1-1-2011

The removal of fats, oils and grease (FOG) from food industry wastewater by magnetic coagulation

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THE REMOVAL OF FATS, OILS AND GREASE (FOG) FROM FOOD INDUSTRY WASTEWATER BY MAGNETIC COAGULATION

by

Bahareh Bavar, Bachelor of Civil Engineering, Ryerson University, 2008

A thesis

presented to Ryerson University

in partial fulfillment of the requirements for the degree of

Master of Applied Science

In program of

Civil Engineering

Toronto, Ontario, Canada, 2011

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ABSTRACT

Wastewater containing fats, oils and grease (FOG) is problematic in several ways: foul odors, blockage of sewer lines, interference with the proper sewage treatment operation and excess amount of FOG that can lead to certain fines for responsible wastewater generator. In this paper, the magnetic coagulation process is used to destabilize the oily wastewater emulsions while assisting with the oil floc formation. The oil/magnetic powder flocs were subsequently deposited and removed with the assistance of magnetic field. Preliminary investigations were devoted to calculations of optimal magnetic powder proportions of various sizes and their oil sorption capacity. The results from the jar tests confirmed the effectiveness of the magnetic coagulation procedure. It was demonstrated that the magnetic coagulation process with optimum amount of magnetic powder of 12 g/L could remove 94.2% of FOG, 96.9% of total suspended solids (TSS), and 86.7% of chemical oxygen demand (COD) on average.

Acknowledgements

I would like to express my sincere appreciation and deep gratitude toward the following people whose support and insight contributed to the research and completion of this thesis:

- *Dr. Grace Luk, Academic and Thesis Advisor- Thank you for devoting your valuable time to this research and the guidance, knowledge and encouragement that you shared with me.*
- *Robin Luong, Civil Technician- Thank you for your cooperation and technical knowledge*
- *"Quebec Metal Powder Limited"- Thank you for your cooperation and donation of material to the research.*

Dedicated to my Parents

Majid and Felor Bavar

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List of Abbreviations

A/m^2	Ampere per meter squared
BOD_5	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
CSTR	Continuously Stirring Tank Reactor
DAF	Dissolved Air Flotation
DDW	Distilled Deionized Water
FFA	Free Fatty Acid
F/m^3	Faraday per meter cubed
GTA	Greater Toronto Area
HTS	High Temperature Superconducting
IAF	Induced Air Flotation
KWh/m^3	Kilowatt hour per Meter cubed
PHAS	Poly Hydroxy Aluminum Sulphate
RBC	Rotating Biological Contactor
rpm	Revolutions per Minute
SSO	Sanitary Sewer Overflow
T	Tesla
TSS	Total Suspended Solids
UASB	Upflow Anaerobic Sludge Blanket
U.S.EPA	United States Environmental Protection Agency
VSS	Volatile Suspended Solids

1. Introduction and Overview

1.1 Introduction

Recently, concerns over wastewater overflow have grown significantly. One major cause of sanitary overflow and sewer's reduced capacity is "Fats, Oils and Grease" (FOG) that builds up and clogs the sewer system. It has been widely documented that the majority of wastewater produced by food industry contains high amount of FOG that causes severe predicaments for the wastewater system and poses an intensive threat to the environment (Stoll and Gupta 1995 and Keener et al. 2008).

FOG can include any number of fatty organics produced by the food industry: fryer oils, food scraps, meat fats, lard, margarine, butter, baking goods, sauces, and dairy products (Canakci 2005). Vegetables, animal fats and oils are predominantly glycerol esters of fatty acids and have low and generally nonspecific melting points (Boulton et al. 1988). The fatty acid constituents of FOG vary significantly based on the source of wastewater. Furthermore, the antioxidants and cleaning chemicals such as bleach used for cleaning may modify the formation of oil component of the wastewater extensively.

FOG can be either in liquid or solid form and has a lesser density than water, and typically is not water-soluble. Therefore, it floats on the water surface unless emulsified or mixed through high temperatures, high turbulence, mechanical devices such as mechanical stirrer, or through addition of surfactants. Any location that prepares, processes or serves food, such as restaurants, food preparation facilities, hotels and even households (single homes, apartment complexes, etc), are among the perpetrators that contribute to FOG escalation in the wastewater system.

Oily wastewater discharged from restaurants and food preparation facilities commonly contains two types of FOG: firstly, “yellow grease” that is in form of waste cooking oil; secondly, “brown grease” which is composed of yellow grease, food solids and water that is trapped by grease traps and grease inceptors (Canakci 2005).

Generally, oil and grease can be categorized in three aspects (Mathavan 1990): (1) by polarity; (2) by biodegradability; and (3) By physical features. Polar oils are usually present in animal and vegetable material discharged in oily wastewater. Non-polar oils are derived from petroleum or mineral sources. Generally, polar oils are biodegradable, while non-polar oils naturally present bioresistant characteristics. Nevertheless, under proper physical conditions and with addition of adequate nutrient supply, the majority of petroleum and mineral oils are biodegradable. Fats, both animal and planet-generated, has various low melting point and maintains liquid form at room temperature. Oils, which are also referred to as triglycerides, are mostly in liquid state. Finally, grease that covers a broader class of materials including oils, fats, animal tissue, waxes and soaps is mainly found in solid form (Mathavan 1990).

The long chains of esters and fatty acids present in FOG make it a rather stable compound that is difficult to break down or degrade. Due to FOG’s tendency to float, the oily content can be separated anywhere along the sewer lines and adhere to sewer walls and pipelines.

1.2 Importance of FOG Removal

Improper disposal of FOG increases the risk of disrupting the sewer lines and wastewater treatment system. According to the United States Environmental Protection Agency (U.S.EPA), FOG is the primary cause of 40 to 50% Sanitary Sewer Overflows (SSO) in the United States. Additionally, Hardened FOG deposits are responsible for pipe blockages in over 138,000 SSO cases annually (U.S. EPA 2003).

Moreover, oil and grease cause disturbances to public health and the environment particularly to the marine life. FOG with no proper treatment may enter rivers and oceans with potentially disastrous environmental impacts. For instance, U.S EPA reported that on average each spill caused by excessive FOG released 14 m^3 of raw wastewater into the environment (U.S.EPA 2003 and Keener et al. 2008). Even if accumulated FOG does not escalate to blocking the pipeline and overflowing sanitary sewer system, it can disturb the wastewater utility operation and cause an increase in operation and maintenance requirement.

Furthermore, FOG can interfere with the wastewater treatment efficiency by reducing the oxygen air transfer rate and disturbing the oil removal treatment process. The nature of FOG as a waxy and viscous component instigates great difficulty during the sludge handling and dewatering process.

Since excessive introduction of any FOG ingredients into wastewater system and environment are disastrous and expensive to clean; most municipal authorities adopt restricted laws to enforce and monitor the FOG quantity discharged to the sewer system. For instance, Greater Toronto Area (GTA) has imposed 150mg/L and 350mg/L limit on FOG and Total Suspended Solids (TSS), respectively, of wastewater content produced by food industry conducting business in the region (City of Toronto Sewers Bylaw, Municipal Code, Chapter 681). Failure to meet these restrictions will incur fines on the imprudent establishment. However, scientific evidences (Stoll and Gupta, Mosely et al. and Chen et al.) show that raw wastewater produced by food industry and catering establishments including restaurants could contain up to 300 times the limit set by municipalities, as demonstrated in Figure 2.1.

Waste management industry considers FOG as waste by-product, produced by food manufacturers, which should be removed and disposed to minimize the environmental impact and waste disposal costs. Pursuing a new approach, waste management monitors various stages of food production and records the accumulating costs of treating the waste and wastewater at each stage of operation (Darlington et al. 2008). Since the traditional means of FOG removal can be time consuming and inefficient, the industry seeks new and inexpensive technologies that can replace the preceding methods.

Oil/water mixture is categorized into three states:

1. Immiscible mixture;

2. Unstable mixture; and

3. Secondary oil/water emulsion.

For the first two states of oil/water, immiscible mixture and unstable mixture, oil removal process is mainly removing the free oil by means of physical mechanisms. However, the secondary oil/water phase, the most common phase in the food industry wastewater, is more stable. This stability is due to the formation of interfacial films surrounding the oil droplets, which are only visible by microscope. The conventional oil removal processes such as skimmers and grease traps are incapable of efficiently removing the oil droplets from the emulsion.

1.3 Study Objectives and Scope

The primary objectives of the study are as follows:

- To develop an artificial wastewater that would be an acceptable representation of regular food industry wastewater;
- To compare and contrast various oil removal mechanisms that are currently used for wastewater management;
- To study oil absorption capability of magnetic powder particles and assess the ideal provisions that leads to separation of oil from water by means of magnetic coagulation; and
- To develop and verify an easily maintained oil removal mechanism that successfully removes the majority of FOG from oily wastewater.

The scope of the study contained the following tasks:

1. Literature review on history of magnetic separation method and its utilization in removing oil from wastewater;

2. Identify the components of artificial waste that is appropriate for the pilot test. There are available resources that have investigated the sources and amount of FOG concentration generated by food industry. The main criteria for generating the artificial wastewater will be based on data retrieved from these investigations;

3. Jar study to assess the optimal conditions that would yield the best oil removal during the magnetic coagulation process when implemented;

4. Study of the magnetic coagulation apparatus performance under different magnetic powder and coagulant dosages; and

5. Perform the oil removal procedure by means of magnetic coagulation apparatus and report the conditions of the effluent in terms of Chemical Oxygen Demand (COD), TSS and FOG removal values.

1.4 Dissertation Outline

The objectives of this paper are to study magnetic coagulation process and to verify optimum conditions, i.e. magnetic powder ratio, coagulant, that effectively separates oil from oily wastewater. This investigation studies the data collected from several food industry sources to establish a baseline for production of a fairly typical oily wastewater. Also, the study, through reviews of acclaimed published literature, comprehensively describes the sources and characteristics of food industry wastewater and compare and contrasts the current FOG removal processes. Additionally, a complete list of materials and methodologies employed in the research are presented in this paper. The study focuses on the designing an effective oil removal procedure by magnetic coagulation mechanism and employing the optimal operating conditions based on desirable decrease in TSS, COD and FOG values. The following outline describes the contents of this thesis:

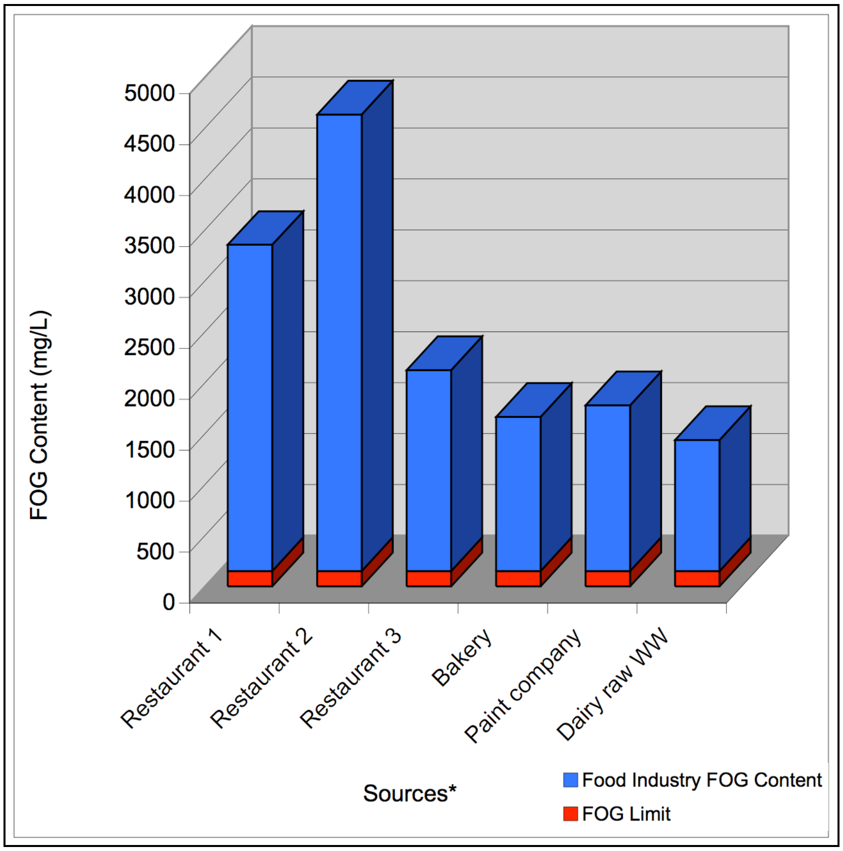
Chapter one begins with an introduction of food industry wastewater and objectives of this thesis. Chapter two extensively reviews the background information regarding the source of oily wastewater, oil/water emulsions, standard FOG removal technologies and application of magnetic coagulation. Chapter three thoroughly describes the experimental methods used in this research including: preparation of artificial wastewater, microscopic, vial and jar test investigations. Chapter four reports and analyzes the results of each investigation. Chapter five comprehensively discusses the results and examines the contributions of each investigation. Chapter six states the conclusions, based on the results of the research and the succeeding analysis and discussion, and recommends further actions to improve the magnetic coagulation procedure and commence the pilot test.

2. Literature Review

2.1 Sources and Characteristics of Oily Wastewater

The common sources of high FOG concentrations are food-processing industries including meat factories, slaughterhouses, pet food industries, dairy industries, vegetable oil industries and restaurants. Furthermore, ingredients such as margarine, butter, lard and vegetable oil from residential and commercial places attribute to rise of the FOG concentration in domestic wastewater. The oily wastewater characteristics vary depending on the source of the wastewater.

In general, oily wastewater discharged from above sources contains high measure of suspended solids, high COD and FOG concentrations. Particularly, the effluent from the pet food industry reported to have TSS concentration of 82,250 mg/L, COD value of 87,480 mg/L and average FOG concentration of 83,000 mg/L (Jeganathan et al. 2005). However, This is considered to be the highest data reported. Figure 2.1 demonstrates FOG content as generated by several sources in food industry in blue columns; meanwhile the red presents the standard municipality FOG limit that is typically set at 150 mg/L.



*Refrences:

Restaurant 1	(Stoll and Gupta 1995)
Restaurant 2	(Mosely et al. 2003)
Restaurant 3	(Chen et al. 1999)
Bakery	(Keenan and Sabelnikov 2000)
Paint Company	(El-Gohary et al. 2002)
Dairy raw WW	(Cammarota and Freire 2006)

Figure 2.1 Example of Food Industry FOG Content and FOG Municipal Limit

Figure 2.1 reflects major categories including retail, food service facilities and industrial food manufacturers. Furthermore, this figure indisputably exposes the enormous gap between the FOG limit set by municipalities and FOG generated by food industry. Also, the FOG concentration varies significantly from place to place; therefore, the actual FOG collected from field can be expressed as one range of data. According to Figure 2.1, the type of restaurant or industry has more effect on FOG generation rather than their size and among them; restaurants generate the highest concentration of FOG. The total FOG concentration in wastewater effluent reported in this figure includes both free oil and emulsified oil.

