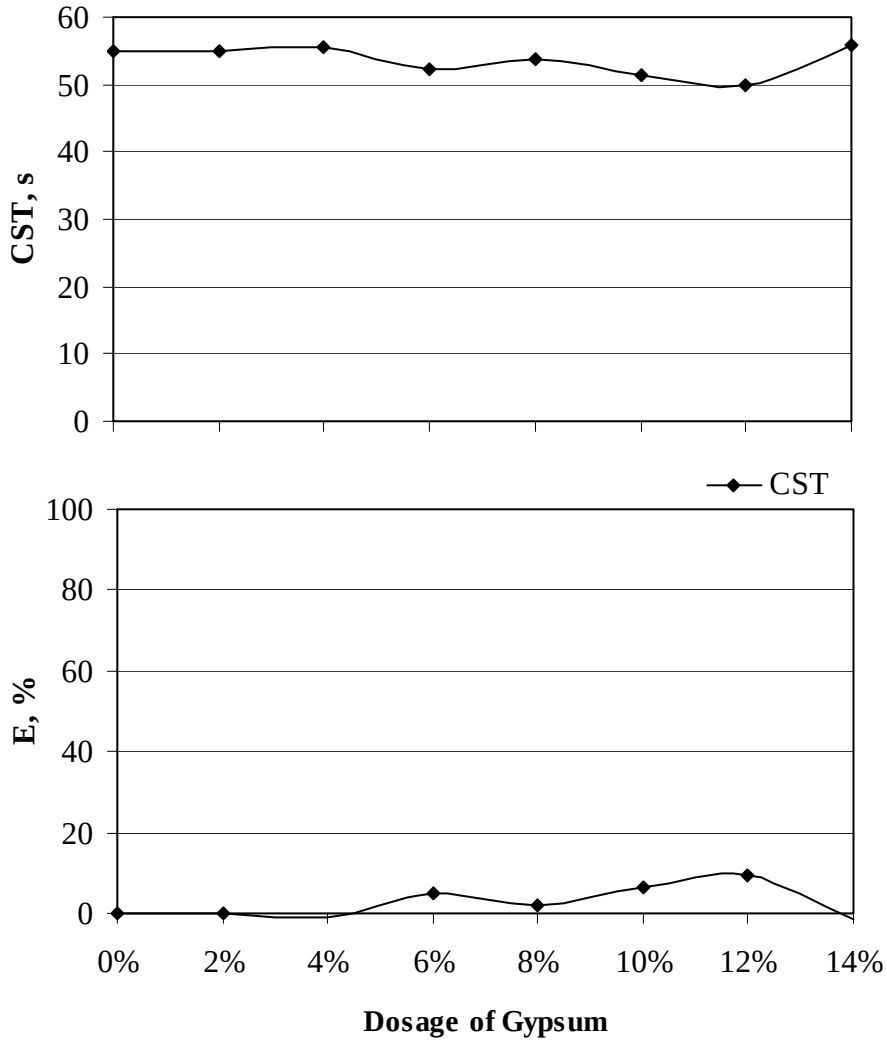


Figure 6.9 Gypsum performances for the Meat Processing Industry sludge conditioning

6.3.6 Polyelectrolyte

Cationic polyelectrolyte was dosed in the range of 0.2 to 1.4%. The best conditioning results was obtained with polyelectrolyte among other applied conditioners. The CST reduced to minimum of 10.1 s (E = 82%) at the 1.0% dosage, while SRF reduced to minimum of $0.25x10^{15}$ m/kg (E = 75%) at the 0.8% (Figure 6.12). Correlation between CST and SRF results was 0.8 at this experiment.

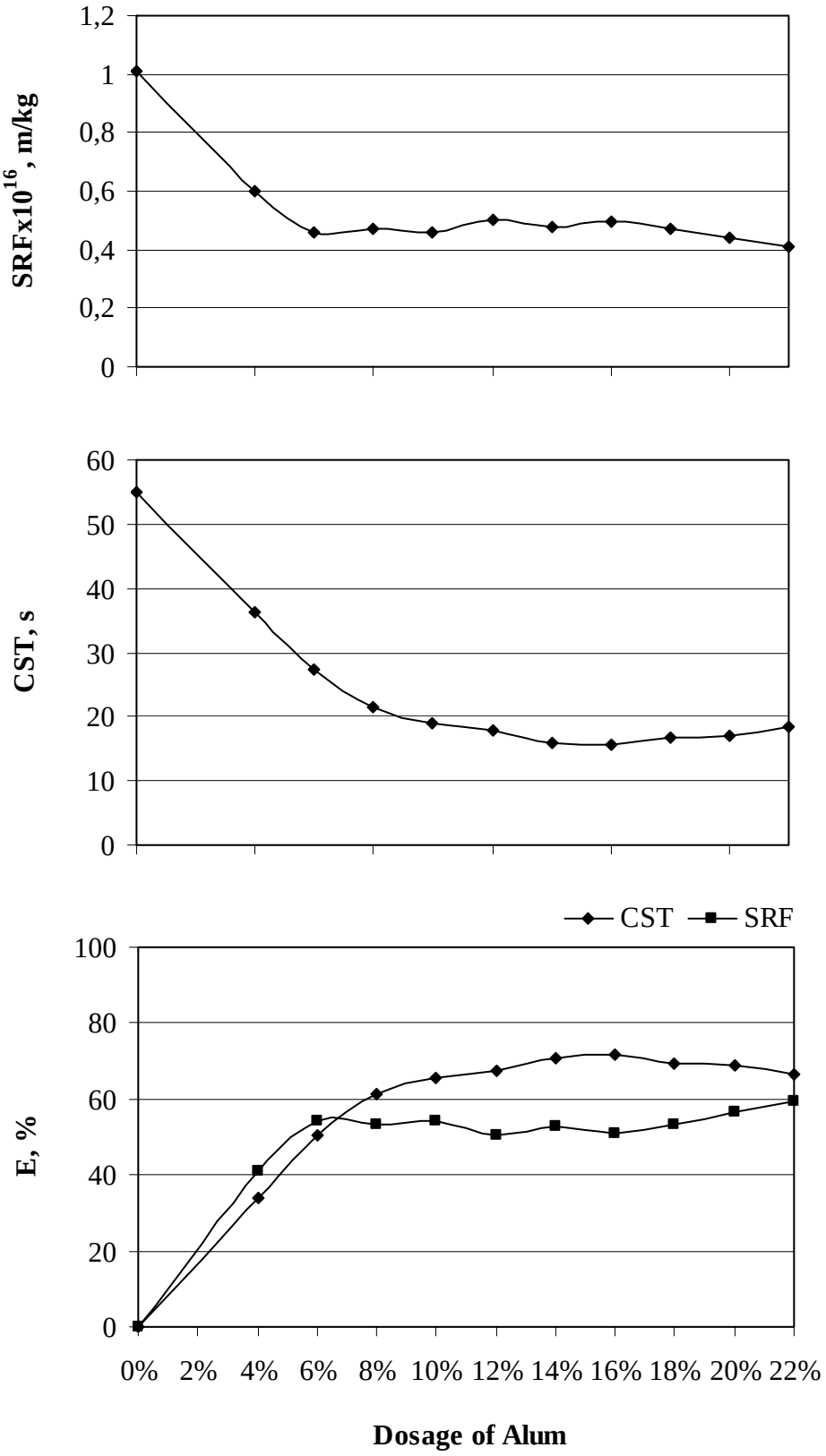


Figure 6.10 Alum performances for Meat Processing Industry sludge conditioning

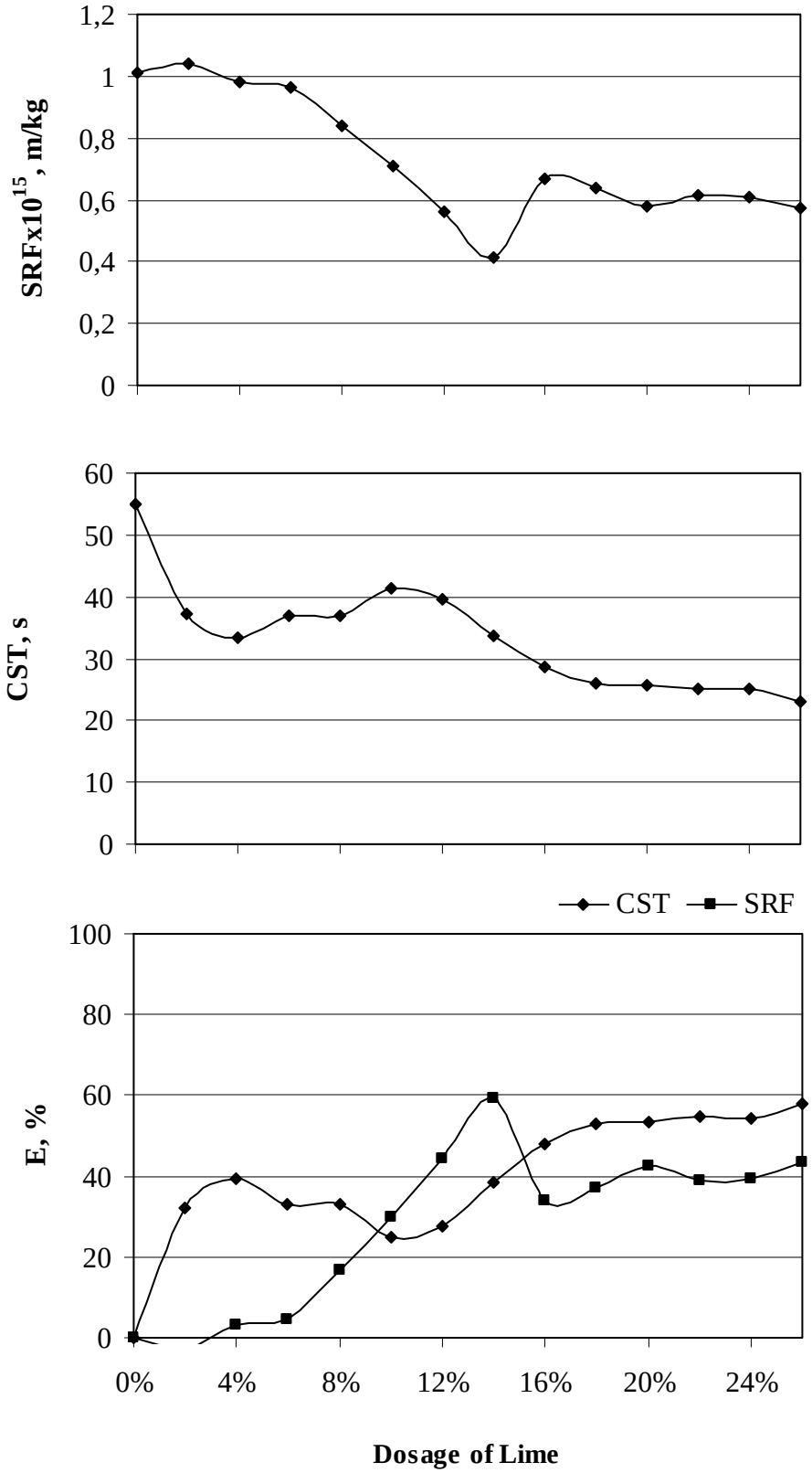


Figure 6.11 Lime performances for the Meat Processing Industry sludge conditioning

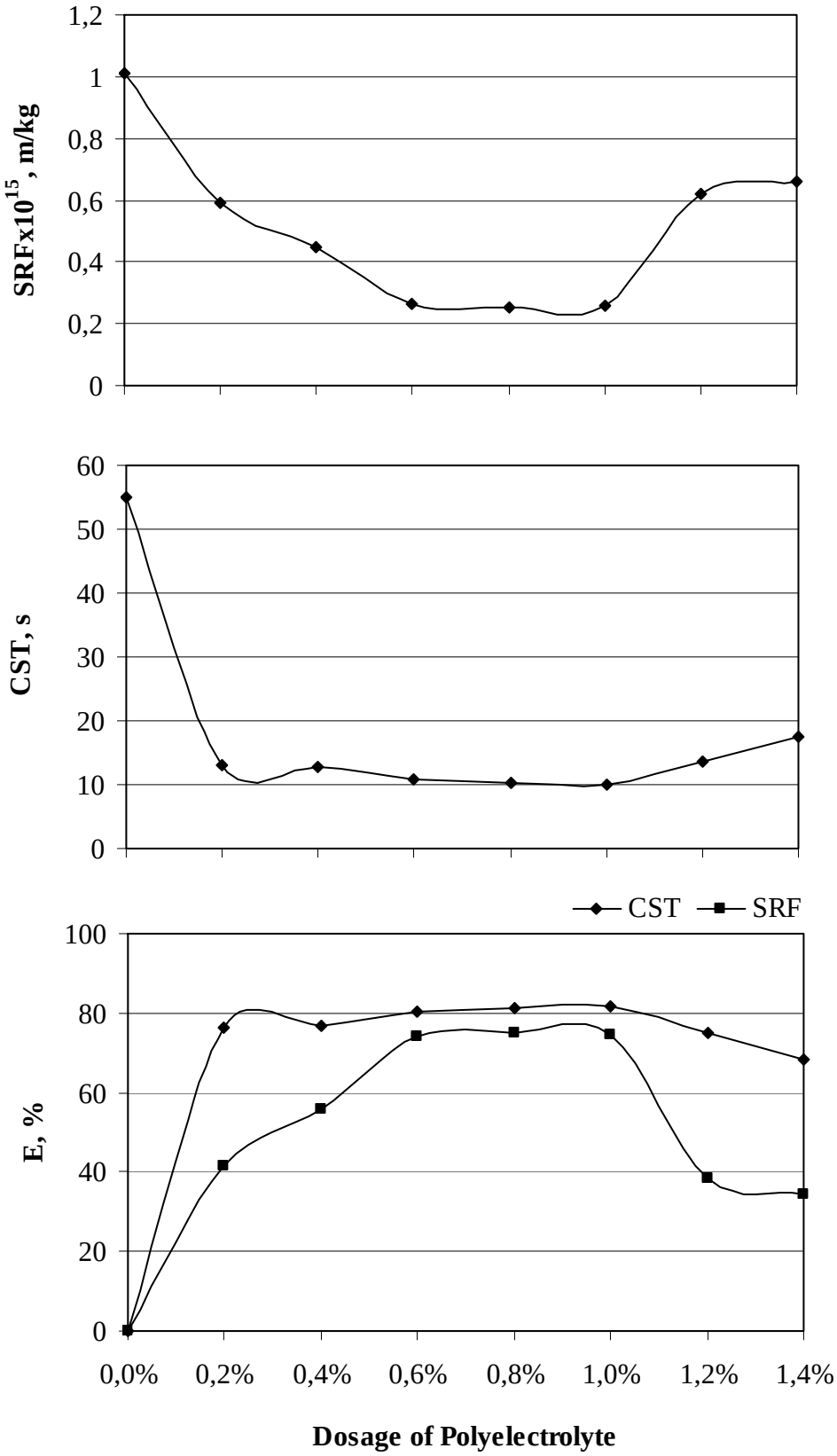


Figure 6.12 Polyelectrolyte performances for the Meat Processing Industry sludge conditioning

6.4 Results of Experimental Studies with Sludge IV

Sludge IV was taken from a wastewater treatment plant of a Petrochemical Industry located in Aliaga, Izmir. The weight fraction of oil in the original sludge was 15 % w/w. CST and SRF values of the raw sludge sample were found as $5.5x10^{16}$ m/kg and 2000 s, respectively.