Figure 2.2 “Oily wastewater build-up” in pipelines

Wastewater pipeline blockage, wastewater flow reduction, odor nuisance, pipeline corrosion and inferior wastewater quality are few consequences of illegal dumping of FOG into the sewer system. Figure 2.2 and Figure 2.3 demonstrate the extent of disturbance and blockage caused by “oily wastewater build-up” in pipeline and sewer system. Based on these figures, oil and grease’s ability to float allows the greasy material to separate from wastewater and adhere to sewer line internal surface and greatly reduce the capacity of wastewater system.

Figure 2.3 “Oily wastewater build-up” in sewer system

Further inquiry into the nature of FOG reveals that it is essentially triglycerides containing esters of fatty acids and glycerol (Jeganathan 2006). Figure 2.4 shows triglyceride molecular structure broken into methyl esters and glycerin with the aid of methanol and a catalyst. This chemical process is called “Transesterification” used to break the triglyceride and reduce the viscosity of the oil (Canakci 2005). Biological processes normally employ similar procedure to degrade the fatty organic.

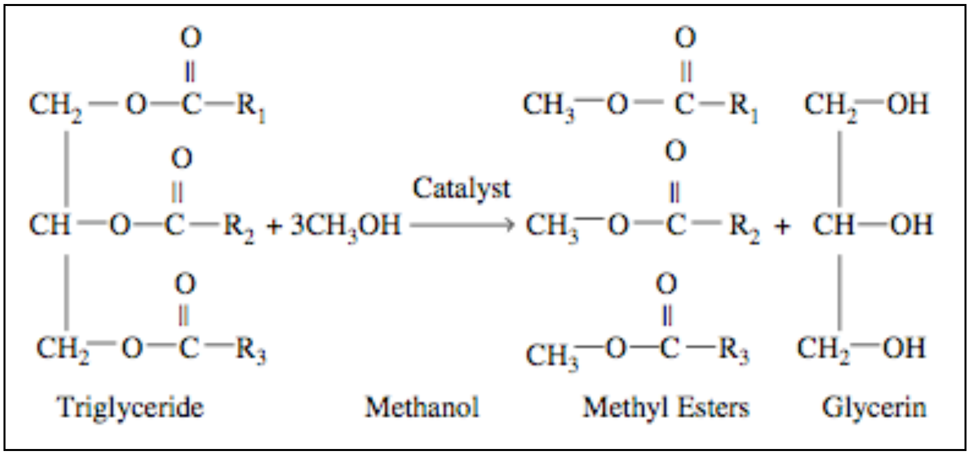


Figure 2.4 Transesterification of triglyceride (Canakci 2005)

The fat components of oily wastewater may feature diverse characteristics depending on its source: 1) they have various chain lengths and number of carbons; 2) they are either from saturated or unsaturated sources; and 3) they can assume free, solve or emulsified forms. Oils mainly remain in liquid form while grease and fat usually tend to be in solid form at room temperature. In addition, many animal fats and hydrogenated vegetable oils appear in solid form at room temperature. Both hydrogenated and non-hydrogenated vegetable oils are used in commercial food frying operations.

As stated before (Canakci 2005), greases are predominantly classified in two categories, “yellow grease” and “brown grease”. Yellow grease is produced from vegetable oil or animal fat that has been heated and used for cooking a wide variety of meat, fish or vegetable products. Yellow grease usually maintains free fatty acid

(FFA) level of less than 15%. The other type of grease is called brown grease with FFA level exceeding the 15% limit. It is also referred to as trap grease, where it may be blended with low FFA material to meet the yellow grease specifications. Brown grease is collected from grease traps or grease inceptors in restaurants to prevent the grease from entering the sanitary sewer system where it could lead to pipeline blockages.

Many rendering plants refuse to process brown grease due to its contamination with cleaning agents. Even though the composition of cleaning agents may not be hazardous to the environment, but detection of harmful substances in presence of cleaning agents will be more difficult (Canakci 2005). The main sources of animal fats are primarily meat animal processing facilities. Another source of animal fats is the collection and processing of animal mortalities by rendering companies.

Primary treatment for removal of oil from wastewater, generated by food industry, consists of trapping the free oil by physical means. Then, secondary treatment is required to separate and remove the emulsified oil. Figure 2.5 demonstrates the oil droplet size based on oil/water form and a corresponding treatment option. Free oil particles of 150 μm and larger are usually in free oil form and can easily be removed by means of mechanical procedures. Oil particles with diameter smaller than 150 μm and larger than 5 μm disperse in water and are partially or completely emulsified in water. The oil particles of 5 μm sizes and smaller are water-soluble and they are mainly found in oil refinery wastewater.

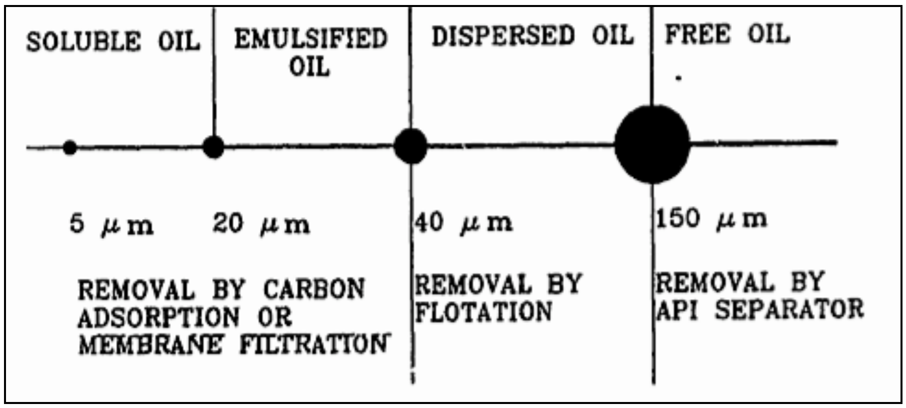


Figure 2.5 Oil droplets and relative treatment options (Rhee et al.1987)

Generally, oily wastewater is capable of causing the following environmental problems, which in turn requires immediate and accurate response of oil removal treatment:

1. Oily film formation on top the water body (i.e. ocean, river)

2. Interfering with biological activity of marine life

3. Taste and odor problem in drinking water

4. Toxic ingredients that may harm soil and marine life

2.2 Oil/Water Emulsion Breakdown Mechanism

The free oil fraction of oil present in food industry wastewater can be removed effortlessly with any removal device capable of gravity separation procedure. The majority of restaurants use grease separators as skimming media.

Nevertheless, oily wastewater contains emulsified oil in significant proportions. For instance, soybean extraction wastewater was reported to contain up to 75% of oil and only a small fraction was released as free oil while the majority of oil was emulsified in aqueous phase (Chabrand 2008).

Oil/water emulsion can be described as suspension of oil droplets within water (immiscible liquid). The formation of oil/water emulsions is usually due to application of mechanical energy to a mixture of oil and water. The shearing action of stirring generates small oil droplets, which can mix with the water phase. In addition to the mechanically mixing, emulsions can also be formed by adding emulsifiers to the mixture.

The dispersed droplets usually have high surface charges, which provide stability to the emulsion systems. Also, emulsifying agents such as surfactants cause stable suspensions of oil droplets constituting the dispersed phase in water. Surfactants must demonstrate the following characteristics:

- High-quality surface activity

- Capable of forming a condensed interfacial film

- Appropriate diffusion rates to interface

Since the solubility of an emulsifying agent (surfactant) signifies the continuous phase, therefore surfactants applied in oil/water emulsions usually are more soluble in water than in oil (PERC publications).

Three procedures have the most influence on destabilization and phase separation of oil/water emulsions: aggregation, coalescence and flocculation (Hempoonsert et al. 2009). The aggregation of droplets occurs when Van der Waals force of attraction is present in the medium. During destabilization of oil/water emulsion, droplet aggregation occurs primarily by the reduction of the net surface charge to a point where the droplets, previously stabilized by electrostatic repulsion, can approach closely enough for Van der Waals forces to hold them together and allow aggregation. Coalescence occurs when two or aggregated droplets merge to form flocs. Application of coagulant could assist the coalescence process.

Floc sizes and composition mainly depend on the floc's settling velocity. Flocs growth is normally limited by applied shear rate that only allows the flocs to reach certain size. Amount of oil captured by flocs is essential in oil removal efficiency. Coagulation process is typically used for oil/water separation to destabilize the emulsions and promote aggregation of oil droplets on flocs, which can be subsequently removed by sedimentation or flotation.

2.3 General FOG Removal Technologies

While food industry has several various technologies at its disposal, the fact remains that these alternatives are either very expensive or lack the anticipated efficiency required by the industry. The oil removal technologies are complex due to various types of oils involved and their diversity in chemical composition and physical characteristics. As a result, the industry continues to explore innovative treatment procedures that simultaneously produce less sludge and cost less than conventional technologies. Generally, current treatments include physico-chemical processes, biological processes, membrane filtration processes and combination of these processes. Figure 2.6 illustrates the various technologies and their particular method of separating oil from water including: skimmers, grease traps or gravity oil/water separator, Induced Air Flotation (IAF), Dissolved Air Flotation

(DAF), membrane technology, magnetic floatation and magnetic coagulation. A more detailed description of each technology is included in the following sections.

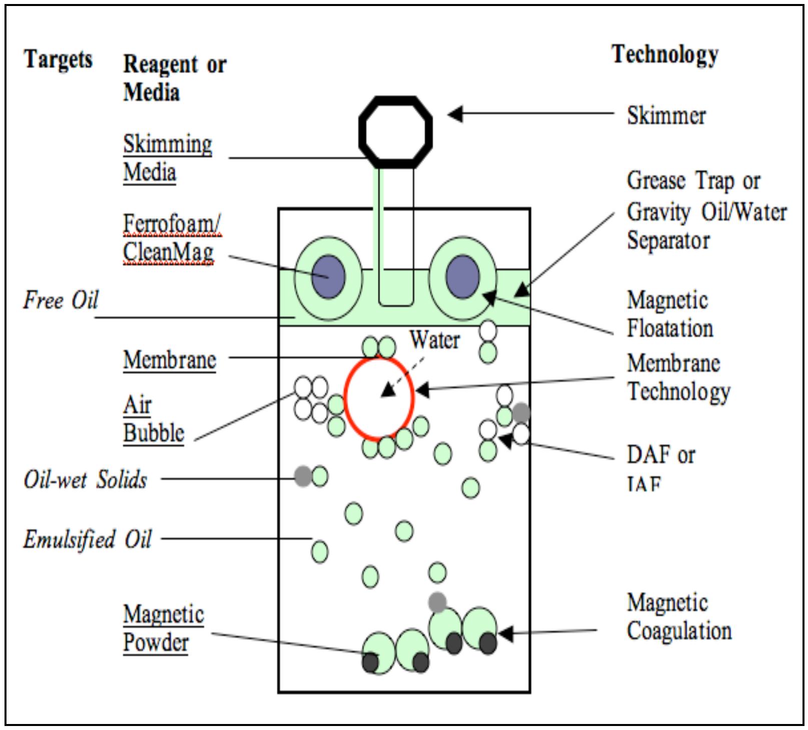


Figure 2.6 Illustrations of different oil removal procedures (Luk 2005)

2.3.1 Physico-chemical Processes

Physico-chemical process mainly relies on precipitation or flotation process to reduce wastewater's organic load. Traditional mechanical coalescence processes include gravity settling separators, skimmers and grease traps. Skimmers, grease traps and grease inceptors mainly target free oil forms and remove them by means of mechanical process.

In a gravity separator system, the free oil floats and forms a film, where oil thickness depends on type of waste, while the sludge accumulates and settles on the bottom. Then, the oil and sludge will be mechanically removed from top and bottom respectively. On average, the effluent filters demonstrated to be capable of removing 41% to 57% of TSS, and 43% to 52% of oils and grease (Wong et al. 2007).

IAF and DAF systems are acknowledged as physico-chemical processes as well. These systems remove emulsified oils and oil/wet solids. Flotation techniques, where adhering to the surface of escalating air bubbles separates fine suspended particles, have proved to be reliable. Similarly, dissolved air is an established separation method for the removal of oils, as well as other contaminants, such as dissolved ions, fats, biomolecules and/or suspended solids from water (Zouboulis et al. 2000).

Flotation is mainly applied, when the application of sedimentation is not sufficient. The low sedimentation rate is due to the presence of very fine particles that do not possess a particular settling rate and therefore the density of the emulsified oil is within the close proximity of density of water. The flotation procedure is more effective in the removing of emulsified oil droplets, since buoyancy difference is improved by attachment to small air bubbles (Zouboulis et al. 2000).

Typical configuration of a DAF sludge removal system is illustrated below (Pan 2007).

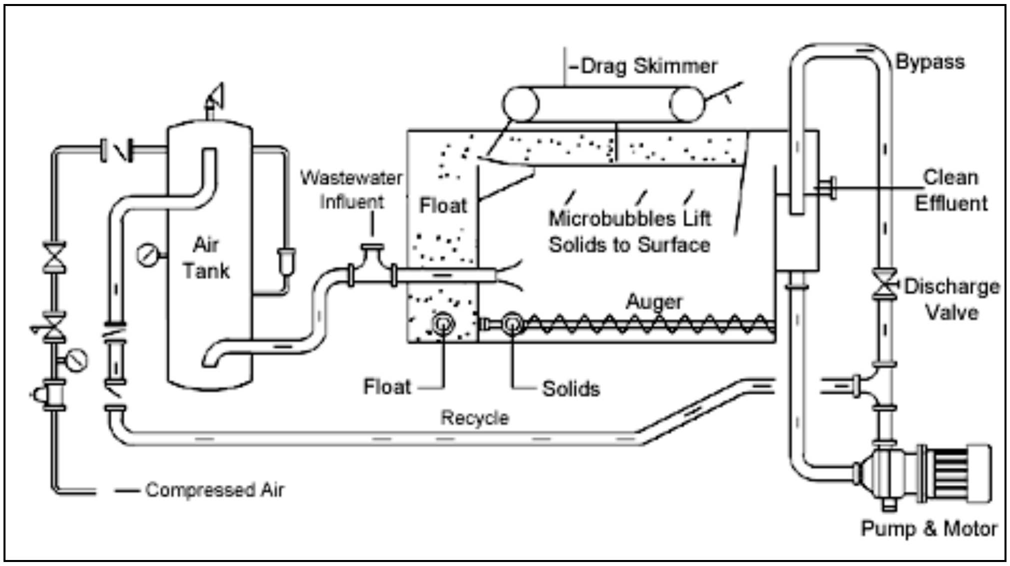


Figure 2.7 Typical DAF configuration (Pan 2007)

The flotation process separates the emulsified particles by altering their surface chemistry. Therefore, the process relies on naturally hydrophobic materials as candidates. This process consists of simultaneous occurrence of several physical phenomena while numerous factors have been discovered to influence the flotation process. It has also been theoretically predicted that the collection efficiency of emulsions will be increased, on increasing the droplet size and decreasing the bubble size (Zouboulis et al. 2000).

There are several reasons that reduce the efficiency of DAF and IAF treatment systems and make them an undesirable option while dealing with food industry wastewater. Although, IAF and DAF systems are more efficient in oil removal than grease traps and skimmers in removing oily wastewater, but they are more expensive.

Furthermore, high contents of suspended solids and oils and grease can lead to rapid clogging and make DAF system quite inefficient. Another disadvantage of flotation is that recovered oils should be extracted from the foam of DAF unit to avoid disruption of oil removal (Mitrakas 1996). As a result, DAF system requires more attentive and frequent maintenance to maintain its efficiency during wastewater treatment. Therefore, reduction oxygen transfer rates, expensive reagents, low removal efficiency and high volume of sludge make the IAF and DAF systems a rather unattractive treatments for removing oil from food industry wastewater.

2.3.2 Biological Processes

Biological process is divided into two categories: anaerobic process and aerobic process. In anaerobic processes, first FOG is hydrolyzed to free long chain fatty acids and glycerol. Then, through β-oxidation process, long chain fatty acid is converted into acetate and hydrogen and finally it is degraded to methane and carbon dioxide. Glycerol is degraded to propandiol and consequently to acetate and hydrogen. Anaerobic digestion of FOG yields higher biogas production since the fraction of degraded substrate for lipids is higher than that of carbohydrates and proteins (Jeganathan 2005).

The aerobic process uses oxygen to successfully degrade fatty acids to of carbon dioxide and water. The treatment of oily wastewater with aerobic process requires application of oxidation ponds, activated sludge process or rotating biological contactor (RBC). The process significantly relies on providing enough oxygen for the degradation process.

Due to environmental protection of microbial cells by their cell envelop, they have more tolerance toward environmental changes subjected to them in food processing facilities and sewer pipelines. Also, microorganism preparations for biological processes are reported to be an economical and stable method (Keenan et al. 2000).

Aerobic and anaerobic oil treatments confront many challenging issues while treating wastewater with high FOG content. Oil and grease can block the gas transfer in anaerobic bioreactors, essential for the biological degradation and in aerobic process, reduce the oxygen transfer rates by altering the surface of the floc with a greasy film of oil. The oily flocs in turn hinder problems in the pumping and aeration systems by causing clogging and reducing treatment efficiency.

In order to improve the anaerobic biodegradability of oil, the use of biosurfactants is recommended. The addition of biosurfactant to anaerobic treatment effectively lowers FOG and COD in the effluent. However, biosurfactants even in small dosage are a rather expensive option for the anaerobic treatment. Furthermore, fatty acids, generated during aerobic and anaerobic procedures, have a tendency of forming micelles. The aggregated particles that settle from solutions during environmental change, for instance pH adjustments, changes in temperature and concentration in grease traps, sewer lines and treatment tanks, can cause clogging.

In recent years, two primary bioremediation approaches are applied to degrade FOG in wastewater (Jeganathan 2005). The first approach employs enzyme, specific protein molecules produced by microorganisms, preparations, which can degrade fats and oils to fatty acids and glycerol. Furthermore, the U.S.EPA still considers the fatty acids as FOG and therefore environmentally undesirable. The second method, biological augmentation uses microorganisms to wastewater, which breaks down, in presence of oxygen, oil and grease further into carbon dioxide and water.

Finally, due to lower substrate fraction for cell synthesis, anaerobic treatment of FOG produces a lesser amount of biomass. High-rate anaerobic reactors, such as Upflow Anaerobic Sludge Blanket (UASB) reactors, hybrid UASB reactors, and expanded granular sludge bed reactors, are widely used for treating oily wastewaters (Jeganathan 2005). Treatment of complex (inhibitory/insoluble) wastewaters, such as oils containing long chain fatty acids, in high-rate reactors causes operational problems and in some cases even failure.

2.3.3 Membrane Filtration Processes

Membrane separation, developed in the last 30 years, is one of the alternative treatments for separating secondary oil/water emulsions. Both microfiltration and ultrafiltration have been used for concentrating emulsions, as they are highly efficient for removing oil, do not require chemical additives and are more economical than conventional separation techniques (Srijaroonrat 1999).

Other types of membrane technology include nanofiltration and reverse osmosis. A complete flow diagram of an ultrafiltration system is illustrated in Figure 2.8 (Chang 2000). As illustrated in Figure 2.8, the ultrafiltration system consists of two pre-filters (F1-F2) that remove suspended solids, a free oil separator to separate free oil, a wash tank that cleanses and sends the wastewater to the ultrafilter membrane.

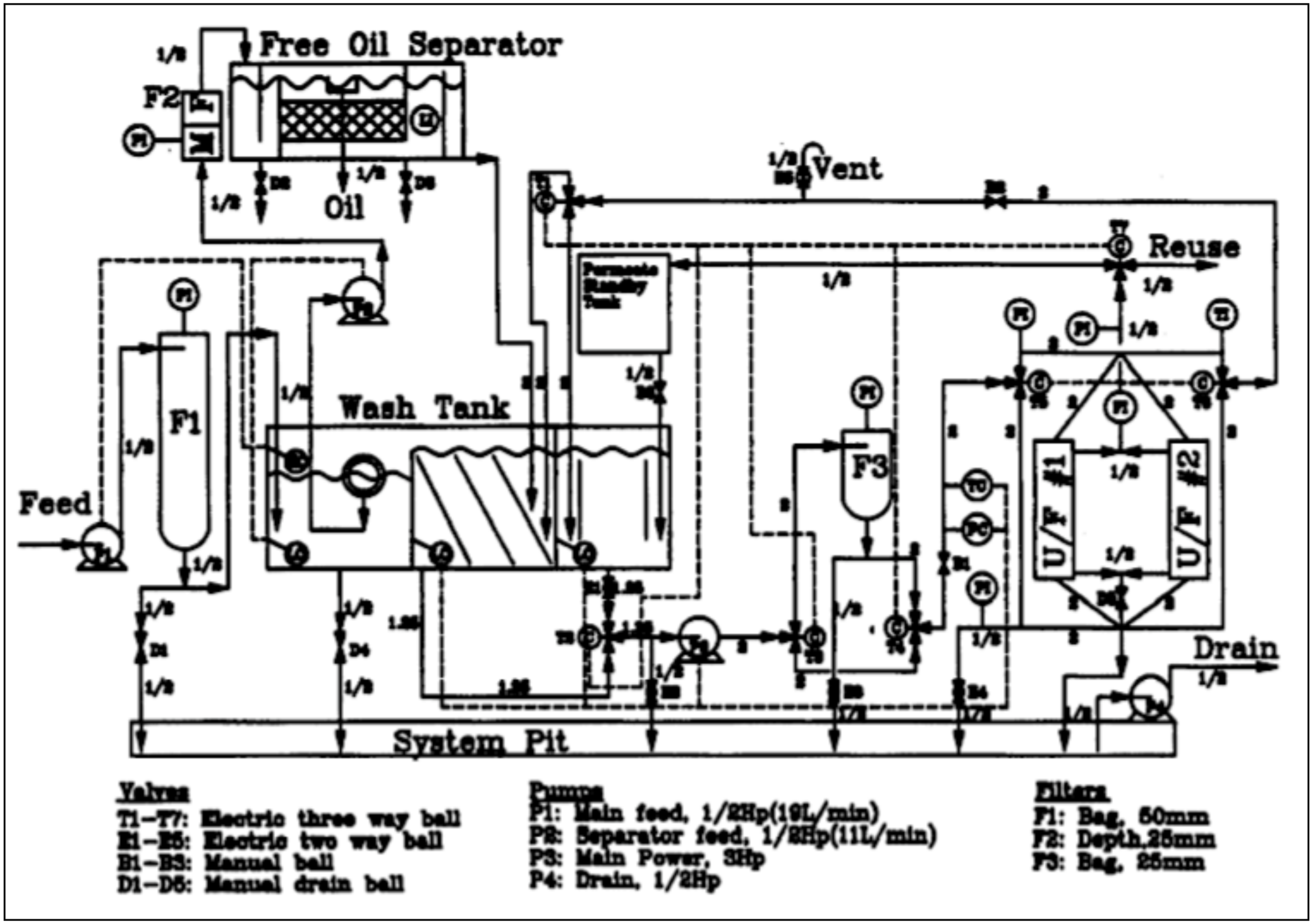


Figure 2.8 Flow diagram of a typical Ultrafiltration membrane system (Chang 2000)

One of the common types of membranes is ceramic membrane, which consists of a fine layer of the porous ceramic filtration element that is in direct contact with the feed stream. It is composed of ceramic particles having specific size, to create a filtering layer of well-defined pore size and typically just a few microns thickness. Ceramic ultrafilters have been developed in the industry for 20 years and widely used in oily wastewater treatment since they present chemical, thermal, and pressure resistance to a wide variety of feed conditions (Srijaroonrat 1999).

However, membrane filtration exhibits drawbacks while treating oily wastewater. The membrane separator relies on filtration of oil particles of specific size in wastewater and can only target particles in a limited range. Therefore, treatment of food industry wastewater that contains several types of oily matter is problematic for membrane filtration process.

Membrane separators have application in treating both petroleum and food industries. Particularly, in metal fishing and petroleum industry where wastewater has large volume of soluble oil emulsion. On the other hand, high FOG concentration and insoluble characteristic is problematic for the membrane filtration. It has been reported that the membrane could face difficulty or even fail while treating food-processing waste (Lee 1984).

Moreover, traditional membrane cleaning methods generate waste cleaning waters; whose disposal costs is an increasing concern. The coalescing membrane must eventually be regenerated in order to maintain a desirable permeate flocs. The results indicate that fouling of microfiltration membranes is due to the presence of oil and grease and seawater colloids in membrane pores (Peng 2008). The main concern remains that unstable oil/water emulsion and emulsified oil are in dire need of a new, cost efficient technology. The new technology must be capable of removing a large fraction of emulsified oil in large concentrations.

2.4 Magnetic Coagulation Application

The application of magnetic separation technology to wastewater treatment has received significant attention in recent years. For instance, finely divided magnetite has effectively clarified sewage effluent through an accelerated coagulation process, which involves adsorption of contaminants onto the surface of the magnetite (Bolto 1989). As early as 1977, magnetic separation method, by employing a polymer of iron powder and three modifiers as sorbent agents, was used to remove oil from water. Turberville (1977) introduced "ferrofoam": a reusable, magnetically retrievable sorbent particle employed for oil spill recovery.

The "ferrofoam" consists of a base polymer, three modifiers and iron powder. It featured high magnetic attraction, floatation on water, and discriminative absorption of oil vs. water. The "ferrofoam" pads could be magnetically recovered on surface after absorbing the spilled oil. The oil sorbent was said to open up for the development of magnetic collection devices, ranging from small hand tools to sea going vessels (Tuberville 1977).

Later, magnetic particles with specific designs were applied to remove oil droplets from dairy industry effluent. These particles consisted of a magnetic core with a polymer coating and targeted specific contaminants by having either a functionalized resin as the coating or selective seed materials embedded in the coating (Orbell 1997). The magnetic particle technology was deemed to be advantageous and its further development and enhancement, to accommodate future applications, was considered beneficial for wastewater treatment in various categories.

Another researcher (Nicolaides 1999) introduced a fairly developed granular material called "Clean-Mag", cleaning magnetically. The large scale application of a new technique for cleaning up oil spills, based on the magnetic separation procedure by use of the "Clean-Mag", an oleophilic, and porous material which was also magnetic with a perceptible density, lower than the water.

This material was sprayed in granular form over the oil spill, absorbed the oil and subsequently it was collected through vessels equipped with magnetic collection devices including electromagnets or magnetic drum conveyor belts. "Clean-Mag" was known to be a non-toxic, recyclable and environment-friendly polymer. The research also confirmed that the polymer, at the laboratory scale, presented capability of removing oil from water surfaces at almost 100% level (Nicolaides 1999).

Conventional chemical coagulation consists of the direct dosing of a coagulant solution to the wastewater in order to reduce the electrical repulsion forces that restrain the aggregation of suspended particles. In the chemical coagulation procedure, the addition of hydrolyzing metal salts such as iron (Fe^{3+}) or aluminum (Al^{3+}) as coagulant is considered to be standard.

The electrochemical coagulation method, on the contrary, consists of the in situ generation of coagulants by electrolytic oxidation of an appropriate anode material, such as iron or aluminum. The following studies in wastewater treatment confirmed that electrochemical process with the aid of coagulation could be a competitive technology with the conventional coagulation process (Cañizares 2007). An earlier study by Chen (1999) demonstrated that electrocoagulation is a feasible process for treating the restaurant wastewater, with high oil and grease content, fluctuated COD, BOD_5 (Biochemical Oxygen Demand) and TSS concentrations. The results showed that aluminum electrodes proved to be more effective for this application. In addition, the influent pH, conductivity and electrical current density did not influence the pollutant removal efficiency significantly. Charge loading was the most important operational variable.

Chen (1999) reported the following as influential parameters: "optimal charge loading and current density were found out to be between 1.67–9.95 F/m^3 (Faraday per meter cubed) and 30–80 A/m^2 (Ampere per meter squared) respectively, depending on wastewater characteristics. The aluminum electrode consumption ranged 17.7-106.4 g/m^3, and the power requirement was usually less than 1.5 KWh/m^3 (Kilowatt hour per meter cubed). The removal efficiency of oil and grease was reported to be over 94% for all the wastewaters tested. The electrocoagulation procedure was capable of neutralizing the pH of wastewater" (Chen 1999).

Also, the electrocoagulation procedure was used with the purpose of treating wastewater with high FOG content under different conditions including pH, current density, reaction time, conductivity, electrode distance and inlet concentration. While the main procedure remained the same, this study used a network of several electrodes in the electrochemical reactor. The research reported that for usual influent wastewater and under experimental conditions, the removal efficiency of FOG and COD exceeded 95% and 75%, respectively (Xu and Zhu 2004).

A more comprehensive explanation of electrocoagulation procedure is as follows: when direct current is applied to emulsion through the electrodes, the anode is dissolved and metal ions (Al^{3+}) are produced instead of oxygen generation as shown in Figure 2.9. These coagulants promote the break-up of the emulsion by reducing the superficial charge of the droplets, and destroying the protective action of emulsifying agent (Tir et al. 2004).