6.4.1 Bentonite

Chemical conditioning efficiencies depending on the dosage of examined bentonite are given in Figure 6.13. Bentonite was not a suitable conditioner for petrochemical sludge dewatering. Minimum SRF ($2.83x10^{16}$ m/kg) was obtained at 2 % bentonite dosage, while the minimum CST (1460 s) was obtained at 1.5% dosage. In other words, approximately 49% SRF and 27% CST reduction was achieved with bentonite. Correlation between SRF and CST results are also very low ($R^2 = 0.59$).

6.4.2 Fly Ash

The conditioning efficiencies of fly ash are given in Figure 6.14 with respect to dosage of fly ash. The most appropriate dosage of alum was determined as 10% for SRF and 6% for CST parameter. At these dosages, SRF and CST was $4x10^{16}$ m/kg (E = 26%) and 1476 s (E = 26%), respectively. Correlation coefficient between SRF and CST is only 0.69.

6.4.3 Gypsum

The results obtained with gypsum application for petrochemical sludge conditioning are depicted in Figure 6.15. Maximum 44% SRF reduction efficiency was obtained at 12% gypsum dosage ($SRF_{min} = 3.1x10^{16}$ m/kg), whereas maximum 32% CST reduction was obtained at 10% (CST_{min} = 1362 s). At this application, only 0.47 correlations were achieved between SRF and CST.

6.4.4 Alum

Figure 6.16 summarizes the experimental results of petrochemical sludge conditioning studies with alum. Alum was the one of the best conditioner and 8% alum dosage was the optimum dosage for both SRF and CST. SRF decreased from $5.5x10^{16}$ to $0.5x10^{16}$ m/kg (E = 92%) while CST reduced from 2000 s to 600 s (E = 70%) for this application. For increasing alum dosages, the CST and SRF values decrease, but the decrease at dosages more than 8% were not significant. Correlation coefficient between SRF and CST was also very high ($R^2 = 0.90$).

6.4.5 Lime

Lime is the one of the most popular conditioner because of its low cost. In this study, intermediate success was obtained with lime (Figure 6.17). Approximately 38.5 % CST (CST_{min} = 1232 s) and 80% SRF ($SRF_{min} = 1.1x10^{16}$ m/kg) reduction was achieved at 8% and 12% lime dosages, respectively. 0.58 correlations between two parameters were obtained at lime additions.

6.4.6 Polyelectrolyte

Cationic polymers are the predominant form of organic additive used in the sludge conditioning. In this experiment, cationic polyelectrolyte also gave the best results among examined conditioners and up to 95% CST and SRF reduction could be obtained (Figure 6.18). CST decreased to until 22.4 s (E=99%) and SRF reduced to $2.8x10^{15}$ m/kg (E=95%). Correlation between SRF and CST is very high as alum experiment ($R^2 = 0.89$).

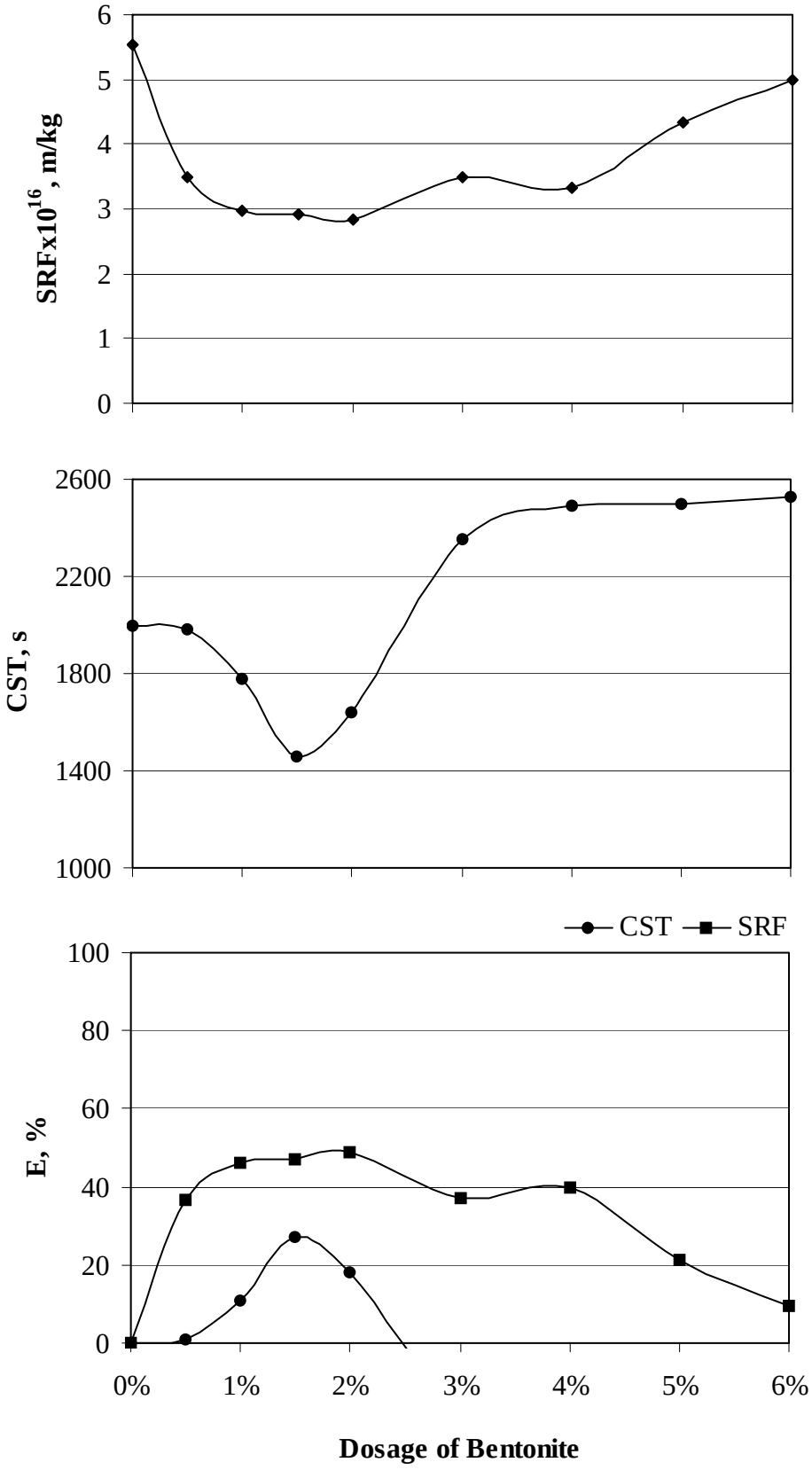


Figure 6.13 Bentonite performances for the Petrochemical Industry sludge conditioning

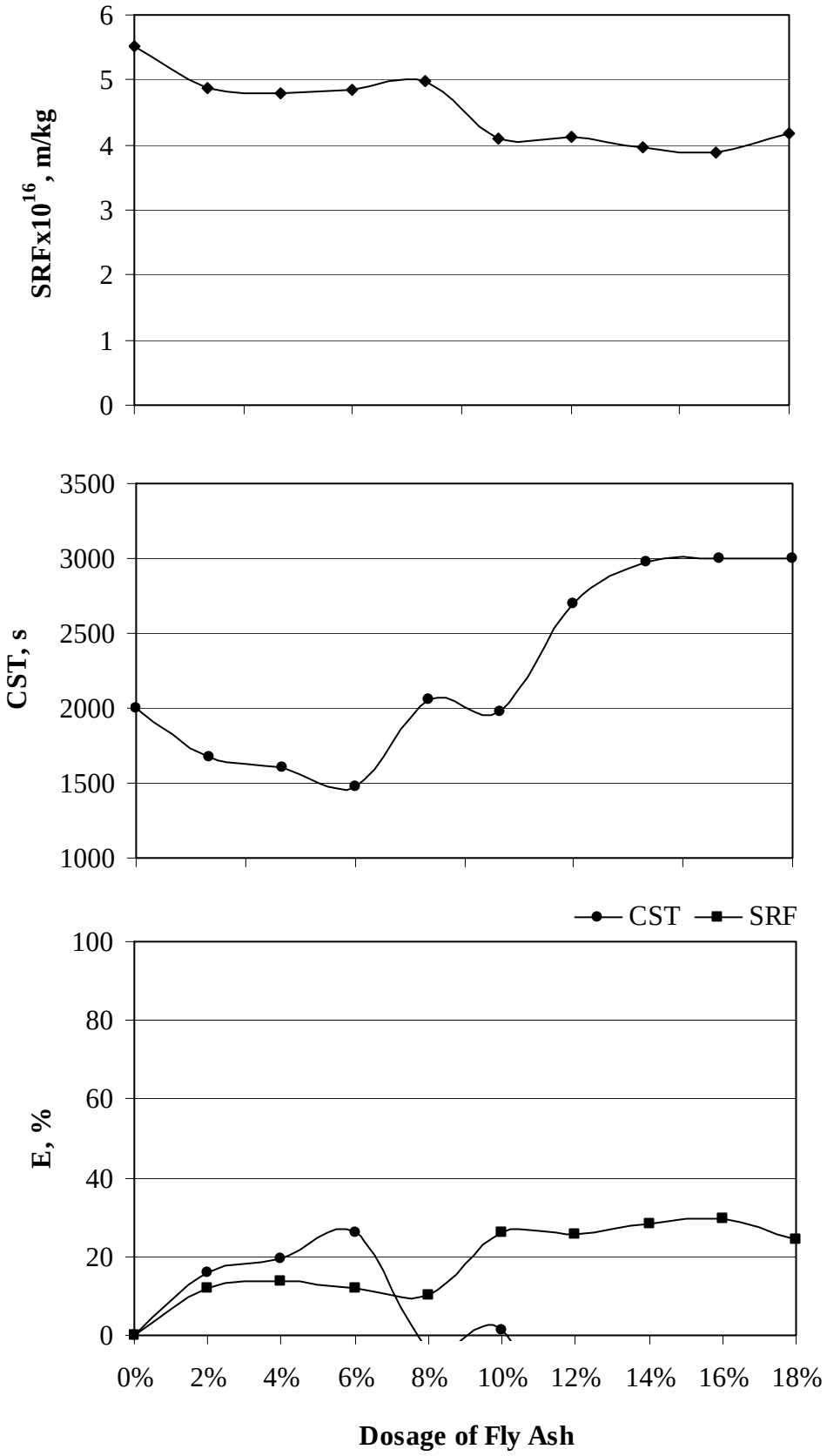


Figure 6.14 Fly ash performances for the Petrochemical Industry sludge conditioning

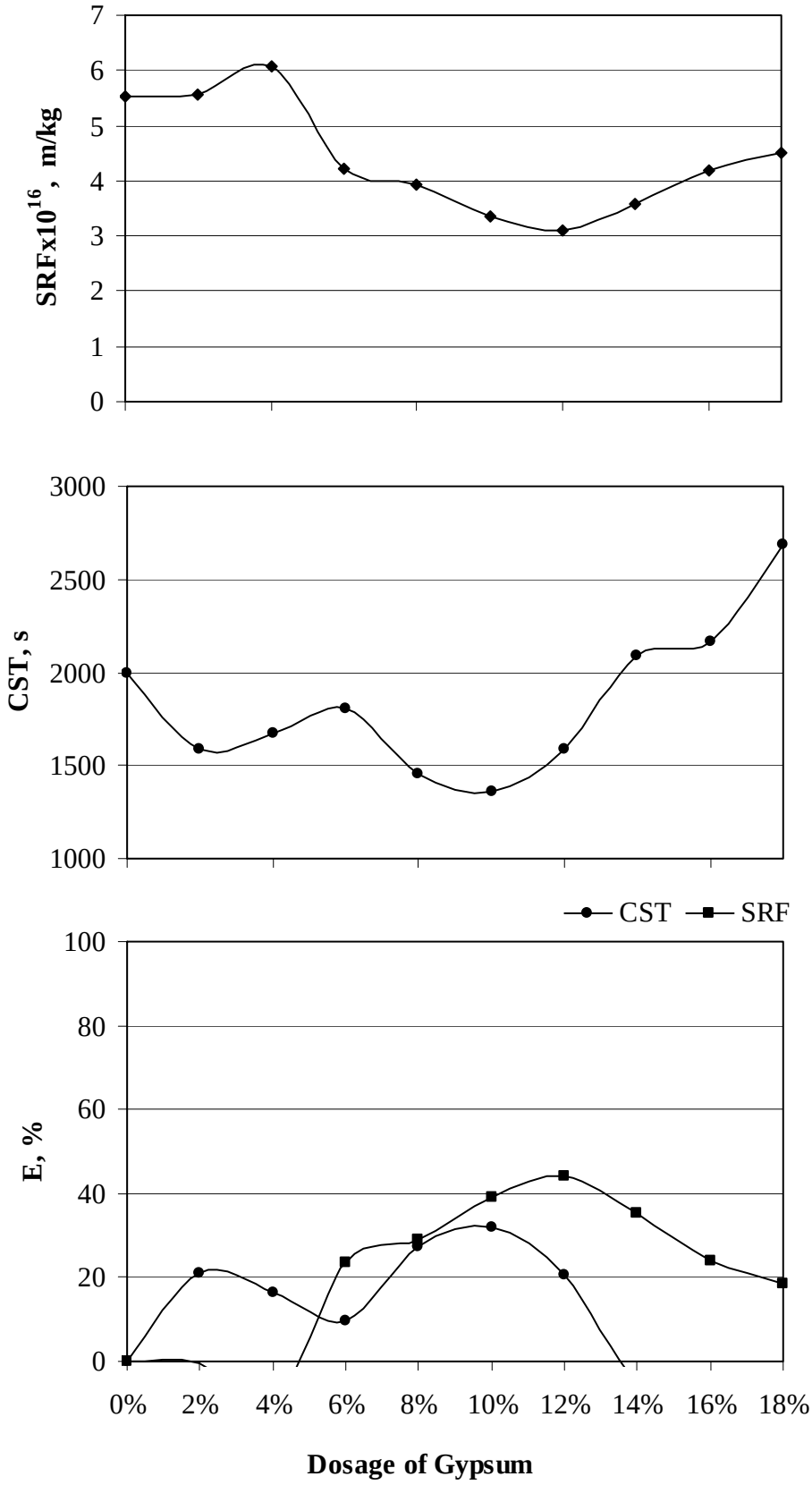


Figure 6.15 Gypsum performances for the Petrochemical Industry sludge conditioning