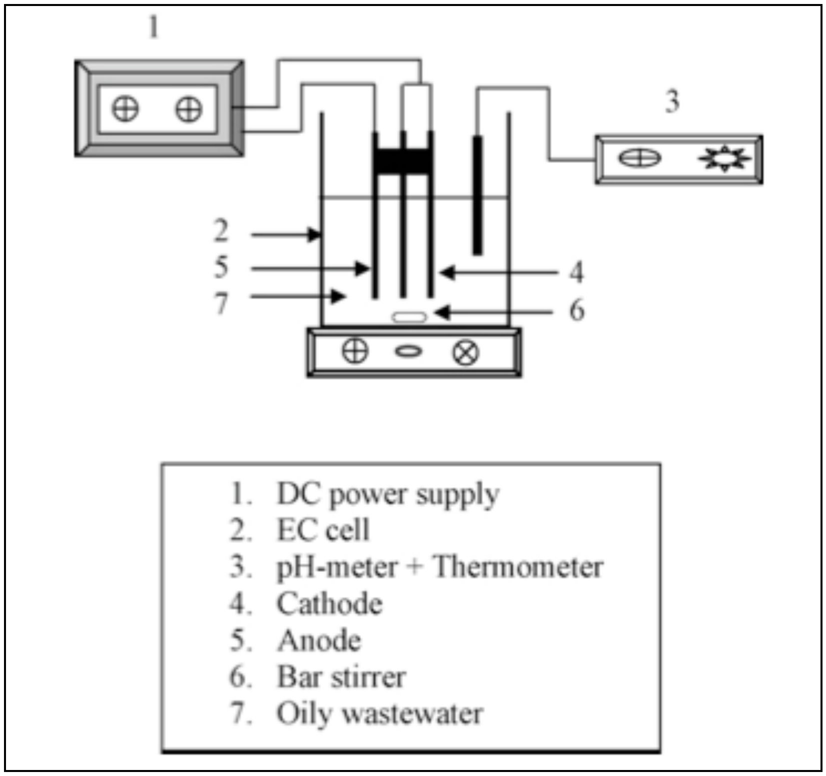


Figure 2.9 Diagram of an electrocoagulation cell (Tir et al. 2004)

Then, the coagulant proceeds to overcome the repulsive effect of the electrical double layer to allow the fine-sized oil droplets to form larger droplets through coalescence. During electrolysis in wastewater treatment, the coagulated oil droplets are trapped into the highly dispersed aluminum hydroxide Al $(OH)_3$ and form large flocs that can be attached to the gas bubbles and involve them with the cell of the engine. At the end of the procedure, an ultimate separation of oil from oil/water emulsion is obtained, which the oil droplets floats on the surface and can be removed by a simple decantation (Tir et al. 2004).

Aluminum and iron are relatively inexpensive and have been demonstrated to be very effective in the electrocoagulation process;

consequently, they have been repeatedly used as electrodes in electrocoagulation systems. One research stated that for applications that are not continuous in time, aluminum electrodes are the best option, because iron can be oxidized effortlessly and corrosion problems on the electrodes are reported when the cell is not connected. In addition, the use of iron as the electrode material has another additional problem because of the color of Fe (III) salts (Cañizares 2007).

Therefore, electrocoagulation procedure, similar to many other procedures, suffers from shortfalls whilst dealing with oily wastewater. The process may face delay due to limitation in use of anode. The procedure requires constant adjustment and material supplement to replace the used anode. Also, in case of flotation, the aggregated suspended solids have to be dealt with in a separate manner resulting in additional cost.

In a more recent study (Chun et al. 2000), magnetic flotation was employed to remove crude oil resulting from oil spills in water. As demonstrated in Figure 2.10, the magnetic powder was mixed into oily solution and then magnetically collected by means of a permanent magnet.

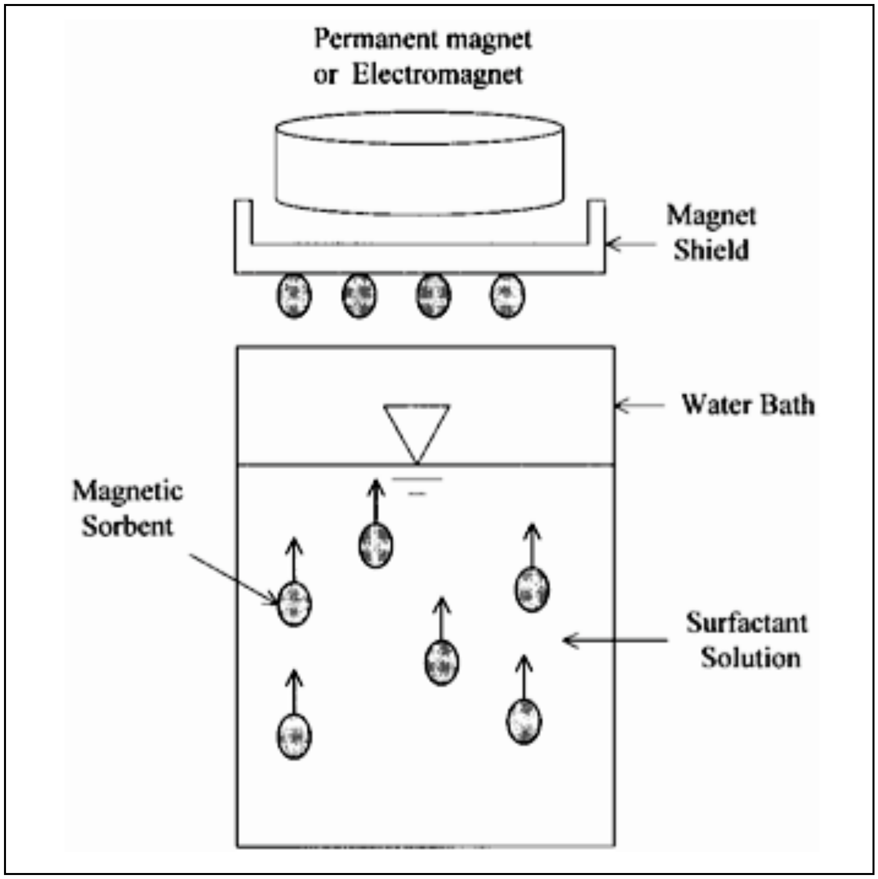


Figure 2.10 Schematic diagram of Magnetic Flotation system (Chun et al. 2000)

The magnet was placed on top of the solution to facilitate the flotation process. Sorption of the dispersants to magnetic polymers was due to fine oil particle flocculation, electrostatic attraction as well as with the structural characteristics of magnetic polymer. The result of magnetic flotation indicated that the oil recovery efficiency of magnetic particles was nearly 100% after the dispersants had been sorbed (Chun et al. 2000).

Finally, magnetic coagulation has gained some momentum as an efficient procedure for oil removal from wastewater. Magnetic coagulator employed fine magnetic powder to coagulate oily matter in a continuously stirred tank reactor. The study of standard jar tests, preliminarily, showed the feasibility of simultaneous removal of the organic matter and FOG (Luk et al. 2001).

Another researcher reported (Dao et al. 2004) of successfully removing 100% of oil from bird feathers, contaminated by oil spill. This research efficiently employed several types of iron powder with nine different particle sizes to remove crude oil from duck feathers. Dao (2004) claimed that the rough surface of iron particle improved the oil removal procedure.

The magnetic coagulation process consisted of three parts: first, magnetic powder was added to the oily waste and initiated the destabilization of oil emulsion and creation of oil-wet powder emulsion. The formation of oil-wet solids was due to magnetic powder sorption and electrostatic attraction where oil's hydrophobic feature, magnetic powder's oleophilic feature and specific structure of magnetic powder played a significant role. Then, a slow mixing rate allowed the oil wet solid to grow in size and attracted more oil fractions thus forming heavy flocs. Gradually, the floc grew larger, with or without the addition of chemical coagulant, and settled. The procedure continued until the mechanical stirring exceeded the surface tension of emulsified oil. Finally, the heavy emulsified flocs were separated from the water column with the assistance of a magnetic field, maintaining sufficient intensity, placed at the bottom of magnetic coagulator (Luk et al. 2005).

Other studies investigated the effect of electro-kinetic processes on the removal of water and oil and grease from the oily sludge and wastes (Yang et al. 2005). Another researcher (Oka 2009) studied the application of strong magnetic field generators, composed of the high temperature superconducting (HTS) bulk magnet systems that used magnetic separation techniques for the wastewater including thin emulsion bearing the cutting oil.

The HTS procedure employed two types of the strong field generators, which were arranged by the face-to-face HTS bulk magnet systems, with magnetic field density of 1 and 2 Tesla (T) in the open spaces between the magnetic poles. The magnetic poles were activated through the pulsed field magnetization and the field cooling methods, respectively. Two water channels containing iron balls were positioned in the strong field in order to trap the magnetized flocs in the wastewater.

The separation ratios of flocs with 200 ppm magnetite powder were evaluated as a function of the flow rates of the wastewater. The bulk magnet system performance showed values of about 100% until the flowing rate reached up to 18 L/ min. The results suggested that the magnetic separation by using bulk magnets was an effective method for the water purification systems (Oka 2009).

Oil as a known group of hydrophobic hydrocarbons, is not only a contaminant in the natural environment but also a reusable resource. Experiments were carried out with two different configurations of electro-dewatering cells, such as vertical and horizontal positioned electrodes. The investigations reported that the electro-dewatering process offered potential for enhanced oil recovery as well as reduction of water content of sludge by more than 40% (Akrama 2010).

Subsequently, a pilot model unit of magnetic coagulator was designed and manufactured; the pilot model design was a more practical design that could be implemented as the on-site oil removal process for the food industry (Luk et al. 2005). The Magnetic coagulator of pilot model system included a main magnetic coagulator tank, an influent storage tank, an effluent storage tank and a sludge storage tank. All sections are set up and connected with each other as demonstrated in Figure 2.11.

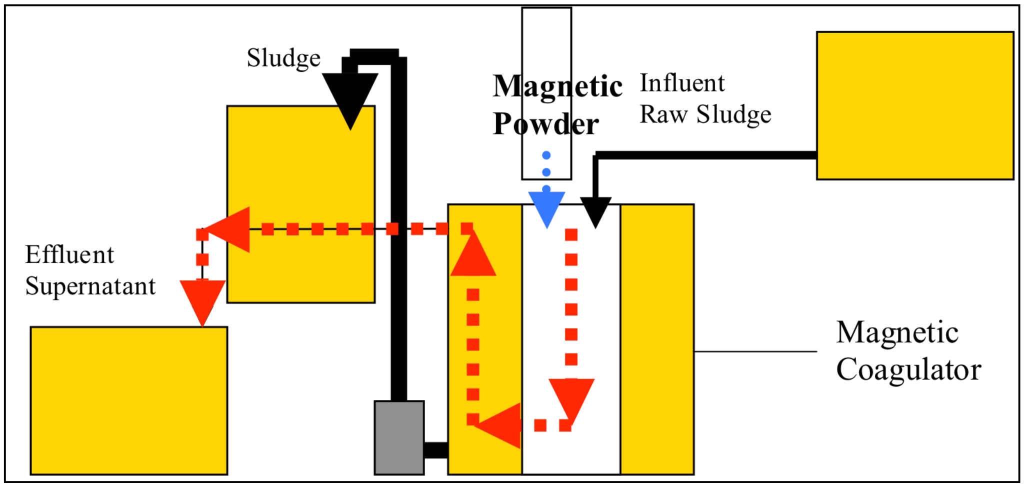


Figure 2.11 Diagram of the pilot model system (Luk et al. 2005)

Magnetic coagulator tank is considered as the main operation part of the system. It consist a continuously stirred tank reactor (CSTR) where magnetic powder is mixed with oily waste flow and then act as absorbent and settling core in order to remove of FOG and COD.

The standard flow rate was set at 1 L/min, which is equivalent to a tank detention time of 98 minutes. For the influent mixture, an oily waste known as DAF sludge, provided by a food processing plant, was used. FOG removal in pilot model test procedure included the following steps:

1.The oily waste from the influent storage tank flew into the inner tank of the pilot model unit.

2.The magnetic powder flew into the inner tank and was mixed with oily waste for the coagulation reaction, then settled down to the bottom of the tank.

3.The supernatant, separated from the coagulated oil, constantly flew out from the top to the effluent storage tank.

4.The settled sludge with deposited magnetic powder was pumped out from the bottom of the tank to the sludge storage tank with the means of a mechanical pump.

5. Magnetic powder was recovered from the settled sludge through thermal treatment and crushing the produced solidified substance.

The pilot tests demonstrated the effectiveness of the magnetic coagulator system in treating DAF sludge. The system could virtually remove all the FOG in the oily waste tested under good settling performance and simultaneously removed TSS, VSS (Volatile Suspended Solids), Turbidity and COD by 96.4%-99.4%, 96.2%-99.2%, 96.8%-98.0%, and 86.2%-87.3%, respectively (Luk et al. 2005).

In conclusion, the magnetic coagulator has proved to efficiently remove one particular type of oily wastewater (DAF sludge) under laboratory conditions. However, the question remains that magnetic coagulation require further tests to study the procedure’s efficacy while treating typical oily wastewater with variable physical and chemical characteristics.

3. Methodology

3.1 Selection of Artificial Wastewater

In the preliminary study, the elements of artificial wastewater were selected in a manner that replicates the typical characterizations of food industry wastewater. The combination of these ingredients should yield the similar FOG, COD and TSS values that represent the average oily wastewater. The FOG content of food industry can be due to any number of sources used to process and prepare food. A variety of diverse oils contribute to FOG: Fryer oils, lard, margarine, butter, baking goods, sauces, and dairy products (Canakci 2005). Predominantly, vegetables, animal fats and oils are complex products glycerol esters of fatty acids and have diverse physical characteristics (Boulton et al. 1988).

Therefore, it is impossible to arrive at a world-standard type of synthetic wastewater with a constant composition. To achieve a formula for synthetic wastewater, which represents the majority of food industry wastewater features, several trials were attempted in the first phase of the investigations. After analyzing several municipal wastewater samples, Keener et al. (2008) reported that “moisture content of FOG samples ranged from 6 to 86% of the total volume of the sample, suggesting that moisture content can fluctuate in FOG deposits. A total of 16 of 19 FOG deposit samples (84%) contained greater than 50% lipid content, with the primary lipid being palmitic, a saturated fat. In addition, 85% of FOG deposit samples contained calcium as the primary metal or mineral present, with average concentrations of 4255 mg/L" (Keener et al. 2008). This information help set the primary water and oil content for artificial wastewater tests. Basically the artificial wastewater was designed to arrive at approximately similar results.

Keener et al. (2008) also stated "no connection was found between calcium concentration in FOG deposit samples and water hardness. The FOG deposits preferentially accumulated saturated fats and calcium, well above background levels, suggesting that a chemical process was responsible for their formation" (Keener et al. 2008). This information led to decision to forfeit the use of Distilled Deionized Water (DDW) and to use typical tap water.

Many sources testify that cleaning products, applied in daily cleaning of food facilities, play a major role in emulsifying the oil/water solution. An investigation by Angiel (2005) reported that the use of harsh cleaning chemicals in the kitchen surfaces and sinks is an additional consideration for the pretreatment community. Chlorine-based chemicals are often used to clean and disinfect kitchen surfaces and sinks. Common household cleaning chemicals can drastically change the pH of the grease interceptor environment. When these chemicals enter the grease interceptor they can kill, inhibit, or inactivate the bacteria. Surfactants used to wash dishes and floors can also affect the metabolic processes of the bacteria (Angiel 2005).

As a result, not only cleaning products are harmful to the environment, but also they significantly alter the oily wastewater transportation and treatment. Therefore it is necessary to include some variety of cleaning product, such as bleach, soap or industrial cleaner, in small dosage in design of artificial wastewater.

According to Keener et al. (2008), a periodic release of concentrated FOG is due to either dishwashing or cleaning of the oil fryer. The debris layer is suspected to result from the cleaning and sanitizing of nonfood contact surfaces in the facility. Dirt and debris from floors, tables, and walls are rinsed into the sanitary sewer and accumulated at the FOG blockage site, probably due to FOG surface charge, settling characteristics, and/or flow restrictions. Only a small portion of saturated FOG and dirt and debris discharged are accumulated, or FOG periodically sloughs off into wastewater (Keener et al. 2008).

Also, another justification for involvement of cooking oil and similar oils is based on by Keener's (2008) affirmation: "FOG deposits results from the accumulation of lipids from waste discharges of highly concentrated lipids. These samples display oil profiles similar to cooking oils, without significant metals or mineral present." As a result of literature review, the following ingredients, as illustrated in Figure 3.1, were the primary constituents used in the generation of artificial wastewater:

1.**Oils**: several sources were used at different dosage to observe, record and compare with typical food industry wastewater. While the majority of oil was supplied by Harvey's used fryer oil, other types of oil dosed in small quantities were also added as illustrated in Figure 3.1.

i. Fryer Oil: used fryer oil (vegetable oil), provided by Harvey's hamburger franchise. The oil had dark brown color, liquid form, at room temperature and with lesser density than density of water. It contained some fried scraps; therefore the sample was filtered and the scraps were separated during the synthetic wastewater preparations.

ii. Olive Oil: store-bought cooking olive oil with 8% acidity. This is a golden color liquid at room temperature which becomes cloudy a temperature below 7° C.

iii. Bacon Oil: Homemade, with instructions to fully cook bacon and extract the bacon oil for the experiment. It maintains a solid form at room temperature; but it was warmed to about 35° C to be fully mixed with other ingredients during preparation.

iv. Animal Fat: Lard, home-source with some scarps that later were filtered out.

v. Motor Oil: Initially used motor oil was also mixed in minor quantities, since many sources exclaimed that traces of motor oil is often be found in the municipal wastewater. However, eventually the evidence of motor oil existence was insufficient for food industry wastewater and consequently the motor oil was eliminated from the list of ingredients.

2. **Water**: The use of DDW was not needed, since food processing industry wastewater usually does not use DDW. The oily wastewater generated from food industry commonly uses tap water, thus tap water was used in the synthetic wastewater preparation. Water fraction was ranged from 40-75%.

3. **Other Ingredients**: The original trial included various other ingredients that were determined be a good candidate for the synthetic wastewater: Including cream, sour cream, salad dressings, cooked rice, creamy pasta and beef stew. The last three were blended to form a homogenous liquid.

Figure 3.1 includes all the ingredients that were used to produce the primary artificial wastewater sample; the components include the following: (from left) Harvey's used oil, cream, vegetable oil, bacon oil, sour cream, animal fat, motor oil, salad dressing, cooked rice, combination of coffee grinds, beef stew and frozen dinner and water.

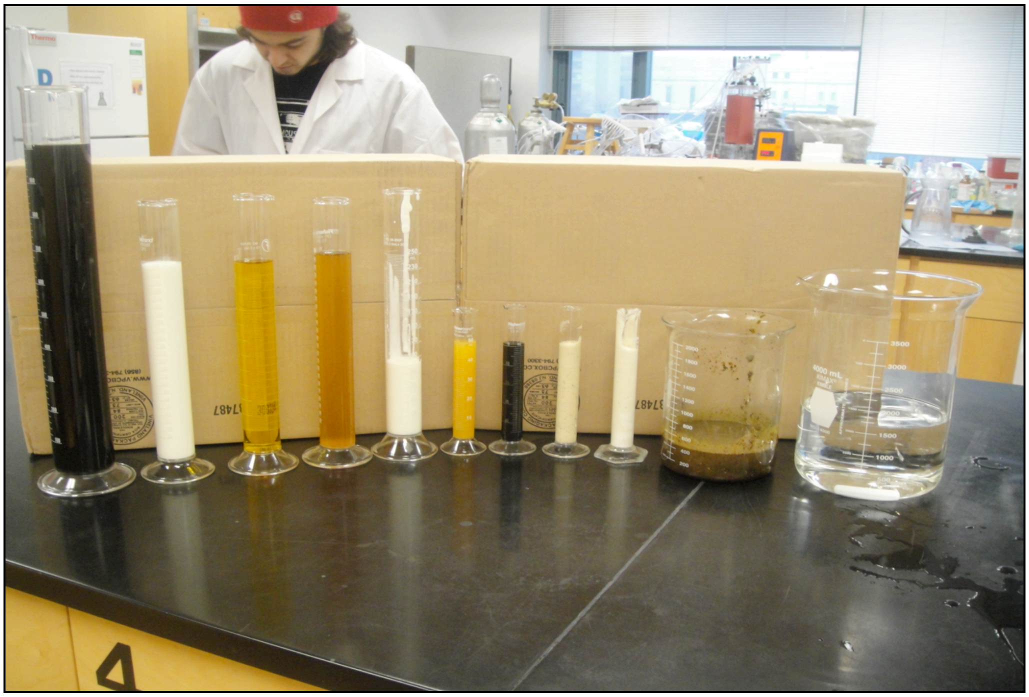


Figure 3.1 Ingredients for the first artificial wastewater trial

During the artificial wastewater trials, the total amount of suspended solid exceeded the expected range by 100 times. Therefore, some of the ingredients from “other” section were eliminated. The final candidates were juice, as an alternative for water in “other” section, and bleach, which presented the presence of cleaning products in food industry wastewater.

As stated before, bleach was applied as a surfactant agent and since traces of bleach as a common household and industry cleaning material is indisputable, the option of bleach to act as both a regular wastewater ingredient and surfactant agent was deemed acceptable. The concentration of bleach fluctuated through the trials. The addition of bleach allowed the oil to be more dispersed in the wastewater. Therefore, the oil/water emulsion stability was enhanced prior to application of magnetic coagulation.

3.2 Selection of Magnetic Powder

Quebec Metal Powder Limited (QMPL) Company provided the magnetic powder with 98% purity. An amount of 2 Kg was gifted to Civil Engineering Department of Ryerson University by the QMPL Company. This certain type of magnetic powder has density of 3.26 g/cm^3. Particle size analysis reveals that 82.5% of sample contains 150 μm powder size and the 12.5% of the sample contains powder sizes that range between 150 μm to 75 μm and the remaining 5% contains magnetic powder sizes of less than 75 μm.

Additionally, 300 g of 45 μm magnetic powder was purchased from “chemicalstore.com” located in New Jersey, USA. This particular type of magnetic powder with 98% purity was obtained to observe the effect of very fine magnetic powder in oil removal especially with smaller oil droplets.

The sample provided by QMLP mostly contains powder with majority of sizes placed into the 150-75μm range. Therefore, the fine powder was added to ascertain that magnetic powder of all sizes were included in the experiment.

3.3 Methodology

Four stages of comprehensive investigations were designed to study and evaluate the optimal elements and conditions for oily wastewater treatment by means of magnetic coagulation. The preliminary stage of investigations was dedicated to generating synthetic wastewater and performing the necessary tests to compare the generated mixture with the data collected from food industry wastewater. The ultimate synthetic wastewater was then used as the testing environment for the subsequent stages: microscopic investigations, vial tests, and jar tests.

In the second stage of investigation, the microscopic investigation was initiated to evaluate and confirm the oil droplet size of emulsified oil/water blend and oleophilic characteristics of magnetic powder by means of a microscope. Also, the microscopic examination provided an insight to the scope of oil dispersion in wastewater.

The next stage of the examination consisted of testing the leading factors that would significantly influence the oil sorption capability of magnetic powder. In this stage several vial tests were performed to observe and record the effect of each factor separately. Furthermore, the experiments were performed in duplicates in order to confirm the accuracy of the results.

The fourth and final stage of investigation consisted of a succession of jar tests that would apply magnetic coagulation to the synthetic wastewater while assessing for the ultimate factor that enhances the oil removal. The effects of magnetic powder dosage and external coagulants were examined in quantitative measures. The results were reported in removal of FOG, TSS and COD removal as a function of magnetic powder and coagulant independently.

3.4 Artificial Wastewater Samples

Synthetic wastewater samples were prepared in 4-Liter volumes in a magnetic stirrer for 90 minutes, with different fraction of water, oil and other components. Since the moisture content could measure into any value between 8-68% (Keener et al. 2008), the following fractions were tested: 40,55,75,65 and 68%. Each time the TSS, COD and FOG values were recorded and compared with the data collected from factual sources. Then, the blend was remained still for 30 minutes. In general, the temperature was found to be 19.8° C, in close proximity of the room temperature, and the pH of the blend fluctuated in the range of 4.5-6.

The result was a slightly acidic yellow-brown liquid that mostly presents secondary oil/water emulsion characteristics. After several hours, thin film of oil floats on top of the mixture. The delay in oil/water separation can be attributed to the repulsion forces of surfactant with oil droplets. In this case bleach functions as the surfactant, which stabilizes the oil/water emulsion.

Once the optimal quantities and proportions of ingredients for artificial wastewater were evaluated, an ultimate trial was carried out to generate the optimal artificial wastewater that would carry typical characteristics of food industry wastewater. A description of the TSS, COD and FOG tests that were performed is provided in the next page. Moreover, the temperature and pH of each mixture were measured and recorded.

TSS is defined as the solids that are retained by a glass fiber filter and dried to constant weight at 103-105°C. Glass fiber filter disk was prepared and the filter disk inserted onto the base and clamped on the funnel. While vacuum was applied, the disk was washed with three successive 20 mL volumes of DDW water. All traces of water were removed by continuous vacuum application after wastewater sample has passed through. Funnel was removed from base and the filter is placed in the aluminum dish. The filter was rewashed with an additional three successive 20 mL volumes of DDW water, and dry in an oven at 103-105°C for one hour (Eaton 1993). Then, dish was removed from the oven, cooled in a desiccators and weigh. Finally, the TSS was calculated by applying the following formula:

$$TSS,\ mg/L = (A\text{-}B) \times 1{,}000/C \qquad [3.1]$$

Where: A = weight of filter and dish + residue in mg

B = weight of filter and dish in mg

C = volume of sample filtered in mL

The COD test computes the oxygen equivalent consumed by organic matter in a sample during. The sample was added to the particular vials designed for the COD test in 1 mL dosage, shook vigorously for 30 seconds and heated in 100°C for 2 hours. The vials were then set still to cool for 30 minutes and allowed any suspended solids to settle (Eaton 1993). Then, the vials were put in the Spectrophotometer as shown in Figure 3.2 and the values were recorded. Since the procedure was deemed very accurate, the COD tests for each trial were performed in a single set. The COD is calculated according to the following equation:

$$Y = 10705X + 180.5 \qquad [3.2]$$

Where: Y is the real COD value

X is the value read by COD reader

Figure 3.2 Spectrophotometer

FOG content is measured based on U.S. EPA method 9071A (U.S. EPA 1994). In brief, a known volume of FOG sample was acidified to pH 2.0 using 1:1 hydrochloric acid solution. Then the sample was transferred to a separatory funnel. The sample bottle s carefully rinsed with 30 mL extracting solvent (100% *n*-hexane) and solvent washings are added to the separatory funnel. The separatory funnel was Shook vigorously for 2 min. Then it remained still to let layers separate. Aqueous layer was drained and small amount of organic layer was poured into original sample container. The solvent layer was drained through a funnel containing a filter paper and 10 g Na_2SO_4, both of which have been solvent-rinsed, into a clean distilling flask. Extraction procedure was repeated twice more with 30 mL solvent each time, but first sample container was rinsed with each solvent portion. The funnel containing the filter was then put in the 85 °C water bath. Consequently, The FOG concentration is calculated by the following equation:

$$FOG\ mg/L = A\text{-}B/(Weight\ of\ the\ Sample\ Volume) \qquad [3.3]$$

Where: A = Weight (mg) of residue

B = Weight (mg) of flask with boiling chips.

3.5 Microscopic Investigation

The oily wastewater essentially contains oily substance in form of oil droplets with various diameter sizes. The microscopic investigation clarifies whether the magnetic powder attracts oil droplets. After the generation of artificial wastewater, a microscopic investigation was commenced to observe and evaluate the typical oil droplet sizes present in the wastewater.

For the microscopic examination and image analysis, 1–2 drops of the artificial wastewater sample, approximately containing 1mL, was placed on a microscope slide using Pasteur pipettes with a large tip to minimize breakage of flocs during transportation from its original source. The flocs were examined with a reflective microscope. The captured images were analyzed through “Image-ProPlus” version 3.0 Software. The digital images were analyzed by using color contrast to single out and clarify the oil droplets and individual magnetic powder. By means of the reflective microscope, micro slides and cover glass slips the oil adsorption levels or water adsorption levels of magnetic powder were observed.