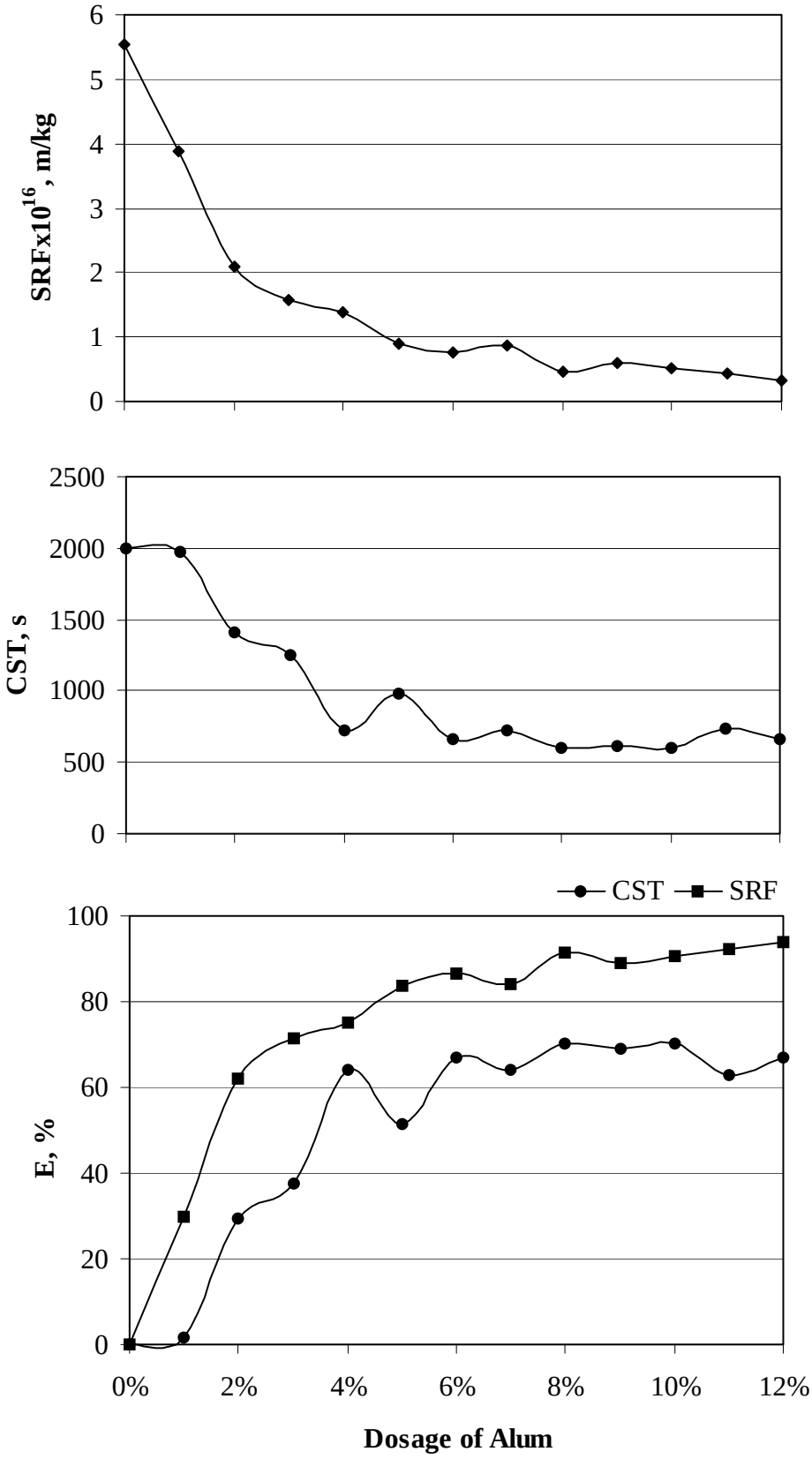


Figure 6.16 Alum performances for the Petrochemical Industry sludge conditioning

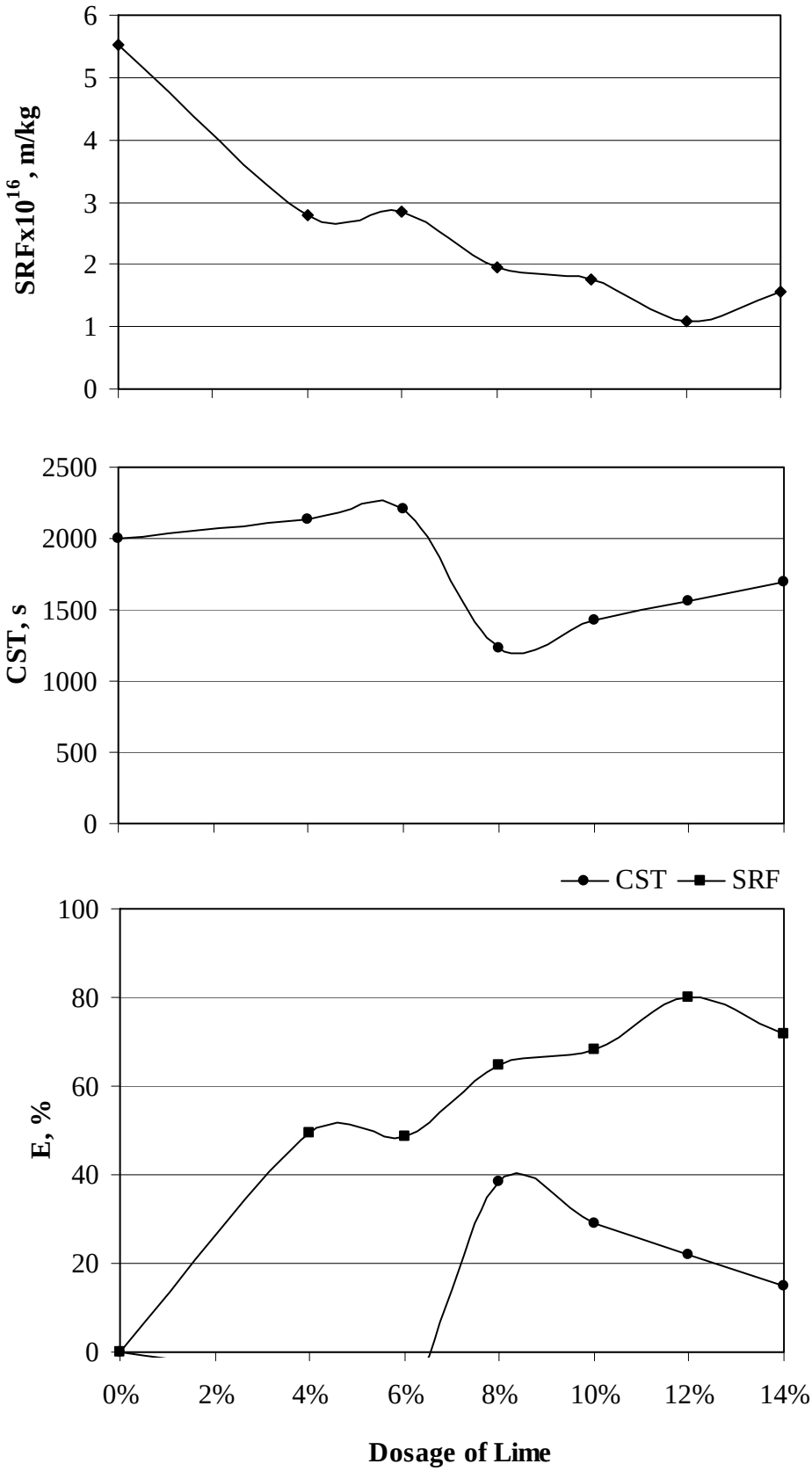


Figure 6.17 Lime performances for the Petrochemical Industry sludge conditioning

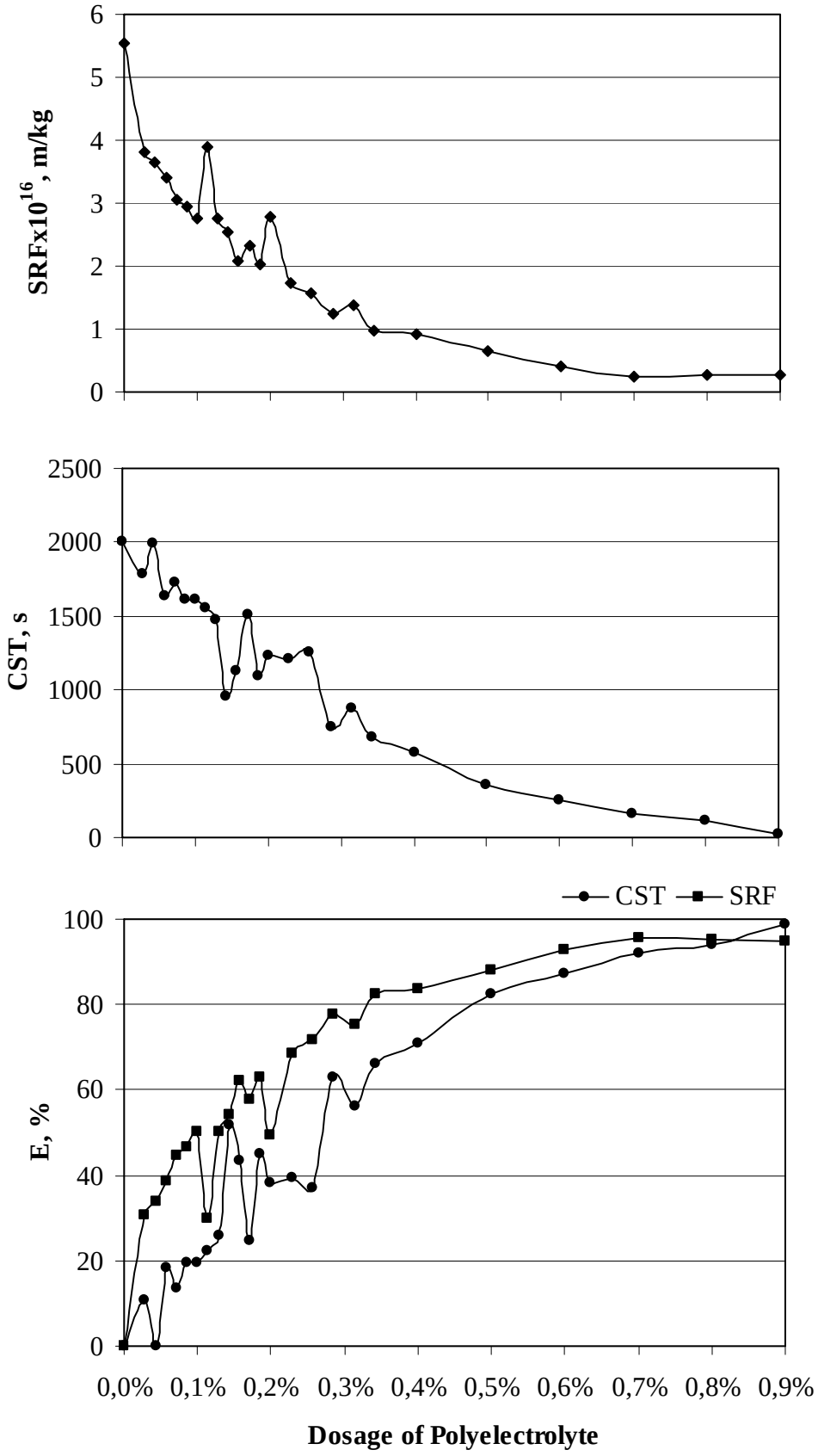


Figure 6.18 Polyelectrolyte performances for the Petrochemical Industry sludge conditioning

CHAPTER SEVEN
CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This study was performed to investigate the effects of both conventional and less conventional conditioners on oily sludge conditioning. For this purpose, oily sludge samples taken from an organized industrial district, a leather industry, a meat processing industry, and a petrochemical industry were used. After characterization studies, all sludge samples were conditioned by using three less conventional conditioners, such as bentonite, fly ash, and gypsum; and two sludge samples (Sludge Sample III and IV) were conditioned with conventional conditioners, such as alum, lime, and cationic polyelectrolyte. To determine the optimum dose range of each type of conditioner applications, specific resistance to filter (Buchner Funnel Test) and capillary suction time tests were applied to the raw and conditioned sludge samples.

According to experimental results, the conclusion remarks from this study could be given as follows:

- The best conditioning performances of each conditioner for each sludge sample are given in Table 7.1.

Table 7.1 The best removal efficiencies (%) results of all experiments

Sludge Sample	Bentonite		Fly Ash		Gypsum		Alum		Lime		Polyelect.	
	SRF	CST	SRF	CST	SRF	CST	SRF	CST	SRF	CST	SRF	CST
I	---	13	61	45	47	51	---	---	---	---	---	---
II	---	20	---	9	17	12	---	---	---	---	---	---
III	---	10	---	9	---	9.5	59	72	59	58	75	82
IV	49	27	26	26	44	32	94	70	80	38	95	99

- Conventional chemical conditioners examined in this study, which are alum, lime, and cationic polyelectrolyte, gave the better results compared to bentonite, fly ash, and gypsum. Hwa, & Jeyaseelan have also reported that the dewaterability of oily sludges could be enhanced by addition of lime or alum in sludge conditioning stage (Hwa, & Jeyaseelan 1997a; Jeyaseelan, & Hwa, 1993). However, they studied the effect of fly ash addition on oily sludge conditioning in their other study and according to this study; fly ash could be chosen for oily sludge conditioning purpose (Hwa, & Jeyaseelan, 1997b).

- Cationic polyelectrolyte gave the better results among the examined conditioners. Up to 95% CST and SRF reductions could be obtained with this conditioner for Sludge Sample IV, and up to 75% SRF, 80% CST reductions could be obtained with again this conditioner for Sludge Sample III.

- Alum was another conditioner giving better dewaterability compared to other conditioners.

- For Sludge Sample I, although fly ash and gypsum gave better results than bentonite, insufficient conditioning performances were observed with them. Therefore, they should not be considered as conditioning reagents for this type of sludge.

- Bentonite, fly ash, and gypsum were applied to sludge taken from a leather industry (Sludge Sample II). Nevertheless, unsatisfactory results were observed with them.

- Lower than 10% removal efficiencies could be obtained with bentonite, fly ash, and gypsum with Sludge Sample III. Alum, lime, and cationic polyelectrolyte were also examined for Sludge Sample III. While alum and lime gave approximately 60% reduction efficiency for CST and SRF, polyelectrolyte gave 75% and 82% reduction for SRF and CST, respectively.

- Up to 95% CST and SRF reductions could be obtained with cationic polyelectrolyte for Sludge Sample IV. Bentonite, fly ash and gypsum again did not give an acceptable result, and lower than 50% CST and SRF reduction could be achieved by using these conditioners. Correlation coefficients between SRF and CST parameters were very low for bentonite, fly ash, gypsum, and lime applications. However, the correlation coefficients exhibited better agreements between two parameters for alum and polyelectrolyte applications.

7.2 Recommendations

- Although bentonite, fly ash, and gypsum did not give suitable results, they can be used as supplementary reagents with alum and polyelectrolyte. Hence, the conditioning efficiency of combination of these chemicals should be examined at further researches.

- This kind of study could be carried out with sludges containing different amount of oil.

- Cost analysis should be carried out in addition to investigation of sludge dewatering properties.

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APPENDICES

Appendices A: Filtration Data Tables and Graphics of the Best Results

Table A1 Filtration data of 6.0% fly ash dosage for Sludge Sample I

T (s)	V (ml)	T/V
10	28	0.357143
20	36	0.555556
30	41.5	0.722892
40	46	0.869565
50	51	0.980392
60	54.5	1.100917
70	58	1.206897
80	61	1.311475
90	64	1.406250
100	67	1.492537
110	69.5	1.582734
120	72	1.666667
130	74	1.756757
140	77	1.818182
150	79	1.898734
160	81	1.975309
170	83	2.048193
180	84.5	2.130178
190	86	2.209302
200	87.5	2.285714
210	89	2.359551
220	90	2.444444
230	91	2.527473
240	92	2.608696
250	93	2.688172
260	93.5	2.780749
270	94.2	2.866242
280	95	2.947368
290	95.2	3.046218
300	95.8	3.131524
310	96	3.229167

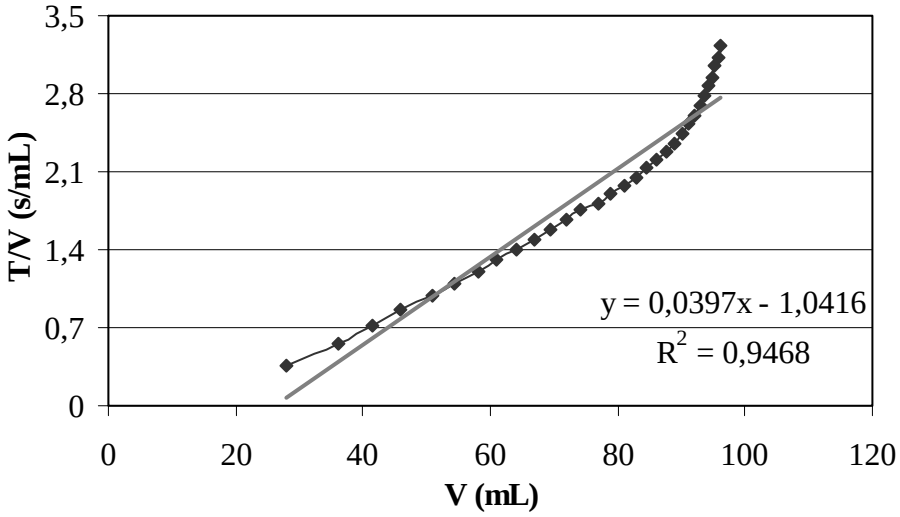


Figure A1 T/V values versus filtrate volume (V) for 6.0% fly ash dosage for Sludge Sample I.