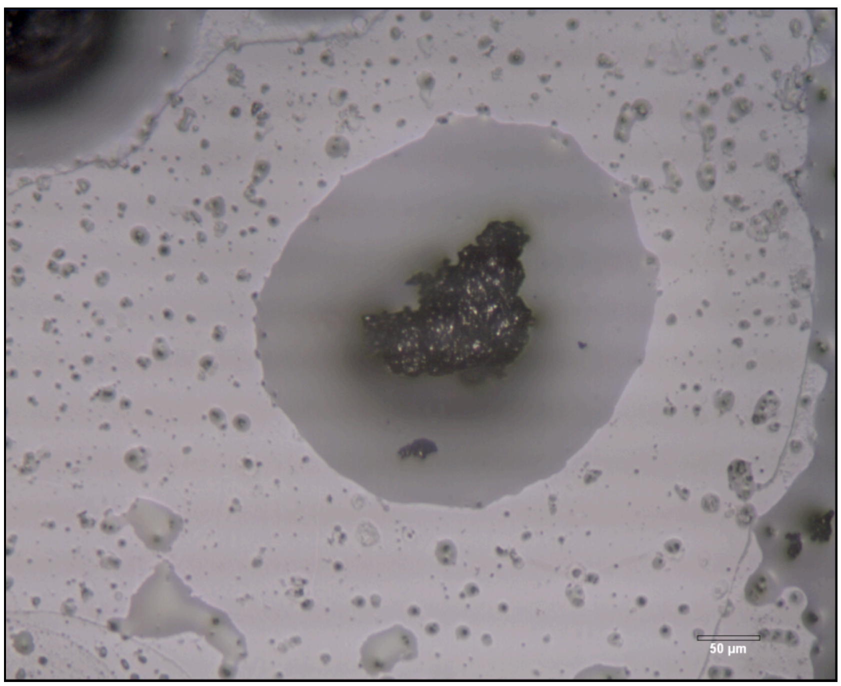


Figure 3.3 Magnetic powder in oil droplet (100x)

The powders employed were 45 µm and 150 µm magnetic powder. The powders were added to olive oil, water and artificial wastewater to observe the absorption properties of the magnetic powder. The investigation was repeated with 50 x, 100 x and 200 x magnification and the contents of each slide were observed carefully. Then, the powder was magnetized with the aid of a bar magnet to study the effect of magnetic field on the powder/oil interaction.

The introduction of magnetic powder to the wastewater and constant stirring will allow the magnetic powder and emulsified oil to constantly contact. The continuous stirring would allow enough oil droplets to be absorbed by magnetic particles as shown in Figure 3.3. The oil droplets will grow larger until they collide with each other and form flocs. The more oil droplets collide the larger the sizes of the flocs and eventually larger flocs become visible.

3.6 Vial Tests

To grasp a better understanding of oil adsorption and prior to jar test, several sets of vial tests were performed with optimum artificial wastewater and various ratios of magnetic powder. The objective was to clarify the ratio of magnetic powder: 150 μm powder and artificial wastewater ratio to magnetic powder blend.

First vial test had the following ratios: (fine powder) 45 μm: 150 μm, 1:10 ratio and 100 g optimum wastewater: powder blend, 1:3. The addition of powder to the wastewater initiated instant adsorption, with some powder settling while most of the fine powder was suspended on the top oil layer. The second phase involved the determination of several factors that might increase the oil absorption and removal efficiency. The investigation in this phase was devoted to the following factors:

1. Magnetic powder dosage;

2. Magnetic powder gradation;

3. Magnetic intensity;

4. Types of coagulants; and

5. Dosage of coagulants

The above were the factors that considered having the most influence on the coagulation process and were analyzed in separate controlled environments. The synthetic wastewater generated in the first phase was employed in the second phase. Also, a series of commercial coagulants, alum, ferrous chloride and Poly Hydroxy Aluminum Sulphate (PHAS) were applied to the mixture to facilitate the development of heavier flocs and increase the settlement rate.

In order to confirm the oil adsorption of magnetic powder, a series of vial tests were performed with different types of magnetic powder: first with very fine magnetic powder (45 μm) interaction was tested with artificial wastewater. Afterwards, the test was repeated with magnetic powder with the larger (150 μm), and artificial wastewater.

Each experiment included 5 vials with various ratios of 1:1,1:2,1:3,1:4 and 1:5. Each vial contained 5 grams of artificial wastewater and magnetic powder with the indicated proportions added gradually to the mixture. Also, a similar series of test included experiments with water and subsequently with olive oil to observe, compare and contrast the effective oil adsorption in presence of magnetic powder.

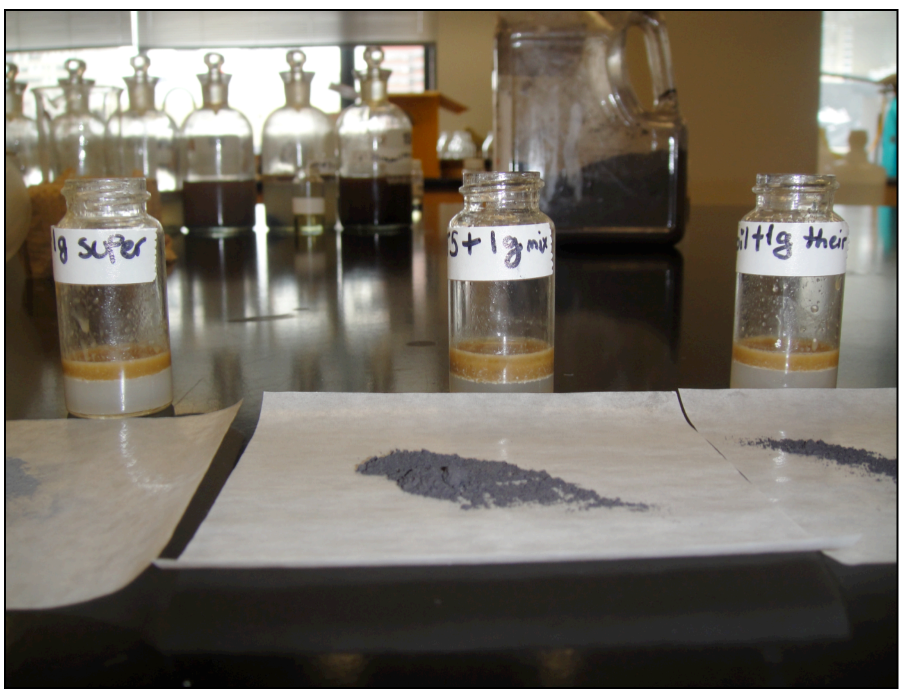


Figure 3.4 Vial tests

The second set of series, as shown in Figure 3.4, was carried with the same number of vials and amount of ingredients but a ratio of 1:2 and

1:3. Once more, the amount of artificial wastewater remained 5 grams and different ratios of 150 μm magnetic powder (1:2 and 1:3) were added to the blend. This experiment was carried out to examine oil adsorption capability of a gradation type of magnetic powder.

Then, a series of vial tests were carried out with 3 vials of artificial wastewater and different ratios of magnetic powder. The third series contained 3 vials with 1:1 ratio of artificial wastewater and various combinations of magnetic powder gradations: fine powder (45 μm), 1:3(blend of 45 μm and 150 μm magnetic powder) and 150 μm. The purpose of the test was based on the hypothesis that a combination of several gradations improves the oil adsorption and therefore removes the oil more significantly.

After that, the effectiveness of magnetic intensity was put to test with subjecting the above vials to magnetic field provided by ceramic magnetic bars. To create an appropriate magnetic field, several arrangements of bar magnets were tested. The magnetic intensity has a significant role in enhancing the sedimentation process. A set of experiments was performed with 5 vials, 150 μm magnetic powder (1:1,1:2,1:3,1:4 and 1:5) and 1-3 magnet bars. However, enough number of bars should be applied to the jar to effectively settle the flocs. Exceeding magnetic intensity could tighten the bonds between the magnetic powders and therefore squeeze out the oil droplets attached to magnetic powder.

On the other hand, the absence of sufficient magnetic intensity would cause the flocs to stay suspended in the mixture or light flocs and free magnetic powder to float. The effect of the magnetic field was best demonstrated when 2 ceramic bar magnets (4.5 x 2 x 1 cm), provided by “Efstone Science Store”, were placed together under the vial. The magnetic field increased the oil adsorption and the oil droplets attaching themselves to magnetic powder was very visible.

In the final vial test, the super fine ratio was decreased to 1:10; thus, less magnetic powder flotation was observed, while oil absorption increased significantly and a clear supernatant with less turbidity was observed. Once the suitable oil/magnetic powder ratio was figured out, the preliminary jar tests were commenced.

3.7 Jar Test Design

The jar tests were initiated by means of a two-paddle jar test apparatus, containing artificial wastewater and various amounts of QMPL magnetic powder as following: 2,6,9,12 and 15 g/L. The magnetic powder portions and coagulant, where applied, was added at a constant rate.

To create a proper magnetic field that would allow the most aggregation of the oily flocs, a set of six 4.5 x 2 x 1 cm magnetic bars were arranged in a circular shape as shown in Figure 3.5. Based on the vial tests, it was decided that applying six bar magnets would create sufficient magnetic field. According to the jar test design and the position of the propeller the arrangement was designed to cover the surface that would attract the most flocs.

Figure 3.5 Bar magnet arrangement

Each dosage of magnetic powder was added to 1500 mL of artificial wastewater in a continuously mixing jar at 125 Revolutions per Minute (rpm) speed followed by slow mixing rate of 15 rpm. The rationale for fast mixing rate was to aid the complete dispersion of magnetic powder and the slow mixing rate facilitated the formation of larger and heavier flocs and sedimentation. Proper sedimentation of oil/powder flocs played a significant role in removing the suspended emulsified oil in the wastewater.

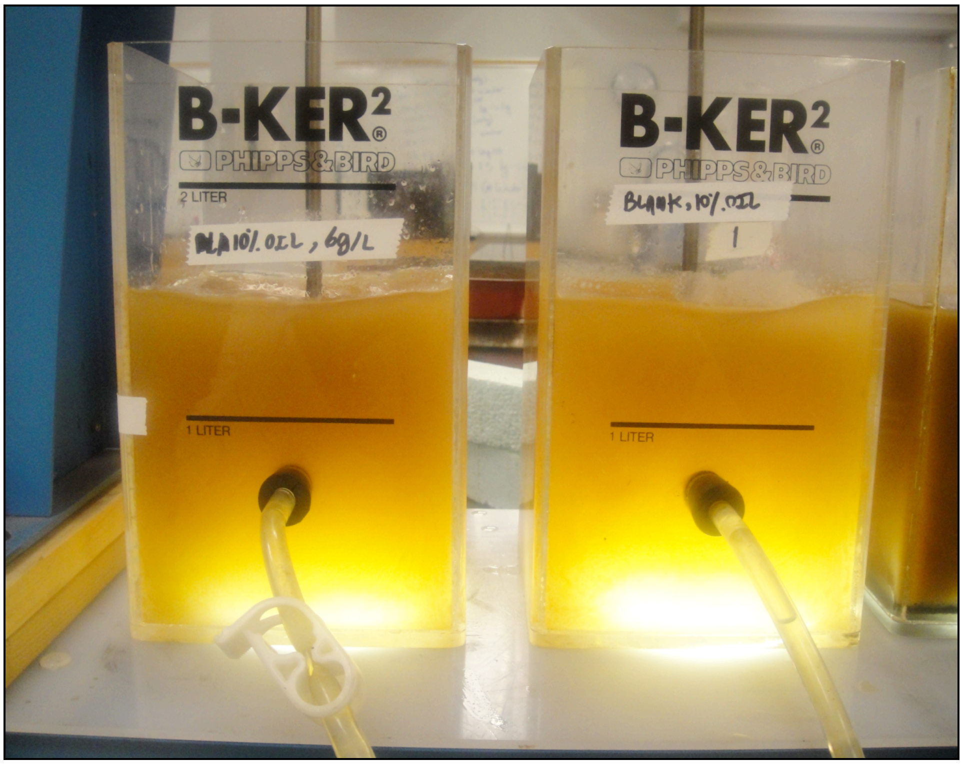


Figure 3.6 Jar tests

Figure 3.6 illustrates a typical set-up of the jar tests, where 2 or more sets of test were performed and not only FOG concentration and other scientific values were recorded, but also an observational comparison and contrast was permitted by this simultaneous commencement of experiments. Since artificial wastewater was initially produced in form of brown liquid, therefore any change in color or clearing of the suspended solids signifies an alternation in the mixture.

The oleophilic characteristic of magnetic powder and its particular gradation allowed a certain bond with the suspended oil droplets present in the synthetic wastewater and led to formation of flocs. During the slow speeding mode, with the aid of coagulants the series of flocs grew bigger and aggregated. In order to assess the best coagulant for the procedure, a set of jar tests was performed with artificial wastewater, 12g/L magnetic powder and various types of coagulants that already proved to be effective in vial tests. A control test was also conducted to record the magnetic aided oil adsorption of magnetic powder in the absence of any coagulant of any kind. The trials consisted of the 450 mL of artificial wastewater mixing in continuously stirring jar in the presence of a magnetic field as shown in Figure 3.5. Since only three coagulants: alum, ferrous chloride and PHAS demonstrated signs of coagulation in vial test, the jar test was limited to these coagulants. Each coagulant was added to the mixture at gradual rate with mixing rate of 15 rpm in effect. The alum solution was added in 1,2,3, 5 and 10 mL/L to the mixture and only FOG concentration was recorded. Also, the other well-known coagulant ferrous chloride was added in of 0.5,1 and 2 g/L dosages. The use of coagulant in the mixture was limited to minimal quantities to constraint the contamination of wastewater with further chemical additives and furthermore, to economize the investigation since industrial coagulants are usually quite expensive.

4. Results and Analysis

4.1 Artificial Wastewater Characteristics

In order to produce a replica of food industry wastewater as artificial wastewater, several samples were generated, tested and recorded. One of the main objectives of this thesis was to produce an acceptable representation of regular food industry wastewater. The artificial wastewater must contain major components that widely contribute to FOG concentration in wastewater such as oils from fryer, animal fats, cream compounds and water. The main target is to develop an artificial wastewater that has TSS, COD and FOG values around the mid-range of the monitored food industry wastewater.

A comprehensive account of each artificial wastewater trial and corresponding proportions and TSS, COD and FOG concentrations are reported in this section. The results of each trial were recorded and compared with data collected from several sources and reports including Figure 2.1. Initially artificial wastewater samples were produced in 4-liter volumes to ascertain that enough samples were available for experiments. Table 4.1 provides a complete list of ingredients and responding proportions. Also, Figure 3.1 illustrates all of the components used in the first trial. Cooked rice, beef stew, frozen dinner and coffee grinds, were among the primary components of the “other” section in artificial wastewater. These ingredients were mixed and thoroughly blended to act as oily solids in the mixture. The first trial included a large number of ingredients to reflect the variety in food industry wastewater. As the trials commenced those components that deemed to have negative effect and/or significantly divert the physical and chemical features of the artificial wastewater from reaching optimal conditions were either eliminated or significantly reduced in volume.

Table 4.1 Composition of artificial wastewater (first trial)

		Content	Source	%
Water	40%	Tap Water	Lab	40
Fats and oils	40%	Vegetable Oil	Harveys	25
		Bacon Oil	Store	6.25
		Olive Oil	Store	6.25
		Motor Oil	Store	1.25
		Animal Fat	Fryer	1.25
Other	20%	Cream	Store	6.25
		Sour Cream	Store	2.5
		Salad Dressing	Store	2.5
		Frozen Dinner*	Store	
		Cooked Rice	Store	
		Beef Stew	Store	8.75
		Coffee Grinds	Store	

*Frozen dinner contained pasta and creamy sauce

Table 4.2 Properties of synthetic wastewater-first trial

Artificial Wastewater Properties

Parameter	TSS (mg/L)	COD (mg/L)	FOG (mg/L)	pH
Mean Value	17,733	12,527	24,173	4.93
Measured Range*	470-9,950	970-13,440	1,286-4,480	4.7-10.5

*Measured range refers to food industry collected data and reflects Figure 2.1

Table 4.2 presents the results of chemical analysis, performed in triplicates for COD and TSS and in duplicates for FOG, of the first trial. Also, a range based on the data collected from several dependable sources was inserted to the table. This range facilitates the comparison between the obtained values and expected range. A review of Table 4.2 demonstrates that almost all parameters excessively exceed the expected range. Particularly, the FOG value is nearly 6 times higher than the maximum value of the measured range, as demonstrated in Table 4.2. This finding implies that for future trials either a number of oily components should be eliminated or be significantly reduced in volume. Therefore, for the second trial, as shown in Table 4.3, frozen dinner, beef stew and salad dressing from the “other” section were replaced with apple juice and oily water collected from a can of tuna. Moreover, bacon oil and animal fat were also eliminated.

Table 4.3 Composition of artificial wastewater (second trial)

		Content	Source	%
Water	55%	Tap Water	Lab	55
Fats and oils	35%	Vegetable Oil	Harveys	25
		Olive Oil	Store	6.25
		Bacon Oil	Store	2.5
		Motor Oil	Store	1.25
Other	10%	Apple Juice	Store	6.25
		Cream	Store	1.25
		Oily Tuna Juice	Store	1.25
		Coffee Grinds	Store	1.25

Table 4.4 Properties of synthetic wastewater- second trial

Artificial WastewaterProperties

Parameter	TSS (mg/L)	COD (mg/L)	FOG (mg/L)	pH
Mean Value	11,200	9,484	16,604	5.49
Measured Range	470-9,950	970-13,440	1,286-4,480	4.7-10.5

Table 4.4 displays the chemical results, performed in triplicates for COD and TSS and in duplicates for FOG, of artificial wastewater in second trial. Compare to prior trial, test parameters are considerably lower, but FOG and TSS values are higher than the expected range. The pH value is higher than pervious trial, which can be attributed to the new components: apple juice and oily tuna water. Based on the results of the second trial, the oil component was further reduced to 25% of the total volume of artificial wastewater. Diluted industrial cleaner was introduced to the mixture. The addition was based on the review of several sources (Keener et al. 2008), which confirmed the presence of chlorine-based cleaner in municipal sewer system. The Industrial cleaner was diluted 10 times with water.

Table 4.5 Composition of artificial wastewater (third trial)

		Content	Source	%
Water	65%	Tap Water	Lab	65
Fats and oils	25%	Vegetable Oil	Harveys	15
		Olive Oil	Store	6.25
		Bacon Oil	Store	1.25
		Motor Oil	Store	2.5
Other	10%	Apple Juice	Store	5
		Cream	Store	2.5
		Oily Tuna Juice	Store	1.25
		Diluted Industrial Cleaner	Store	1.25

Table 4.6 Properties of synthetic wastewater- third trial

Artificial Wastewater Properties

Parameter	TSS (mg/L)	COD (mg/L)	FOG (mg/L)	pH
Mean Value	6,933	6,693	3,982	5.05
Measured Range	470-9,950	970-13,440	1,286-4,480	4.7-10.5

The chemical parameters of the third trial were measured in same manner, where the COD and TSS tests were performed in triplicates and FOG test was performed in duplicates. As shown in Table 4.6, all parameters are within the expected range. However, FOG value is very close to maximum range. Compare to second trial, the third trial is less acidic and less oily. The significant reduction of TSS can be attributed to the elimination of coffee grinds. In order to achieve a lower FOG value, water volume was increased to 75%. The ingredients are the same as previous trial and only the volume of diluted industrial cleaner was increased.

Table 4.7 Composition of artificial wastewater (fourth trial)

		Content	Source	%
Water	75%	Tap Water	Lab	75
Fats and oils	15%	Vegetable Oil	Harveys	10
		Olive Oil	Store	2.5
		Motor Oil	Store	2.5
Other	10%	Apple Juice	Store	6.25
		Diluted Industrial Cleaner	Store	3.75

Table 4.8 Properties of synthetic wastewater- fourth trial

Artificial Wastewater Properties

Parameter	TSS (mg/L)	COD (mg/L)	FOG (mg/L)	pH
Mean Value	2,200	4,134	1,018	5.33
Measured Range	470-9,950	970-13,440	1,286-4,480	4.7-10.5

According to the results, based on the COD tests performed in triplicates and FOG test performed in duplicates, displayed in Table 4.8, all parameters are extensively lower than preceding trials. With all the parameters placed in the measured range. The fourth trial can be regarded as a suitable representation of regular food industry wastewater; however, all parameters, particularly the FOG value, now fall below the average of measured range, which is not a desirable condition.

For the fifth trial, the volume of water was slightly reduced and cream and bleach were added to the components to regain a portion of FOG content. Other ingredients were not replaced, but their proportions were slightly modified.

Table 4.9 Composition of artificial wastewater (fifth trial)

		Content	Source	%	V (mL)
Water	60%	Tap Water	Lab	60	2700
Fats and oils	20%	Vegtable Oil	Harveys	15	675
		Olive Oil	Store	2.5	112.5
		Motor Oil	Store	2.5	112.5
other	20%	Juice	Store	10	450
		diluted bleach 10x	Store	2.5	112.5
		Cream	Store	7.5	337.5

Table 4.10 Properties of synthetic wastewater- fifth trial

Artificial Wastewater Properties

Parameter	TSS (mg/L)	COD (mg/L)	FOG (mg/L)	pH
Mean Value	3,033	5,534	1,951	5.11
Measured Range	470-9,950	970-13,440	1,286-4,480	4.7-10.5

Table 4.10 illustrates the result for the fifth trial, performed in triplicates for COD and TSS and in duplicates for FOG, which included an improved FOG and COD values. The artificial blend has all the requirements for optimum synthetic wastewater. However, further study demonstrated that the presence of motor oil is not necessary and it could even alter the results in an unfavorable manner. Also, in

order to stabilize the oil/water emulsion in artificial wastewater, the diluted industrial cleaner was replaced with bleach. Bleach as emulsifying agent or surfactant delays the formation of free oil layer and improves the dispersion of suspended oil particles in the artificial wastewater. Subsequently, the ingredients and their proportions were altered for the final time and a new artificial wastewater sample was generated. The ultimate artificial wastewater generated in the first stage contained the same feature that is generally present in the food industry oily wastewater, as presented in Table 4.11. The resulting mixture is brown liquid, with emulsified oil and free oil states both apparent in the blend. While free oil almost instantly appears on top after the mixing, the emulsified oil needs a break-up mechanism to separate from the waste. Figure 4.1 illustrates contents prior to the stirring.

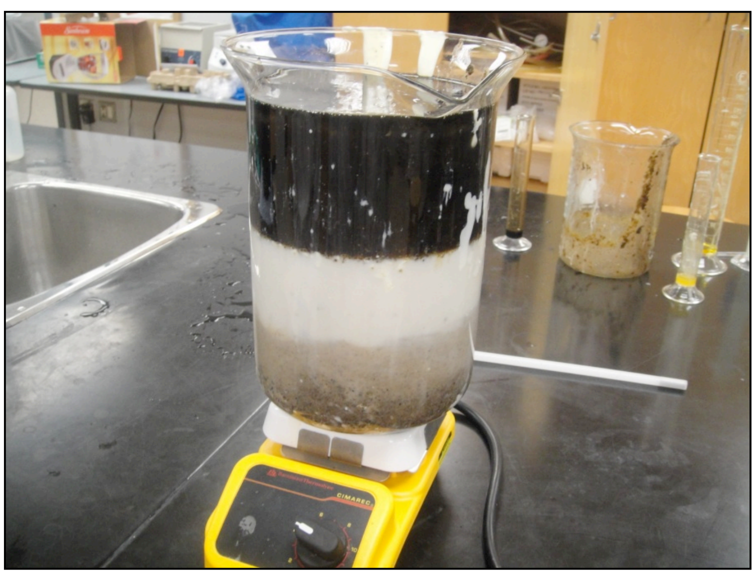


Figure 4.1 contents of the synthetic wastewater

Table 4.11 Composition of optimal artificial wastewater

		Content	Source	%
Water	68%	Tap Water	Lab	68
Fats and oils	20%	Vegetable Oil	Harveys	10
		Olive Oil	Store	2.5
		Bacon Oil	Home-made	2.5
		Animal Fat	Store	5
Other	12%	Apple Juice	Store	5
		Bleach	Store	7

Table 4.12 Properties of synthetic wastewater

Artificial Wastewater Properties

Parameter	TSS (mg/L)	COD (mg/L)	FOG (mg/L)	pH
Mean Value	3,100	3,758	2,208	5.81
Measured Range	470-9,950	970-13,440	1,286-4,480	4.7-10.5

Table 4.11 represents the contents of artificial wastewater and the contributing proportions of each ingredient present in the mixture. Table 4.12 displays the result of the chemical analysis of the synthetic wastewater and its corresponding values in accordance with the Standard Methods (Eaton 1995), which is in the same range as those of the food industry wastewater. The COD and TSS tests were performed in triplicates and the FOG test was performed in duplicates and the mean value of each test was reported in Table 4.12.

The optimum artificial wastewater is slightly less acidic due to presence of bleach in the mixture. Also, FOG and TSS values are within the range of the typical food industry FOG and TSS values, which indicate that artificial wastewater, may carry the same features as the original wastewater.

4.2 Results of Microscopic Investigation

Each drop of oil was observed to secure one or more magnetic powder fraction at their core. Furthermore, the magnetized powder, with the aid of magnetic field, formed a complex structure of magnetic powder with oil droplets attached to them. Therefore the larger the magnetic powder structures attracted and adsorbed more oil droplets than powder with smaller sizes.

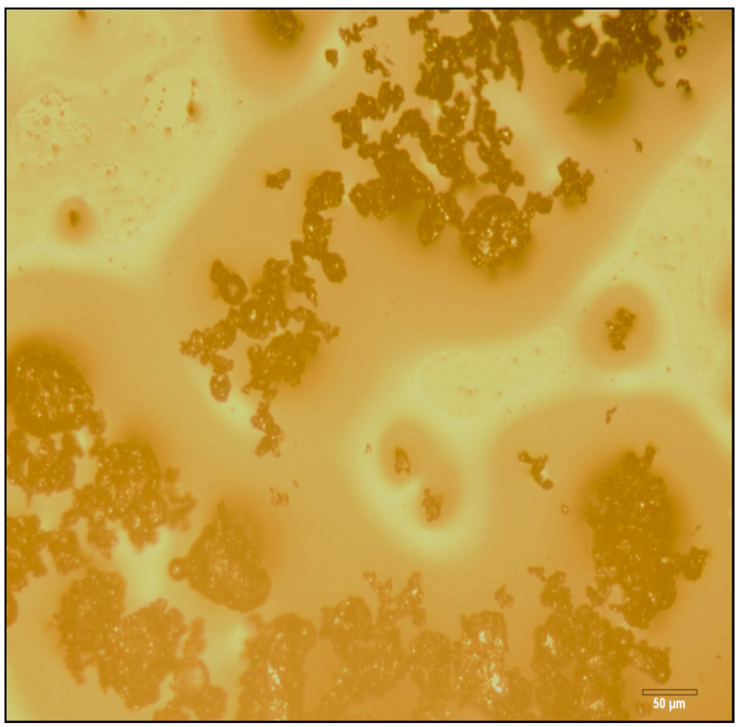


Figure 4.2 150 µm magnetic powder in artificial wastewater (100x)

Figure 4.2 illustrates magnetic powder, mostly with particle size of 150 µm, in artificial wastewater magnified 100 times. Several flocs of various sizes were observed with magnetic powder forming an irregular shape. The contents of slide in Figure 4.2 yielded better and more visible results. Flocs of less than 50 µm in size were attached to each other and formed larger flocs, while flocs of greater than 50 µm only stayed relatively close together. Few finer magnetic powders were also independently visible with oil droplets surrounding them.

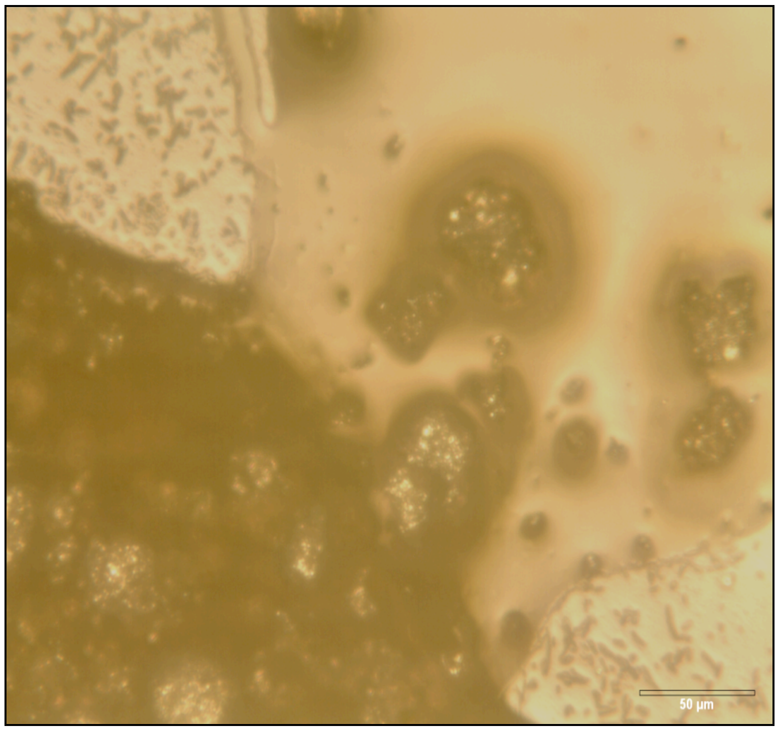


Figure 4.3 45 µm magnetic powder in artificial Wastewater (200x)

Figure 4.3 illustrates 45 µm in the artificial wastewater. The oil appeared as the darker liquid surrounding the magnetic powder structures and the aqueous portion of wastewater appeared as the lighter color in the vicinity with minor amount of powder materializing in the water. The formation of oil/magnetic powder structure was less visible due to larger size of magnetic powder, while there were some smaller magnetic powders that did not adhere to the flocs and settled in singular oil drops in isolation.