Table A2 Filtration data of 10.0% gypsum dosage for Sludge Sample I

T (s)	V (ml)	T/V
10	24	0.416667
20	31	0.645161
30	37	0.810811
40	41.5	0.963855
50	45.5	1.098901
60	49.5	1.212121
70	52.5	1.333333
80	55	1.454545
90	57.5	1.565217
100	60	1.666667
110	62	1.774194
120	64	1.875000
130	65.5	1.984733
140	67	2.089552
150	68.5	2.189781
160	70	2.285714
170	71.5	2.377622
180	73	2.465753
190	74	2.567568
200	75	2.666667
210	76.5	2.745098
220	77.5	2.838710
230	78.5	2.929936
240	79.5	3.018868
250	80.5	3.105590

Table A2 Filtration data of 10.0% gypsum dosage for Sludge Sample I (continue)

260	81.5	3.190184
270	82.5	3.272727
280	83	3.373494
290	84	3.452381
300	85	3.529412
310	85.5	3.625731
320	86	3.720930
330	87	3.793103
340	87.8	3.872437
350	88.2	3.968254
360	89	4.044944
370	89.8	4.120267
380	90.1	4.217536
390	90.8	4.295154
400	91.5	4.371585
410	92	4.456522
420	92.1	4.560261

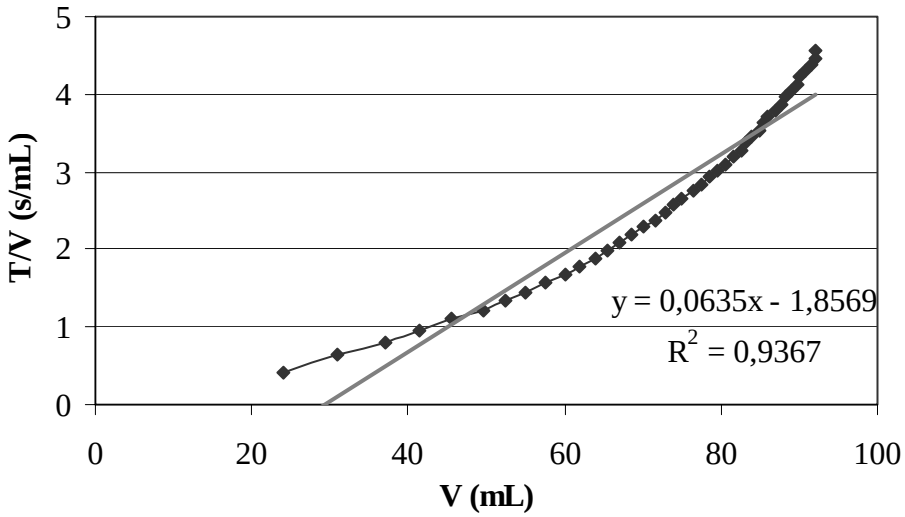


Figure A2 T/V values versus filtrate volume (V) for 10.0% gypsum dosage for Sludge Sample I.

Table A3 Filtration data of 1.5% bentonite dosage for Sludge Sample II

T (s)	**V (ml)**	**T/V**
10	5.5	1.818182
20	6.5	3.076923
30	7.5	4.000000
40	8.5	4.705882
50	9.5	5.263158
60	10	6.000000

Table A3 Filtration data of 1.5% bentonite dosage for Sludge Sample II (continue)

70	10.4	6.730769
80	10.8	7.407407
90	11.2	8.035714
100	11.6	8.620690
110	12	9.166667
120	12.5	9.600000
130	13	10.00000
140	13.4	10.44776
150	13.8	10.86957
160	14.1	11.34752
170	14.5	11.72414
180	15	12.00000
190	15.3	12.41830
200	15.7	12.73885
210	16	13.12500
220	16.4	13.41463
230	16.8	13.69048
240	17.1	14.03509
250	17.4	14.36782
260	17.7	14.68927
270	18	15.00000
280	18.3	15.30055
290	18.6	15.59140
300	18.9	15.87302
310	19.2	16.14583
320	19.6	16.32653
330	19.9	16.58291
340	20.2	16.83168
350	20.5	17.07317
360	20.8	17.30769
370	21.1	17.53555
380	21.4	17.75701
390	21.7	17.97235
400	21.9	18.26484
410	22	18.63636
420	22.1	19.00452
430	22.4	19.19643
440	22.7	19.38326
450	23	19.56522
460	23.2	19.82759
470	23.5	20.00000
480	23.8	20.16807
490	24	20.41667
500	24.2	20.66116
510	24.5	20.81633

Table A3 Filtration data of 1.5% bentonite dosage for Sludge Sample II (continue)

520	24.8	20.96774
530	25	21.20000
540	25.2	21.42857
550	25.4	21.65354
560	25.6	21.87500
570	25.8	22.09302
580	26	22.30769

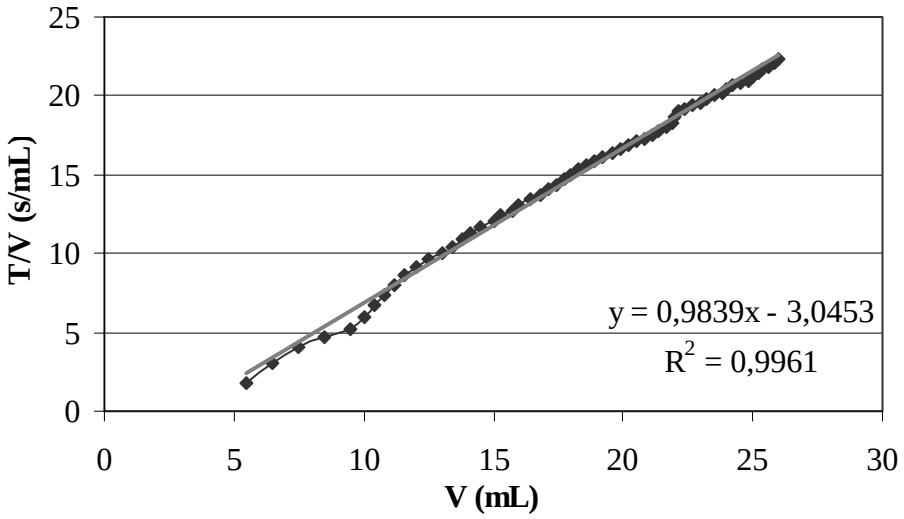


Figure A3 T/V values versus filtrate volume (V) for 1.5% bentonite dosage for Sludge Sample II.

Table A4 Filtration data of 2.0% fly ash dosage for Sludge Sample II

T (s)	V (ml)	T/V
10	5	2.000000
20	6	3.333333
30	7	4.285714
40	8	5.000000
50	8.5	5.882353
60	9.5	6.315789
70	10	7.000000
80	10.5	7.619048
90	11	8.181818
100	11.5	8.695652
110	12	9.166667
120	12.5	9.600000
130	13	10.00000
140	13.3	10.52632
150	13.6	11.02941
160	14	11.42857

Table A4 Filtration data of 2.0% fly ash dosage for Sludge Sample II (continue)

170	14.4	11.80556
180	14.8	12.16216
190	15	12.66667
200	15.2	13.15789
210	15.6	13.46154
220	16	13.75000
230	16.3	14.11043
240	16.6	14.45783
250	16.9	14.79290
260	17.1	15.20468
270	17.3	15.60694
280	17.7	15.81921
290	18	16.11111
300	18.3	16.39344
310	18.7	16.57754
320	19	16.84211
330	19.2	17.18750
340	19.5	17.43590
350	19.9	17.58794
360	20.1	17.91045
370	20.4	18.13725
380	20.8	18.26923
390	21	18.57143
400	21.1	18.95735
410	21.2	19.33962
420	21.4	19.62617
430	21.7	19.81567
440	21.9	20.09132
450	22	20.45455
460	22.3	20.62780
470	22.8	20.61404
480	23	20.86957
490	23.2	21.12069
500	23.4	21.36752
510	23.7	21.51899
520	23.9	21.75732
530	24.1	21.99170
540	24.2	22.31405
550	24.6	22.35772
560	24.8	22.58065
570	25	22.80000
580	25.2	23.01587
590	25.4	23.22835
600	25.6	23.43750
610	25.8	23.64341

Table A4 Filtration data of 2.0% fly ash dosage for Sludge Sample II (continue)

620	26.1	23.75479
630	26.3	23.95437
640	26.6	24.06015
650	26.8	24.25373
660	27	24.44444

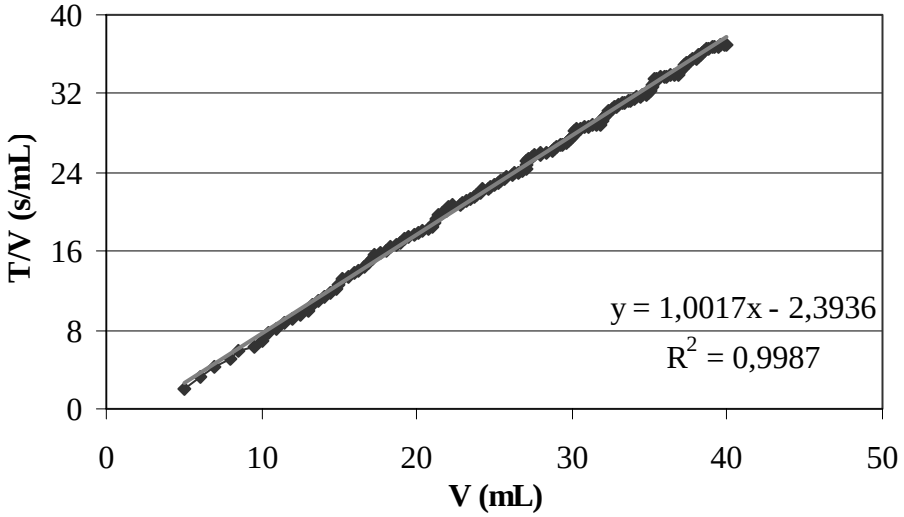


Figure A4 T/V values versus filtrate volume (V) for 2.0% fly ash dosage for Sludge Sample II.

Table A5 Filtration data of 10.0% gypsum dosage for Sludge Sample II

T (s)	V (ml)	T/V
10	6.5	1.538462
20	7.5	2.666667
30	8.5	3.529412
40	9.5	4.210526
50	10.2	4.901961
60	10.8	5.555556
70	11.3	6.194690
80	11.8	6.779661
90	12.3	7.317073
100	12.8	7.812500
110	13.3	8.270677
120	13.8	8.695652
130	14.4	9.027778
140	14.9	9.395973
150	15.3	9.803922
160	15.8	10.12658
170	16.1	10.55901
180	16.5	10.90909

Table A5 Filtration data of 10.0% gypsum dosage for Sludge Sample II (continue)

190	16.9	11.24260
200	17.3	11.56069
210	17.7	11.86441
220	18.1	12.15470
230	18.5	12.43243
240	18.9	12.69841
250	19.3	12.95337
260	19.6	13.26531
270	19.9	13.56784
280	20.3	13.79310
290	20.6	14.07767
300	20.9	14.35407
310	21.3	14.55399
320	21.6	14.81481
330	21.9	15.06849
340	22.2	15.31532
350	22.5	15.55556
360	22.8	15.78947
370	23.1	16.01732
380	23.4	16.23932
390	23.8	16.38655
400	24	16.66667
410	24.2	16.94215
420	24.5	17.14286
430	24.7	17.40891
440	25	17.60000
450	25.2	17.85714
460	25.4	18.11024
470	25.7	18.28794
480	26	18.46154
490	26.3	18.63118
500	26.6	18.79699
510	26.9	18.95911
520	27.2	19.11765
530	27.4	19.34307
540	27.6	19.56522
550	27.8	19.78417
560	28	20.00000
570	28.2	20.21277
580	28.4	20.42254
590	28.6	20.62937
600	28.8	20.83333
610	29	21.03448

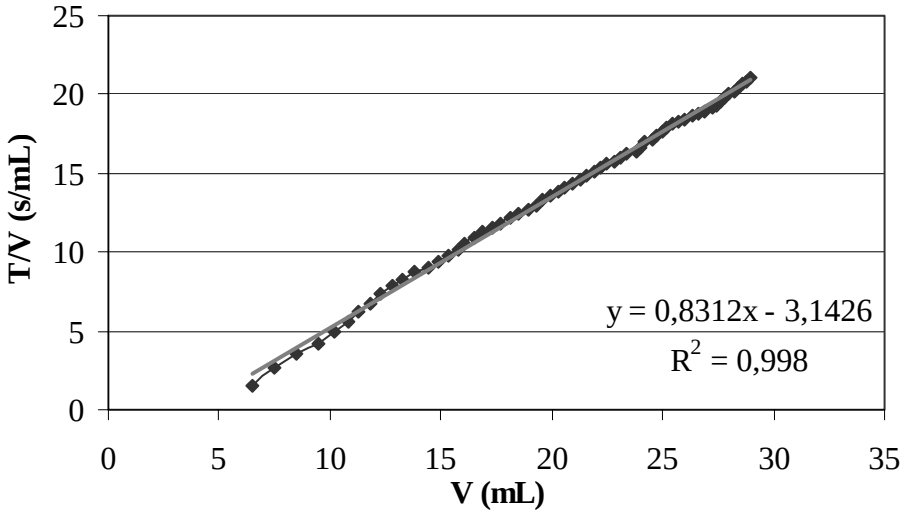


Figure A5 T/V values versus filtrate volume (V) for 10.0% gypsum dosage for Sludge Sample II.

Table A6 Filtration data of 22.0% alum dosage for Sludge Sample III

T (s)	V (ml)	T/V
10	60	0.166667
20	66	0.303030
30	69.5	0.431655
40	71.8	0.557103
50	73	0.684932
60	74	0.810811
70	74.5	0.939597
80	75	1.066667
90	75	1.200000
100	75.2	1.329787
110	75.3	1.460823
120	75.5	1.589404
130	75.6	1.719577
140	75.7	1.849406
150	75.7	1.981506
160	75.9	2.108037
170	75.9	2.239789
180	76	2.368421

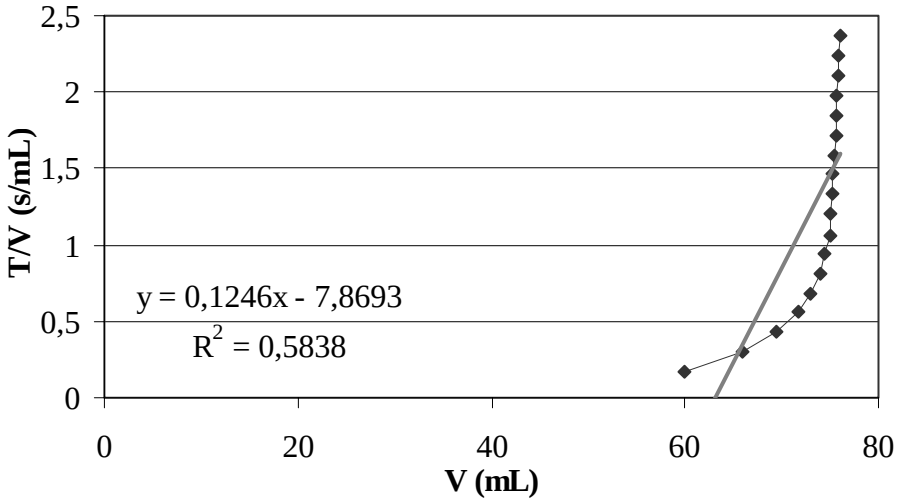


Figure A6 T/V values versus filtrate volume (V) for 22.0% alum dosage for Sludge Sample III.

Table A7 Filtration data of 14.0% lime dosage for Sludge Sample III

T (s)	V (ml)	T/V
10	48	0.208333
20	53	0.377358
30	57	0.526316
40	60.5	0.661157
50	64	0.781250
60	67	0.895522
70	69	1.014493
80	71.5	1.118881
90	73	1.232877
100	74.5	1.342282
110	75.5	1.456954
120	76.5	1.568627
130	77.2	1.683938
140	78	1.794872
150	79	1.898734
160	79.4	2.015113
170	79.8	2.130326
180	80	2.250000
190	80.2	2.369077
200	80.4	2.487562
210	80.6	2.605459
220	80.8	2.722772
230	80.9	2.843016
240	80.9	2.966625
250	81	3.086420
260	81	3.209877

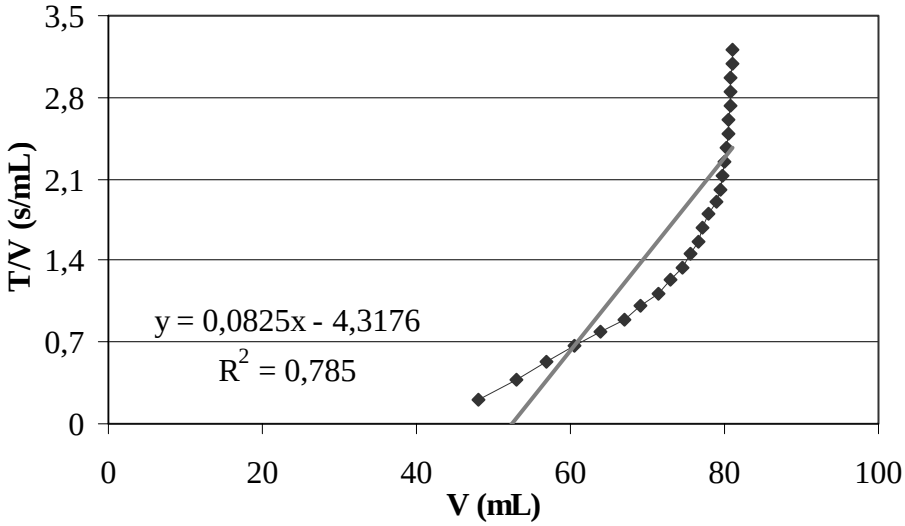


Figure A7 T/V values versus filtrate volume (V) for 14.0% lime dosage for Sludge Sample III.

Table A8 Filtration data of 0.8% polyelectrolyte dosage for Sludge Sample III

T (s)	V (ml)	T/V
10	73	0.136986
20	78	0.256410
30	79	0.379747
40	80	0.500000
50	80.2	0.623441
60	80.4	0.746269
70	80.6	0.868486
80	80.8	0.990099
90	81	1.111111
100	81	1.234568
110	81.05	1.357187
120	81.05	1.480568
130	81.1	1.602959
140	81.1	1.726264

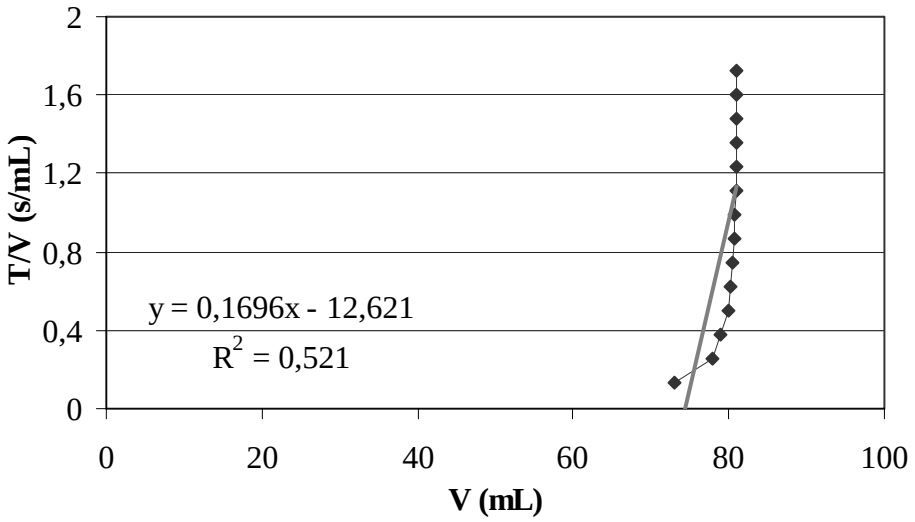


Figure A8 T/V values versus filtrate volume (V) for 0.8% polyelectrolyte dosage for Sludge Sample III.

Table A9 Filtration data of 2.0% bentonite dosage for Sludge Sample IV

T (s)	V (ml)	T/V
10	6.3	1.587302
20	6.7	2.985075
30	7	4.285714
40	7.3	5.479452
50	7.7	6.493506
60	8	7.500000
70	8.2	8.536585
80	8.4	9.523810
90	8.6	10.46512
100	8.7	11.49425
110	8.9	12.35955
120	9	13.33333
130	9.2	14.13043
140	9.3	15.05376
150	9.5	15.78947
160	9.6	16.66667
170	9.7	17.52577
180	9.8	18.36735
190	9.9	19.19192
200	10	20.00000
210	10.1	20.79208
220	10.2	21.56863
230	10.3	22.33010
240	10.4	23.07692
250	10.5	23.80952

Table A9 Filtration data of 2.0% bentonite dosage for Sludge Sample IV (continue)

260	10.6	24.52830
270	10.7	25.23364
280	10.8	25.92593
290	10.9	26.60550
300	11	27.27273
310	11.1	27.92793
320	11.2	28.57143
330	11.3	29.20354
340	11.4	29.82456
350	11.5	30.43478
360	11.6	31.03448
370	11.7	31.62393
380	11.7	32.47863
390	11.8	33.05085
400	11.9	33.61345
410	11.9	34.45378
420	12	35.00000
430	12.1	35.53719
440	12.2	36.06557
450	12.3	36.58537
460	12.4	37.09677
470	12.4	37.90323
480	12.5	38.40000
490	12.6	38.88889
500	12.7	39.37008
510	12.7	40.15748
520	12.8	40.62500
530	12.9	41.08527
540	13	41.53846
550	13.1	41.98473
560	13.2	42.42424
570	13.3	42.85714
580	13.4	43.28358
590	13.5	43.70370
600	13.6	44.11765
610	13.6	44.85294
620	13.7	45.25547
630	13.8	45.65217
640	13.9	46.04317
650	13.9	46.76259
660	14	47.14286
670	14.1	47.51773
680	14.1	48.22695
690	14.2	48.59155
700	14.3	48.95105

Table A9 Filtration data of 2.0% bentonite dosage for Sludge Sample IV (continue)

710	14.3	49.65035
720	14.4	50.00000
730	14.4	50.69444
740	14.5	51.03448
750	14.5	51.72414
760	14.6	52.05479
770	14.6	52.73973
780	14.7	53.06122
790	14.7	53.74150
800	14.8	54.05405
810	14.8	54.72973
820	14.9	55.03356
830	14.9	55.70470
840	15	56.00000

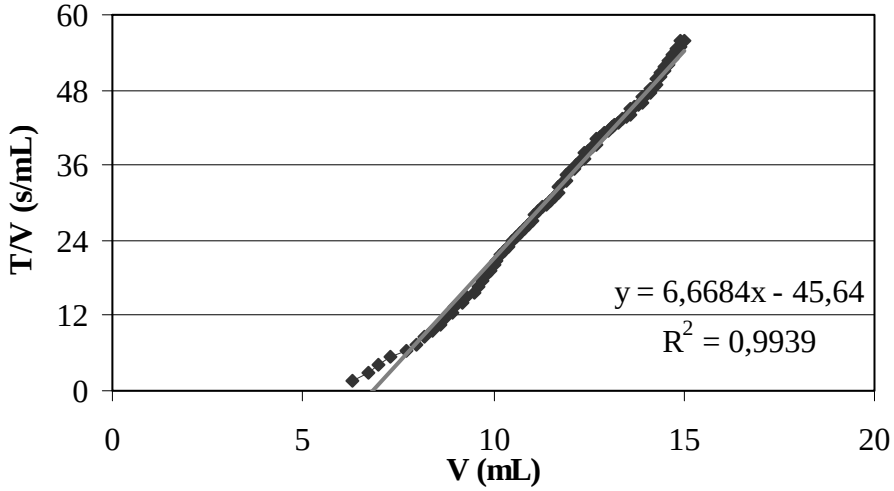


Figure A9 T/V values versus filtrate volume (V) for 2.0% bentonite dosage for Sludge Sample IV.

Table A10 Filtration data of 16.0% fly ash dosage for Sludge Sample IV

T (s)	V (ml)	T/V
10	7	1.428571
20	7.5	2.666667
30	8	3.750000
40	8.3	4.819277
50	8.6	5.813953
60	8.8	6.818182
70	9	7.777778
80	9.2	8.695652
90	9.4	9.574468
100	9.5	10.52632

Table A10 Filtration data of 16.0% fly ash dosage for Sludge Sample IV (continue)

110	9.6	11.45833
120	9.7	12.37113
130	9.8	13.26531
140	9.9	14.14141
150	10	15.00000
160	10.1	15.84158
170	10.2	16.66667
180	10.4	17.30769
190	10.5	18.09524
200	10.6	18.86792
210	10.7	19.62617
220	10.8	20.37037
230	10.9	21.10092
240	11	21.81818
250	11.1	22.52252
260	11.2	23.21429
270	11.3	23.89381
280	11.4	24.56140
290	11.5	25.21739
300	11.6	25.86207
310	11.7	26.49573
320	11.7	27.35043
330	11.8	27.96610
340	11.8	28.81356
350	11.9	29.41176
360	11.9	30.25210
370	12	30.83333
380	12	31.66667
390	12.1	32.23140
400	12.1	33.05785
410	12.2	33.60656
420	12.3	34.14634
430	12.4	34.67742
440	12.4	35.48387
450	12.5	36.00000
460	12.5	36.80000
470	12.6	37.30159
480	12.6	38.09524
490	12.7	38.58268
500	12.7	39.37008
510	12.8	39.84375
520	12.8	40.62500
530	12.9	41.08527
540	12.9	41.86047
550	13	42.30769

Table A10 Filtration data of 16.0% fly ash dosage for Sludge Sample IV (continue)

560	13	43.07692
570	13.1	43.51145
580	13.1	44.27481
590	13.2	44.69697
600	13.2	45.45455
610	13.3	45.86466
620	13.4	46.26866
630	13.5	46.66667
640	13.6	47.05882
650	13.6	47.79412
660	13.7	48.17518
670	13.7	48.90511
680	13.8	49.27536
690	13.8	50.00000
700	13.9	50.35971
710	13.9	51.07914
720	14	51.42857
730	14	52.14286
740	14.1	52.48227
750	14.1	53.19149
760	14.2	53.52113
770	14.2	54.22535
780	14.3	54.54545
790	14.3	55.24476
800	14.4	55.55556
810	14.4	56.25000
820	14.5	56.55172
830	14.5	57.24138
840	14.6	57.53425
850	14.6	58.21918
860	14.7	58.50340
870	14.7	59.18367
880	14.7	59.86395
890	14.8	60.13514
900	14.8	60.81081
910	14.8	61.48649
920	14.9	61.74497
930	14.9	62.41611
940	14.9	63.08725
950	15	63.33333

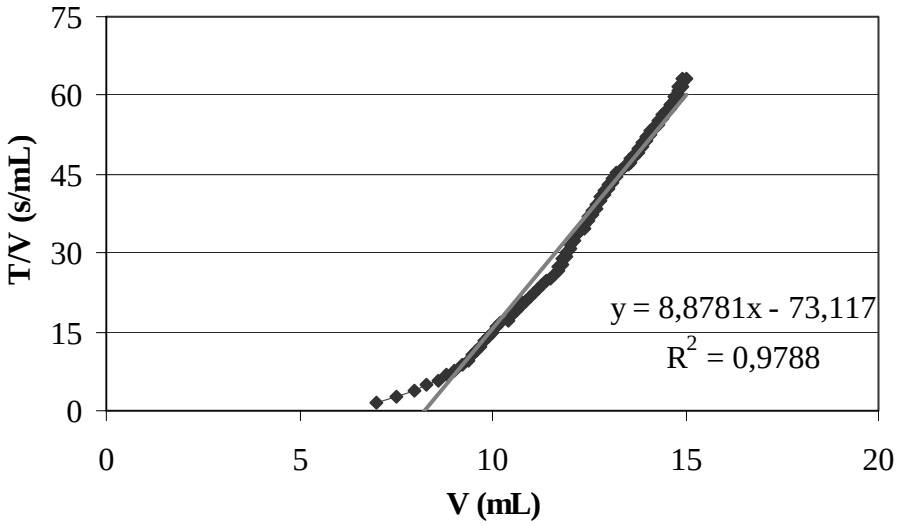


Figure A10 T/V values versus filtrate volume (V) for 16.0% fly ash dosage for Sludge Sample IV.

Table A11 Filtration data of 12.0% gypsum dosage for Sludge Sample IV

T (s)	V (ml)	T/V
10	6.8	1.470588
20	7.3	2.739726
30	7.7	3.896104
40	8.1	4.938272
50	8.5	5.882353
60	8.8	6.818182
70	9	7.777778
80	9.2	8.695652
90	9.4	9.574468
100	9.6	10.41667
110	9.7	11.34021
120	9.8	12.24490
130	9.9	13.13131
140	10	14.00000
150	10.1	14.85149
160	10.2	15.68627
170	10.3	16.50485
180	10.4	17.30769
190	10.5	18.09524
200	10.6	18.86792
210	10.7	19.62617
220	10.7	20.56075
230	10.8	21.29630
240	10.9	22.01835
250	11	22.72727

Table A11 Filtration data of 12.0% gypsum dosage for Sludge Sample IV (continue)

260	11.1	23.42342
270	11.1	24.32432
280	11.2	25.00000
290	11.3	25.66372
300	11.4	26.31579
310	11.5	26.95652
320	11.6	27.58621
330	11.6	28.44828
340	11.7	29.05983
350	11.8	29.66102
360	11.9	30.25210
370	12	30.83333
380	12	31.66667
390	12.1	32.23140
400	12.2	32.78689
410	12.3	33.33333
420	12.3	34.14634
430	12.4	34.67742
440	12.5	35.20000
450	12.6	35.71429
460	12.7	36.22047
470	12.8	36.71875
480	12.8	37.50000
490	12.9	37.98450
500	12.9	38.75969
510	13	39.23077
520	13	40.00000
530	13.1	40.45802
540	13.1	41.22137
550	13.2	41.66667
560	13.2	42.42424
570	13.3	42.85714
580	13.3	43.60902
590	13.4	44.02985
600	13.4	44.77612
610	13.5	45.18519
620	13.5	45.92593
630	13.6	46.32353
640	13.6	47.05882
650	13.7	47.44526
660	13.7	48.17518
670	13.8	48.55072
680	13.8	49.27536
690	13.9	49.64029
700	13.9	50.35971

Table A11 Filtration data of 12.0% gypsum dosage for Sludge Sample IV (continue)

710	14	50.71429
720	14	51.42857
730	14.1	51.77305
740	14.1	52.48227
750	14.2	52.81690
760	14.2	53.52113
770	14.3	53.84615
780	14.3	54.54545
790	14.4	54.86111
800	14.4	55.55556
810	14.5	55.86207
820	14.5	56.55172
830	14.6	56.84932
840	14.6	57.53425
850	14.7	57.82313
860	14.7	58.50340
870	14.8	58.78378
880	14.8	59.45946
890	14.9	59.73154
900	14.9	60.40268
910	15	60.66667

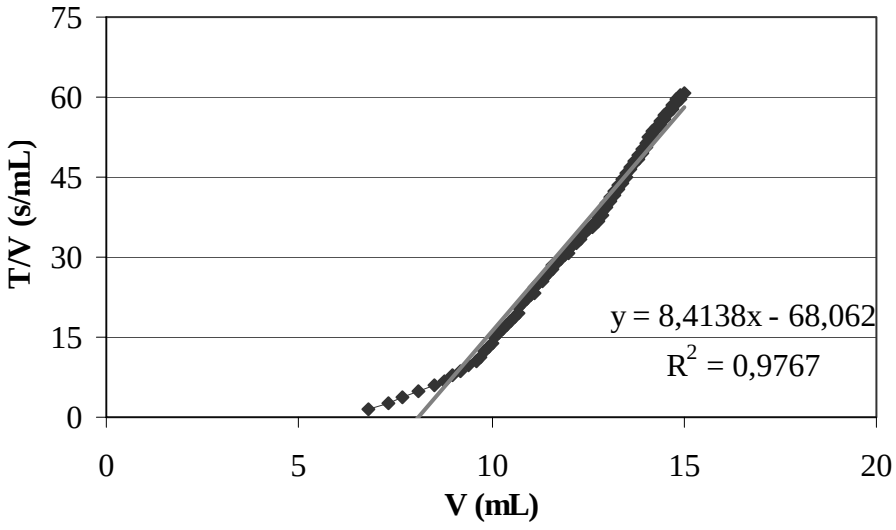


Figure A11 T/V values versus filtrate volume (V) for 12.0% gypsum dosage for Sludge Sample IV.

Table A12 Filtration data of 12.0% alum dosage for Sludge Sample IV

T (s)	V (ml)	T/V
10	8.5	1.176471
20	9.5	2.105263
30	10.3	2.912621
40	11	3.636364
50	11.8	4.237288
60	12.5	4.800000
70	13	5.384615
80	13.5	5.925926
90	14	6.428571
100	14.4	6.944444
110	14.7	7.482993
120	15	8.000000

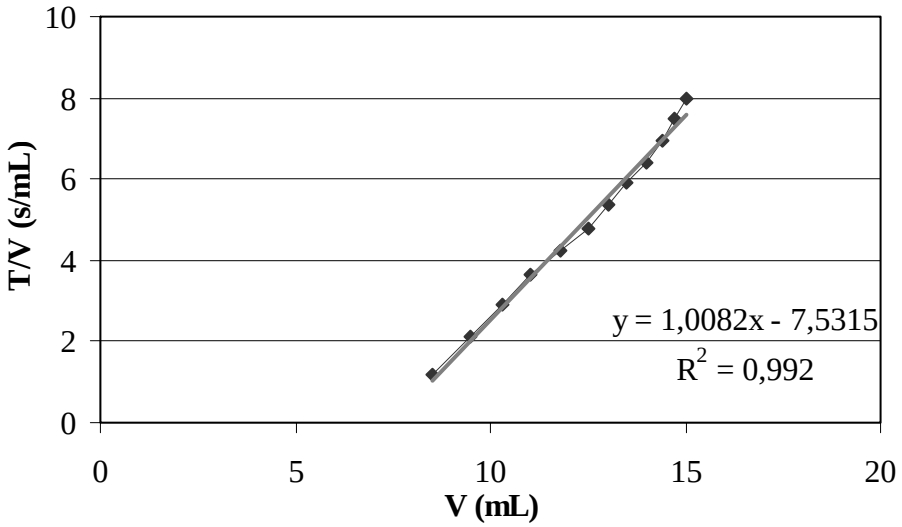


Figure A12 T/V values versus filtrate volume (V) for 12.0% alum dosage for Sludge Sample IV.

Table A13 Filtration data of 12.0% lime dosage for Sludge Sample IV

T (s)	V (ml)	T/V
10	7.5	1.333333
20	8	2.500000
30	8.5	3.529412
40	9	4.444444
50	9.3	5.376344
60	9.6	6.250000
70	9.8	7.142857
80	10	8.000000
90	10.2	8.823529

Table A13 Filtration data of 12.0% lime dosage for Sludge Sample IV (continue)

100	10.4	9.615385
110	10.6	10.37736
120	10.8	11.11111
130	11	11.81818
140	11.2	12.50000
150	11.4	13.15789
160	11.5	13.91304
170	11.6	14.65517
180	11.8	15.25424
190	11.9	15.96639
200	12	16.66667
210	12.2	17.21311
220	12.3	17.88618
230	12.5	18.40000
240	12.6	19.04762
250	12.7	19.68504
260	12.9	20.15504
270	13	20.76923
280	13.1	21.37405
290	13.2	21.96970
300	13.3	22.55639
310	13.4	23.13433
320	13.5	23.70370
330	13.6	24.26471
340	13.7	24.81752
350	13.8	25.36232
360	13.9	25.89928
370	14	26.42857
380	14.1	26.95035
390	14.2	27.46479
400	14.3	27.97203
410	14.4	28.47222
420	14.5	28.96552
430	14.6	29.45205
440	14.7	29.93197
450	14.8	30.40541
460	14.8	31.08108
470	14.9	31.54362
480	14.9	32.21477
490	15	32.66667

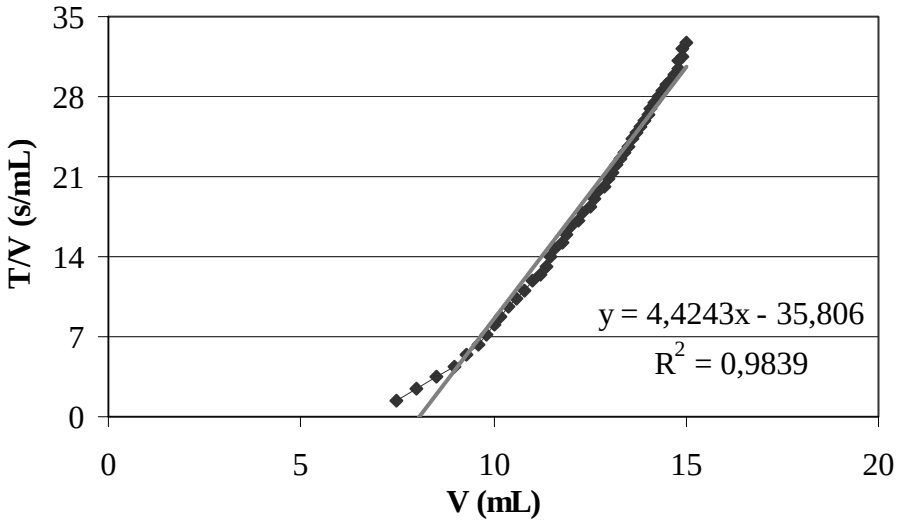


Figure A13 T/V values versus filtrate volume (V) for 12.0% lime dosage for Sludge Sample IV.

Table A14 Filtration data of 0.9% polyelectrolyte dosage for Sludge Sample IV

T (s)	V (ml)	T/V
10	36.5	0.273973
20	39	0.512821
30	41.5	0.722892
40	42.5	0.941176
50	44	1.136364
60	45	1.333333
70	46.5	1.505376
80	47.5	1.684211
90	48.5	1.855670
100	49.5	2.020202
110	50.5	2.178218
120	51.2	2.343750
130	52	2.500000
140	52.6	2.661597
150	53.2	2.819549
160	53.8	2.973978
170	54.6	3.113553
180	54.8	3.284672
190	55	3.454545
200	55.3	3.616637
210	55.7	3.770197
220	56	3.928571
230	56.4	4.078014
240	56.7	4.232804
250	57	4.385965

Table A14 Filtration data of 0.9% polyelectrolyte dosage for Sludge Sample IV (continue)

260	57.3	4.537522
270	57.6	4.687500
280	57.9	4.835924
290	58.1	4.991394
300	58.3	5.145798
310	58.6	5.290102
320	58.8	5.442177
330	59	5.593220
340	59.2	5.743243
350	59.4	5.892256
360	59.6	6.040268
370	59.8	6.187291
380	60	6.333333
390	60.2	6.478405
400	60.4	6.622517
410	60.6	6.765677
420	60.8	6.907895
430	60.9	7.060755
440	61	7.213115
450	61.2	7.352941
460	61.4	7.491857
470	61.6	7.629870
480	61.7	7.779579
490	61.8	7.928803
500	61.9	8.077544
510	62	8.225806
520	62.2	8.360129
530	62.3	8.507223
540	62.5	8.640000
550	62.6	8.785942
560	62.8	8.917197
570	62.9	9.062003
580	63	9.206349
590	63.2	9.335443
600	63.3	9.478673
610	63.4	9.621451
620	63.5	9.76378
630	63.6	9.90566
640	63.7	10.04710
650	63.8	10.18809
660	63.9	10.32864
670	64	10.46875

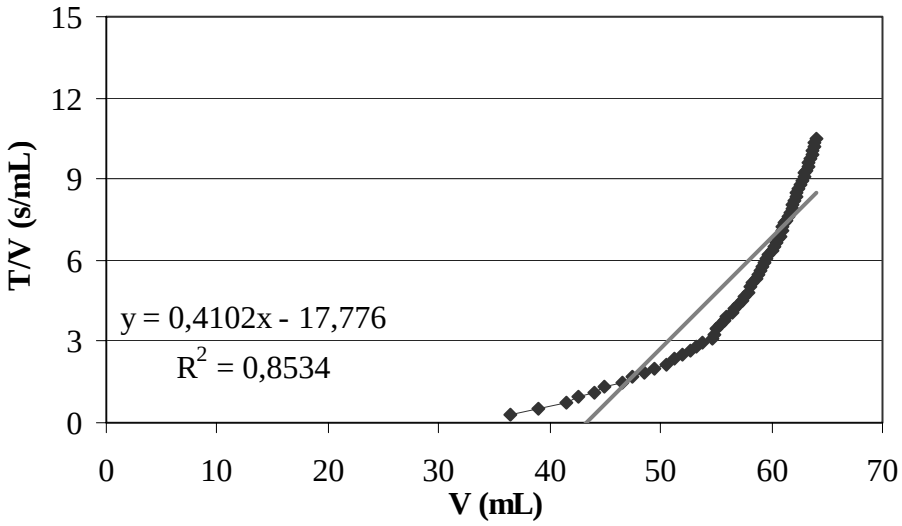


Figure A14 T/V values versus filtrate volume (V) for 0.9% polyelectrolyte dosage for Sludge Sample IV.

Appendices B: CST and SRF Results

Table B1 Results of Sludge Sample I after conditioned by bentonite

Dosage of Bentonite	CST, s	SRFx10^{14}, m/kg	% Removal Efficiency (E)	
			CST	SRF
0.0%	155.5	2.61541	0	0
0.1%	176.9	-	0	-
0.2%	134.7	-	13.38	-
0.3%	149.6	-	3.79	-
0.5%	179.2	-	0	-
1.0%	160.6	-	0	-
1.5%	232.4	-	0	-
4.0%	200.6	-	0	-

Table B2 Results of Sludge Sample I after conditioned by fly ash

Dosage of Fly Ash	CST, s	SRFx10^{14}, m/kg	% Removal Efficiency (E)	
			CST	SRF
0.0%	155.5	2.61541	0	0
1.5%	146.6	1.89574	5.72	27.52
2.0%	117.5	1.61550	24.44	38.23
4.0%	85.8	1.75787	44.82	32.79
6.0%	**86.0**	**1.03022**	**44.69**	**60.61**
8.0%	111.9	1.24820	28.039	52.27
10.0%	122.9	1.40109	20.96	46.43

Table B3 Results of Sludge Sample I after conditioned by gypsum

Dosage of Gypsum	CST, s	SRFx10^{14}, m/kg	% Removal Efficiency (E)	
			CST	SRF
0.0%	155.5	2.61541	0	0
1.5%	99.8	2.04638	35.82	21.76
2.0%	**76.5**	**1.54245**	**50.80**	**41.02**
4.0%	80.6	1.57291	48.17	39.86
6.0%	88.7	1.45853	42.96	44.23
8.0%	95.6	1.46587	38.52	43.95
10.0%	96.5	1.38001	37.94	47.23

Table B4 Results of Sludge Sample II after conditioned by bentonite

Dosage of Bentonite	CST, s	SRFx10^{15}, m/kg	% Removal Efficiency (E)	
			CST	SRF
0.0%	425.2	1.60084	0	0
0.5%	345.5	2.16295	18.74	0
1.0%	340.1	2.32896	20.01	0
1.5%	350.6	2.10573	17.54	0
2.0%	412.6	2.47162	2.96	0
4.0%	460.2	2.65294	0	0

Table B5 Results of Sludge Sample II after conditioned by fly ash

Dosage of Fly Ash	CST, s	SRFx10^{15}, m/kg	% Removal Efficiency (E)	
			CST	SRF
0.0%	425.2	1.60084	0	0
2.0%	453.1	1.97530	0	0
4.0%	404.3	2.23020	4.91	0
6.0%	387.7	2.35468	8.82	0
8.0%	420.8	2.37898	1.03	0
10.0%	445.3	2.09549	0	0
12.0%	418.4	2.33235	1.60	0

Table B6 Results of Sludge Sample II after conditioned by gypsum

Dosage of Gypsum	CST, s	SRFx10^{15}, m/kg	% Removal Efficiency (E)	
			CST	SRF
0.0%	425.2	1.60084	0	0
2.0%	419.7	2.19042	1.29	0
4.0%	425.6	1.94219	0	0
6.0%	405.6	1.67733	4.61	0
8.0%	373.0	1.55639	12.28	2.78
10.0%	405.1	1.33618	4.73	16.53
12.0%	408.8	1.73197	3.86	0

Table B7 Results of Sludge Sample III after conditioned by bentonite

Dosage of Bentonite	CST, s	SRFx10^{15}, m/kg	% Removal Efficiency (E)	
			CST	SRF
0.0%	55.0	1.01045	0	0
0.5%	54.0	-	1.82	-
1.0%	55.8	-	0	-
1.5%	50.2	-	8.73	-
2.0%	49.3	-	10.36	-
2.5%	50.4	-	8.36	-
3.0%	52.7	-	4.18	-

Table B8 Results of Sludge Sample III after conditioned by fly ash

Dosage of Fly Ash	CST, s	SRFx10^{15}, m/kg	% Removal Efficiency (E)	
			CST	SRF
0.0%	55.0	1.01045	0	0
2.0%	57.2	-	0	-
4.0%	60.0	-	0	-
6.0%	55.6	-	0	-
8.0%	52.5	-	4.54	-
10.0%	52.6	-	4.36	-
12.0%	50.2	-	8.73	-
14.0%	52.0	-	5.45	-
16.0%	51.5	-	6.36	-
18.0%	52.7	-	4.18	-

Table B9 Results of Sludge Sample III after conditioned by gypsum

Dosage of Gypsum	CST, s	SRFx10^{15}, m/kg	% Removal Efficiency (E)	
			CST	SRF
0.0%	55.0	1.01045	0	0
2.0%	55.0	-	0	-
4.0%	55.6	-	0	-
6.0%	52.4	-	4.73	-
8.0%	53.9	-	2	-
10.0%	51.4	-	6.54	-
12.0%	49.8	-	9.45	-
14.0%	55.9	-	0	-

Table B10 Results of Sludge Sample III after conditioned by alum

Dosage of Alum	CST, s	SRFx10^{15}, m/kg	% Removal Efficiency (E)	
			CST	SRF
0.0%	55.0	1.01045	0	0
4.0%	36.4	0.597468	33.82	40.87
6.0%	27.3	0.461366	50.36	54.34
8.0%	21.4	0.471241	61.09	53.36
10.0%	19.0	0.460183	65.45	54.46
12.0%	17.8	0.499644	67.64	50.55
14.0%	**16.0**	**0.475589**	**70.91**	**52.93**
16.0%	15.5	0.496746	71.82	50.84
18.0%	16.8	0.471435	69.45	53.34
20.0%	17.1	0.438497	68.91	56.60
22.0%	18.3	0.411011	66.73	59.32

Table B11 Results of Sludge Sample III after conditioned by lime

Dosage of Lime	CST, s	SRFx10^{15}, m/kg	% Removal Efficiency (E)	
			CST	SRF
0.0%	55.0	1.01045	0	0
2.0%	37.3	1.03946	32.18	0
4.0%	33.4	0.978635	39.27	3.15
6.0%	36.9	0.962650	32.91	4.73
8.0%	36.9	0.840440	32.91	16.82
10.0%	41.4	0.710571	24.73	29.68
12.0%	39.7	0.561573	27.82	44.42
14.0%	**33.8**	**0.413262**	**38.54**	**59.10**
16.0%	28.6	0.669401	48.00	33.75
18.0%	26.0	0.636087	52.73	37.05
20.0%	25.7	0.580146	53.27	42.58
22.0%	25.0	0.615623	54.54	39.07
24.0%	25.1	0.611289	54.36	39.50
26.0%	**23.2**	**0.573253**	**57.82**	**43.27**

Table B12 Results of Sludge Sample III after conditioned by polyelectrolyte

Dosage of Polyelectrolyte	CST, s	SRFx10^{15}, m/kg	% Removal Efficiency (E)	
			CST	SRF
0.0%	55.0	1,01045	0	0
0.2%	13.1	0,588840	76,18	41,72
0.4%	12.7	0,446860	76,91	55,78
0.6%	**10.8**	**0,262710**	**80,36**	**74,00**
0.8%	10.4	0,253320	81,09	74,93
1.0%	10.1	0,257230	81,64	74,54
1.2%	13.7	0,622120	75,09	38,43
1.4%	17.5	0,662326	68,18	34,45

Table B13 Results of Sludge Sample IV after conditioned by bentonite

Dosage of Bentonite	CST, s	SRFx10^{16}, m/kg	% Removal Efficiency (E)	
			CST	SRF
0.0%	2000.0	5.52840	0	0
0.5%	1980.3	3.50000	0.98	36.69
1.0%	1780.0	2.97537	11.00	46.18
1.5%	**1460.0**	**2.92000**	**27.00**	**47.18**
2.0%	1640.0	2.82722	18.00	48.86
3.0%	2350.0	3.48950	0	36.88
4.0%	2492.9	3.33384	0	39.70
5.0%	2500.0	4.34526	0	21.40
6.0%	2527.8	5.00000	0	9.56

Table B14 Results of Sludge Sample IV after conditioned by fly ash

Dosage of Fly Ash	CST, s	SRFx10^{16}, m/kg	% Removal Efficiency (E)	
			CST	SRF
0.0%	2000.0	5.52840	0	0
2.0%	1678.7	4.87197	16.06	11.87
4.0%	1606.4	4.78147	19.68	13.51
6.0%	1475.5	4.85995	26.22	12.09
8.0%	2059.2	4.97478	0	10.01
10.0%	1976.8	4.09139	1.16	25.99
12.0%	2697.7	4.12005	0	25.47
14.0%	2981.9	3.95368	0	28.48
16.0%	3000.0	3.88233	0	29.77
18.0%	3000.0	4.18341	0	24.33

Table B15 Results of Sludge Sample IV after conditioned by gypsum

Dosage of Gypsum	CST, s	SRFx10^{16}, m/kg	% Removal Efficiency (E)	
			CST	SRF
0.0%	2000.0	5.52840	0	0
2.0%	1583.6	5.54983	20.82	0
4.0%	1671.0	6.08766	16.45	0
6.0%	1807.5	4.22670	9.62	23.55
8.0%	1456.3	3.91622	27.18	29.16
10.0%	**1361.6**	**3.35923**	**31.92**	**39.24**
12.0%	1590.5	3.10012	20.47	43.92
14.0%	2093.5	3.58001	0	35.24
16.0%	2169.6	4.19292	0	24.16
18.0%	2690.6	4.50000	0	18.60

Table B16 Results of Sludge Sample IV after conditioned by alum

Dosage of Alum	CST, s	SRFx10^{16}, m/kg	% Removal Efficiency (E)	
			CST	SRF
0.0%	2000.0	5.52840	0	0
1.0%	1968.6	3,88871	1.57	29.66
2.0%	1414.8	2,10113	29.26	61,99
3.0%	1249.1	1,58757	37.54	71,28
4.0%	720.0	1,37559	64.00	75,12
5.0%	975.0	0,897092	51.25	83,77
6.0%	663.5	0,749238	66.82	86,45
7.0%	717.9	0,876293	64.10	84,15
8.0%	**598.4**	**0,467262**	**70.08**	**91,55**
9.0%	617.7	0,598194	69.11	89,18
10.0%	594.5	0,51705	70.27	90,65
11.0%	741.2	0,423133	62.94	92,35
12.0%	661.6	0,335735	66.92	93,93

Table B17 Results of Sludge Sample IV after conditioned by lime

Dosage of Lime	CST, s	SRFx10^{16}, m/kg	% Removal Efficiency (E)	
			CST	SRF
0.0%	2000.0	5.52840	0	0
4.0%	2130.6	2.79106	0	49.51
6.0%	2212.0	2.83540	0	48.71
8.0%	1231.5	1.94311	38.42	64.85
10.0%	1422.7	1.74806	28.86	68.38
12.0%	**1557.2**	**1.10130**	**22.14**	**80.08**
14.0%	1700.0	1.55226	15.00	71.92

Table B18 Results of Sludge Sample IV after conditioned by polyelectrolyte

Dosage of Polyelectrolyte	**CST, s**	**SRFx10^{16}, m/kg**	**% Removal Efficiency (E)**	
			CST	**SRF**
0.00%	2000.0	5.52840	0	0
0.03%	1784.0	3.82402	10.8	30.83
0.04%	1996.7	3.66000	0.16	33.80
0.06%	1636.1	3.40079	18.19	38.48
0.07%	1732.9	3.05617	13.35	44.72
0.09%	1610.0	2.95522	19.50	46.54
0.10%	1607.8	2.75573	19.61	50.15
0.11%	1556.4	3.88670	22.18	29.70
0.13%	1479.4	2.76208	26.03	50.04
0.14%	961.7	2.52778	51.91	54.28
0.16%	1129.3	2.08883	43.53	62.22
0.17%	1508.1	2.32875	24.59	57.88
0.19%	1099.2	2.03946	45.04	63.11
0.20%	1237.3	2.79613	38.13	49.42
0.23%	1208.2	1.73343	39.59	68.64
0.26%	1259.5	1.56724	37.02	71.65
0.29%	743.8	1.23153	62.81	77.72
0.31%	874.0	1.36796	56.30	75.26
0.34%	680.3	0.973329	65.98	82.39
0.40%	580.6	0.911062	70.97	83.52
0.50%	351.6	0.656762	82.42	88.12
0.60%	252.1	0.395673	87.39	92.84
0.70%	158.9	0.252535	92.05	95.43
0.80%	117.5	0.273347	94.12	95.06
0.90%	**22.4**	**0.283631**	**98.88**	**94.87**

Appendices C: Correlation Tables and Graphics

Table C1 Correlations between CST and SRF values of sludge samples

Sludge Samples	Conditioners	Correlation Coefficient (R^2)
Sample I	Bentonite	-
	Fly Ash	0.5280
	Gypsum	**0.7625**
Sample II	**Bentonite**	**0.8165**
	Fly Ash	0.6387
	Gypsum	0.3696
Sample III	Bentonite	-
	Fly Ash	-
	Gypsum	-
	Alum	**0.8497**
	Lime	0.3194
	Polyelectrolyte	**0.7998**
Sample IV	Bentonite	0.5940
	Fly Ash	0.6856
	Gypsum	0.0133
	Alum	**0.9023**
	Lime	0.5387
	Polyelectrolyte	**0.8901**

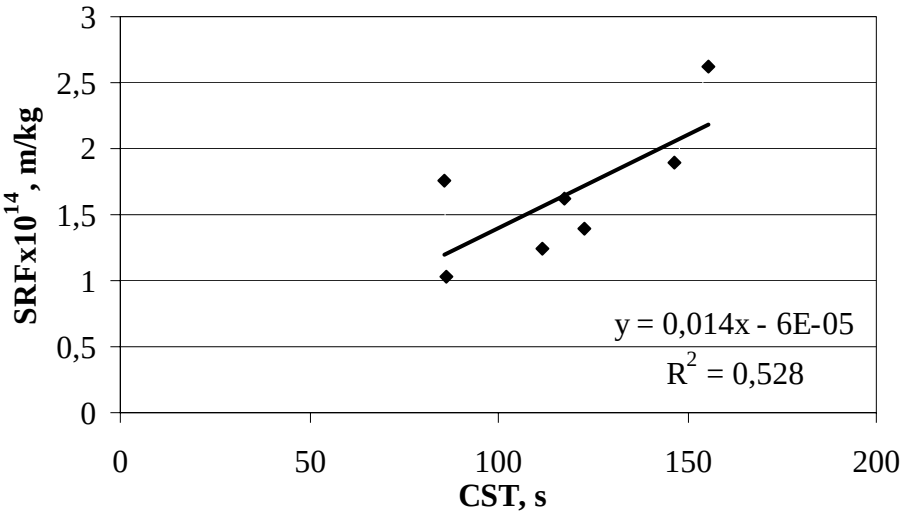


Figure C1 Correlation between SRF & CST for Sludge Sample I after conditioned by fly ash

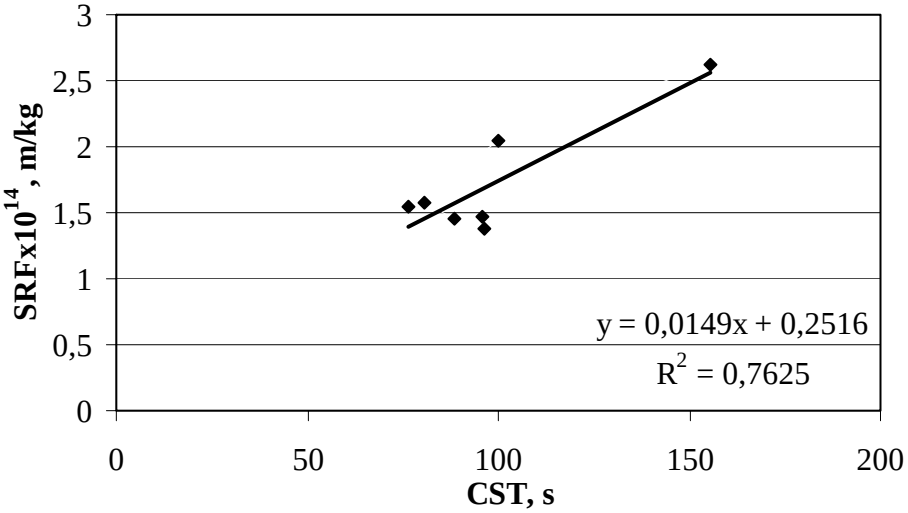


Figure C2 Correlation between SRF & CST for Sludge Sample I after conditioned by gypsum

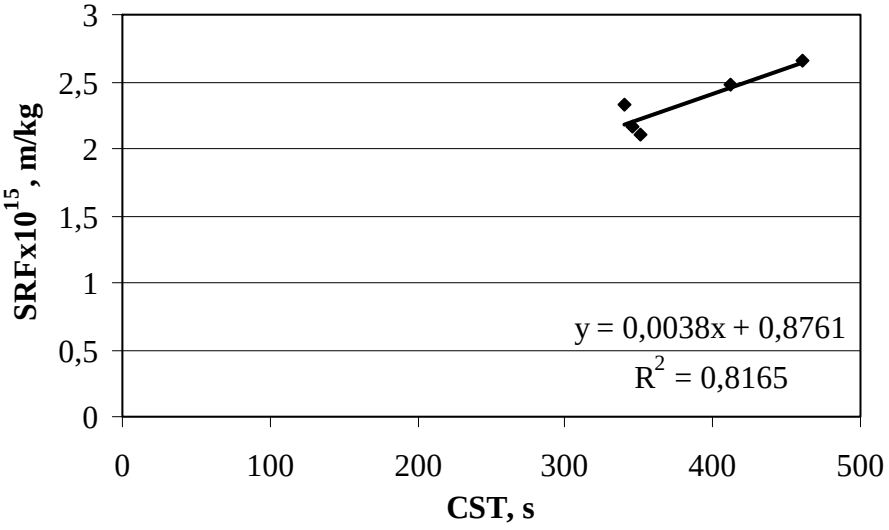


Figure C3 Correlation between SRF & CST for Sludge Sample II after conditioned by bentonite

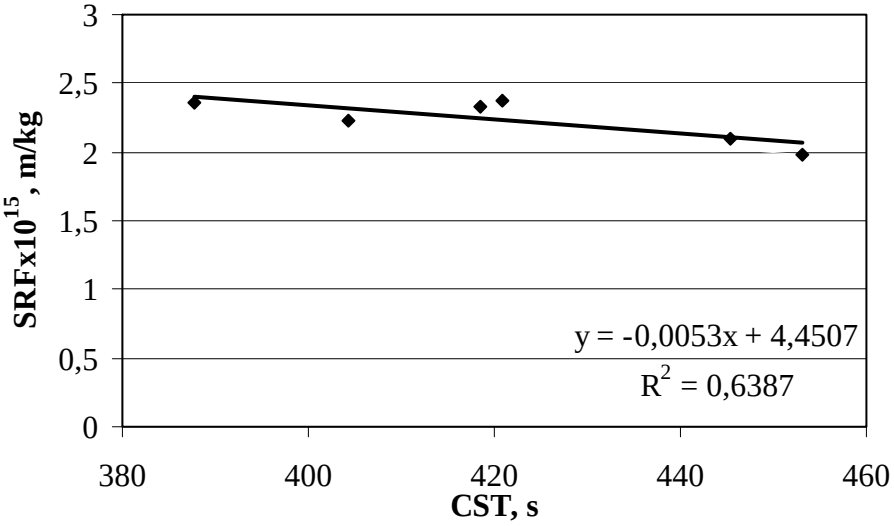


Figure C4 Correlation between SRF & CST for Sludge Sample II after conditioned by fly ash

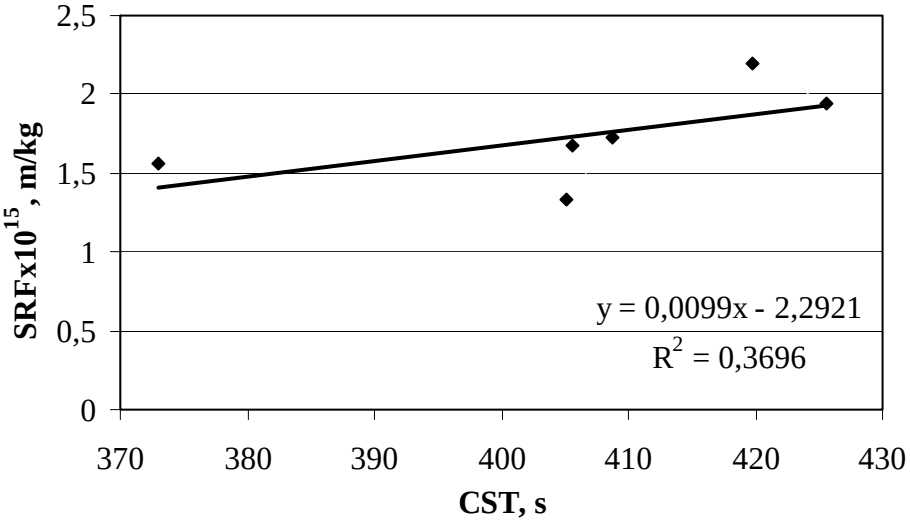


Figure C5 Correlation between SRF & CST for Sludge Sample II after conditioned by gypsum

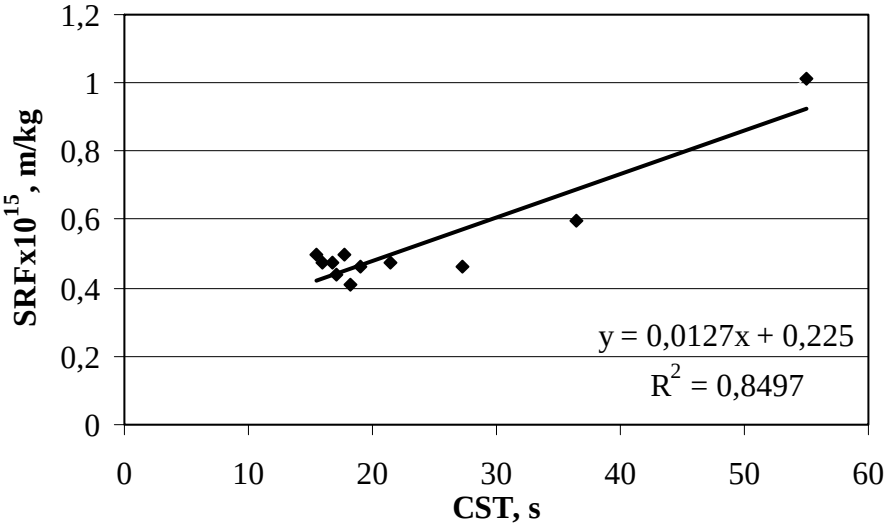


Figure C6 Correlation between SRF & CST for Sludge Sample III after conditioned by alum

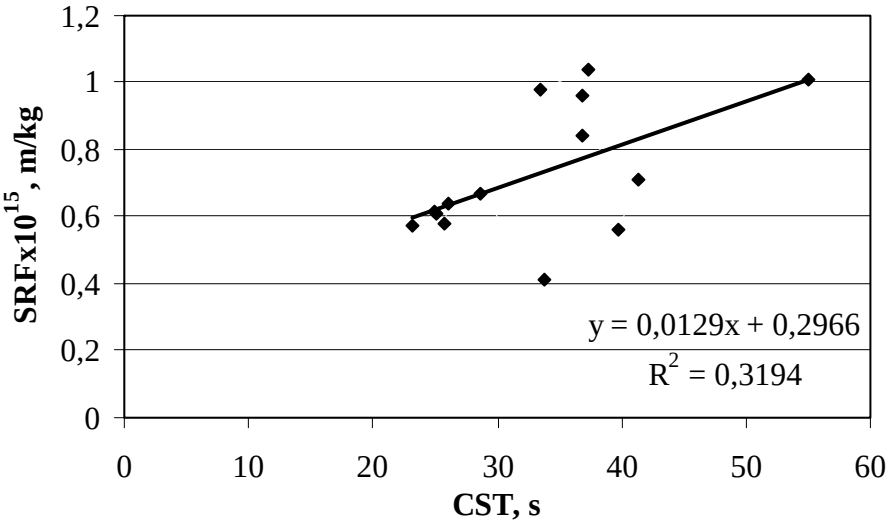


Figure C7 Correlation between SRF & CST for Sludge Sample III after conditioned by lime

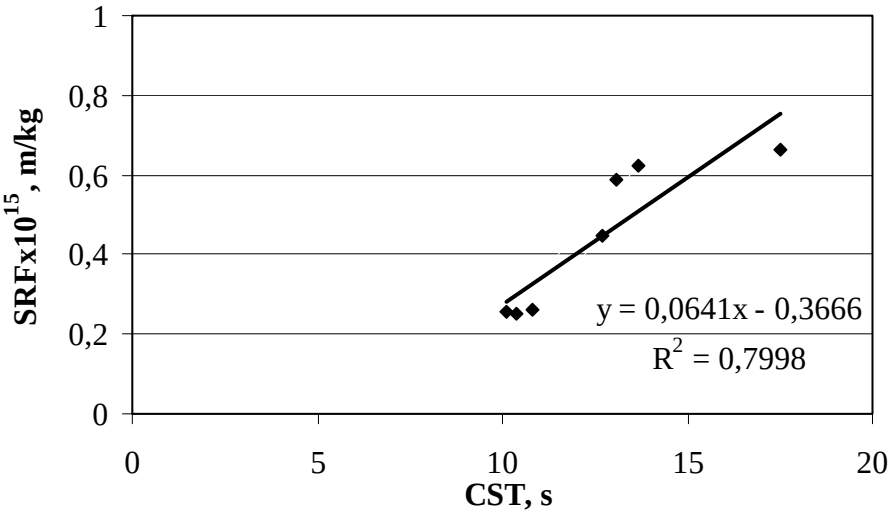


Figure C8 Correlation between SRF & CST for Sludge Sample III after conditioned by polyelectrolyte

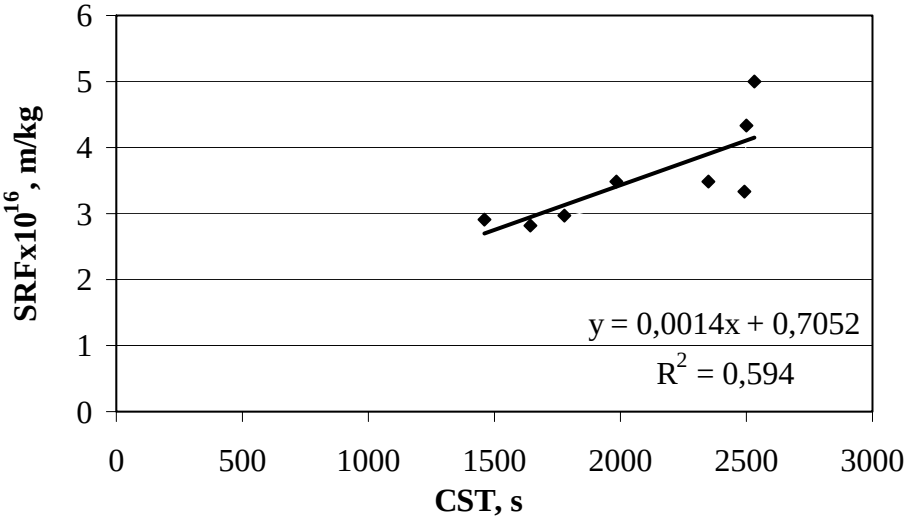


Figure C9 Correlation between SRF & CST for Sludge Sample IV after conditioned by bentonite

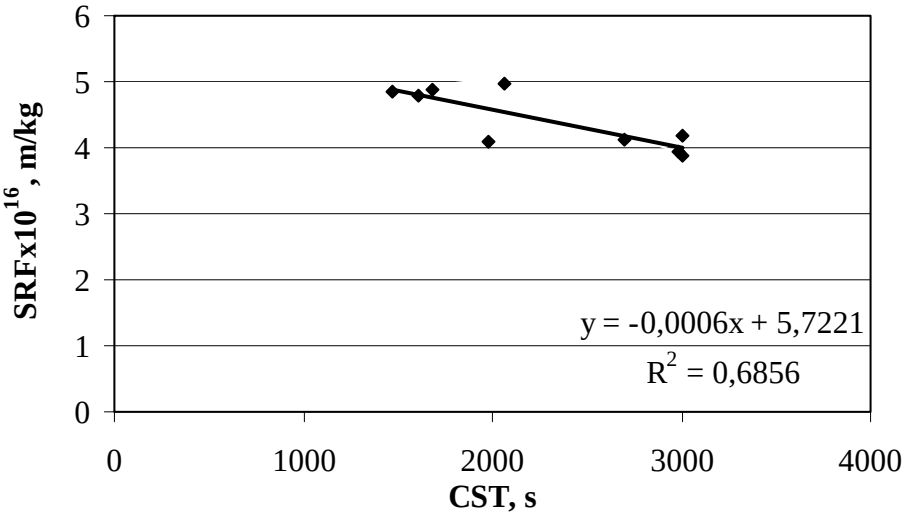


Figure C10 Correlation between SRF & CST for Sludge Sample IV after conditioned by fly ash

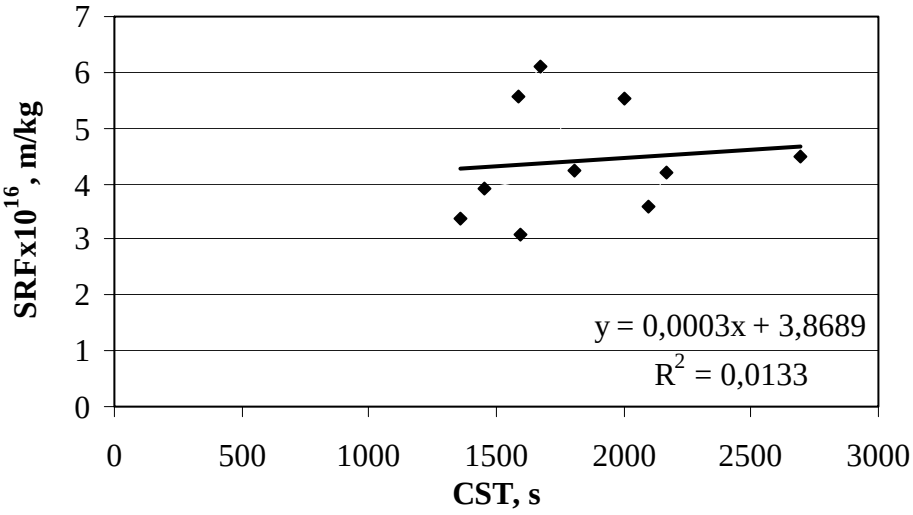


Figure C11 Correlation between SRF & CST for Sludge Sample IV after conditioned by gypsum

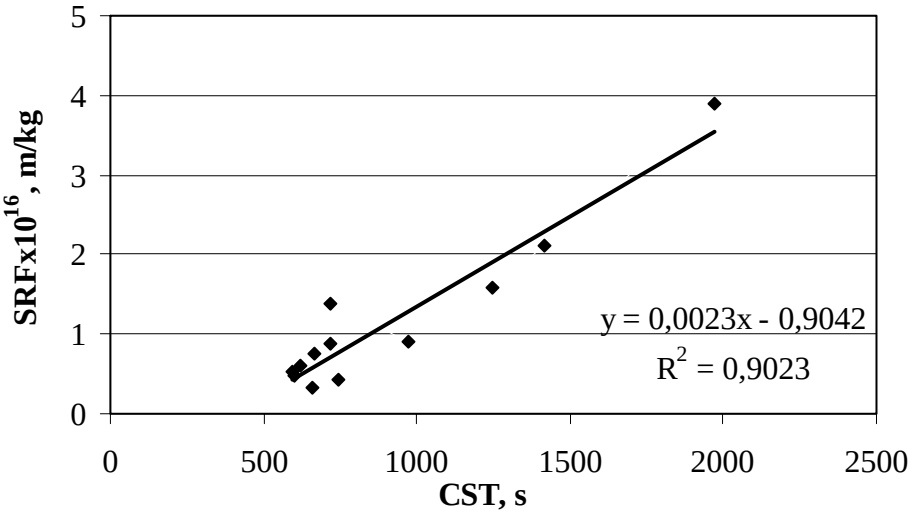


Figure C12 Correlation between SRF & CST for Sludge Sample IV after conditioned by alum

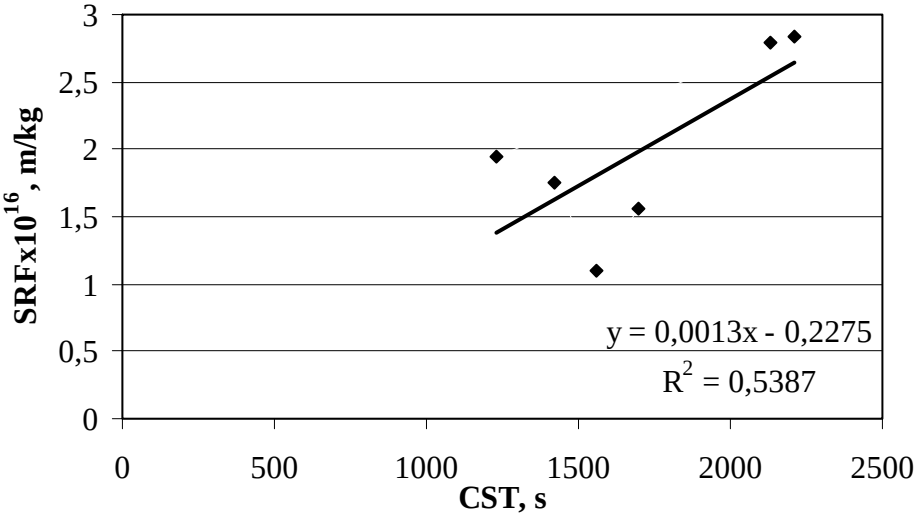


Figure C13 Correlation between SRF & CST for Sludge Sample IV after conditioned by lime

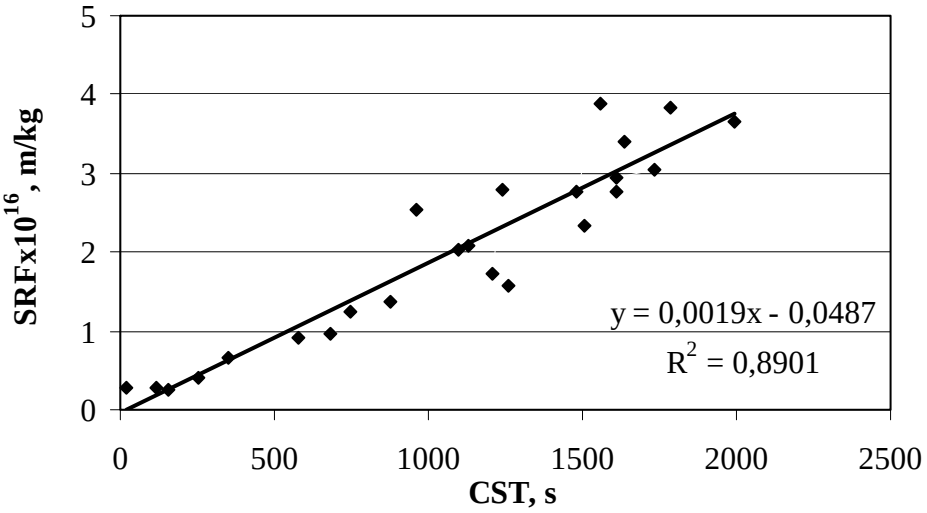


Figure C14 Correlation between SRF & CST for Sludge Sample IV after conditioned by polyelectrolyte