The concept of the magnetic field was only introduced subsequent to magnetic powder application as a flocculation inducer. In precedent tests and other applications of a magnetic field, the main purpose of magnetic field was to promote an improved settlement of the flocs at the bottom. The use of a magnetic field can induce better settling characteristics by affecting the poles in the water molecule. Therefore, the magnetic field could also be perceived as progression in separation of emulsified oil from water.

4.3 Results of Vial Tests

The initial comparison of multiple vials illustrated that magnetic powder has an oleophilic behavior that intensifies even more in the presence of magnetic field. The oleophilic characteristic of magnetic powder particularly depends on magnetic powder gradation. The larger powder sizes yield to a greater contact area and more oil absorption. Additionally, the vial test demonstrated that the application of a singular grade of magnetic powder might not be sufficient since the oil/water emulsion consists of oil droplets of various sizes.

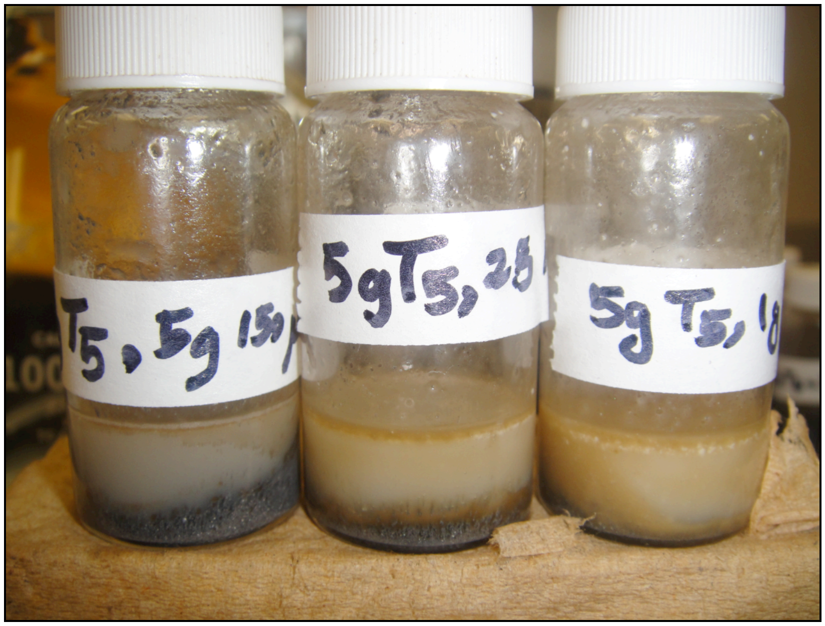


Figure 4.4 Vials holding artificial wastewater and various magnetic powder sizes

Figure 4.4 illustrates different magnetic powder gradation and the amount of oil removed. First vial from left, the combination of 150 μm magnetic powder and fine magnetic powder (45 μm) targeted an entire range of emulsified oil and increased the oil removal more successfully. Since it was confirmed that food industry wastewater could contain various sizes of oil droplets, the magnetic powder combination appears to yield the best results. The middle vial from Figure 4.4 contains only 150 μm magnetic powder and the vial on the right only contains 45 μm magnetic powder.

Moreover, it was determined that the proportions of each grade impact the oil absorption. The vial tests confirmed that a 1:10 ratio of 45 μm to 150 μm would yield effective result. However, the excess 45 μm powder could negatively affect the oil removal by replacing and squeezing out the attached oil from the flocs. Therefore, the ratio of super fine magnetic powder (45 μm) should stay at minimum level.

Since the magnetic coagulation mechanism relies on a good settling velocity, the efforts were concentrated on employing adequate number of magnetic bars creating the proper magnetic field to enhance the settling process. The vial test determined that while sufficient number of magnetic bars can improve the settling performance and prevent the re-suspension of flocs, the excess magnetic field could squeeze out the oil from the oil/magnetic powder flocs.

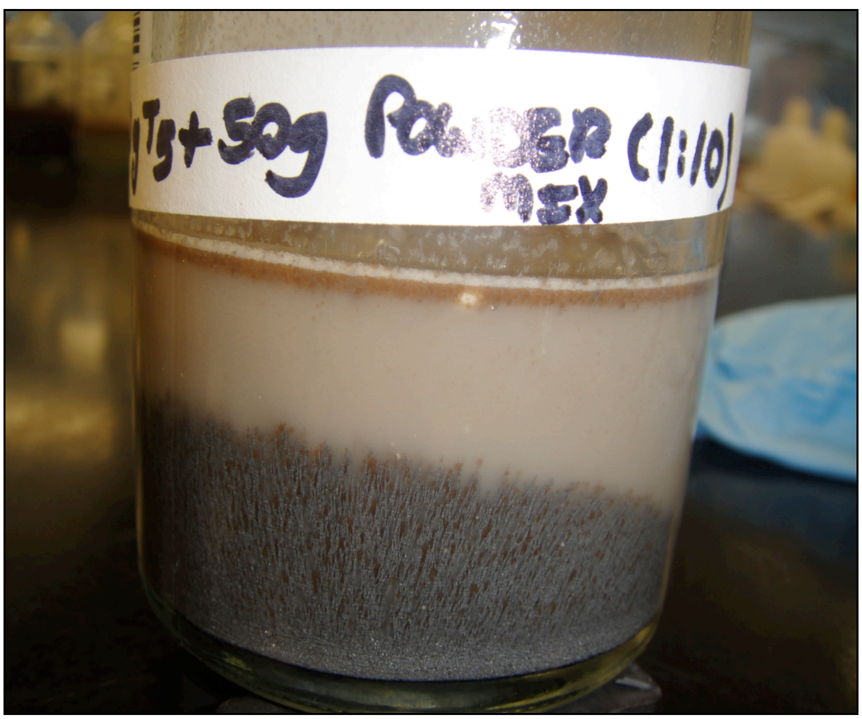


Figure 4.5 Coagulated oil droplets

The magnetic field and coagulants were the major factors influencing the settling of the flocs. While the magnetic field attracted and aggregated the powder and oil droplets attached to it, the coagulant led to formation of heavier flocs. The magnetic powder with the aid of magnetic field formed a particular structure, as shown in Figure 4.5, to trap and move the small oil droplets to the bottom.

4.4 FOG, COD and TSS Results

The jar tests were performed to quantify the effectiveness of magnetic powder's oil adsorption capabilities. The goal in clearing the food industry wastewater is to eliminate certain features of wastewater that is undesirable. FOG, COD and TSS parameters are among the best indicators that could demonstrate the oil removal and other solid in a statically scientific approach.

Based on jar test results, figures for COD, TSS and FOG removal were drawn to evaluate the optimum magnetic powder/oil ratio. All figures including Figure 4.6,4.8, 4.10 and 4.11 illustrate the removal efficiency of magnetic powder as a function of magnetic powder dosage. While, during the vial test, several operating factors were analyzed and optimized, the main focus for the jar test was the effect of the magnetic powder dosage in the oil removal process.

The jar test experiment also arrived at the conclusion that the increase in magnetic powder dosage improved the coagulation mechanism. The larger amount of magnetic powder increased surface area and attracted more oil but to a certain extent, in this case 15g/L. The oil removal process suffered appreciably with addition of extra magnetic powder afterwards, since the magnetic powder formed stronger bond with other magnetic powders and released some of the entrapped oil. At 18g/L dosage the magnetic powder was observed to gradually release the oil from oil/powder clusters. Therefore, to avoid this phenomenon the jar test stopped experiments with 15 g/L.

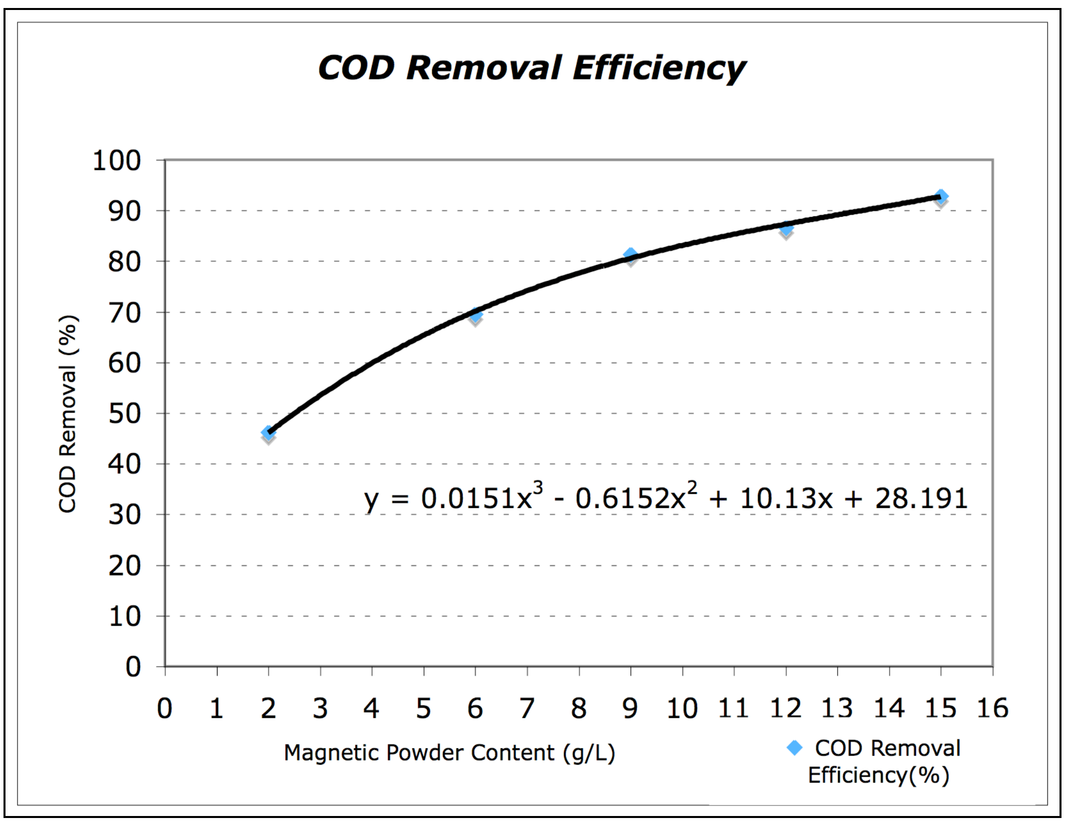


Figure 4.6 COD removal efficiency

Since the new COD assessment procedure is very accurate and the material for conduction the COD test is fairly expensive, the COD removal efficiency test was performed once after each magnetic powder dosage. As Figure 4.6 demonstrates the increase in powder dosage improved the COD removal.

It was found out that at 15 g/L 92.9% of COD was removed. Addition of powder dosage after 15g/L was not efficient since some of the oil droplets were released from bottom briefly after mixing. The equation that best describes the COD removal trend, as a function magnetic powder dosage is the following:

$$Y = 0.0151X^3 - 0.6152X^2 + 10.13X + 28.191 \qquad [4.1]$$

$$R^2 = 0.9990$$

The coefficient of determination or R^2 is a statistical measure that indicates how well the trendline fits the plotted data. R^2 ranges from 0 to 1, where reaching the value of one indicates that the drawn line and generated equation are perfectly coordinated with the plotted points. In this case the R^2 value demonstrates that plotted data and fitted trendline are very close. Therefore, the equation can be applied to find other powder dosages and corresponding COD removal efficiency.

The TSS removal tests were performed in duplicates for each powder dosage, as shown in Figure 4.7. Each series of highlighted bars (red and green) presents a set the TSS removal from the artificial wastewater.

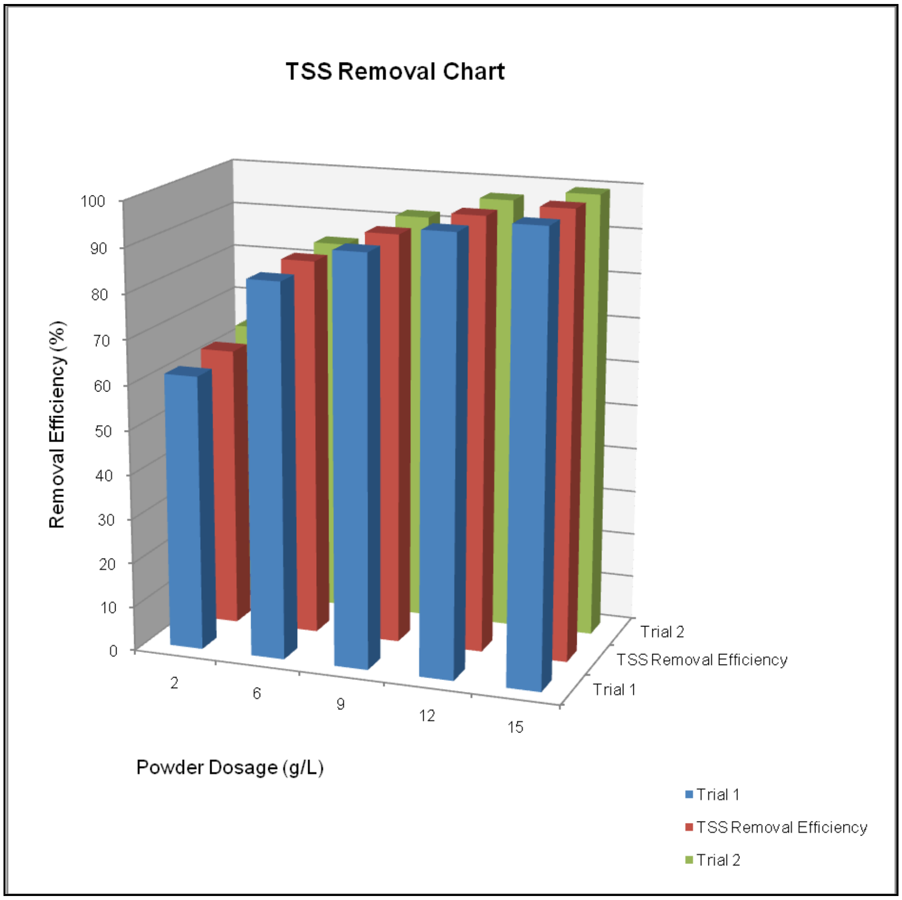


Figure 4.7 TSS removal chart

The test was initiated with 2 g/L of magnetic powder and 0.05mL/L of PHAS and the powder dosage was increased. Similar bar magnet arrangement, as shown in Figure 3.5, was employed to enhance the oil adsorption. Afterward, the average is illustrated in blue bars in the chart above.

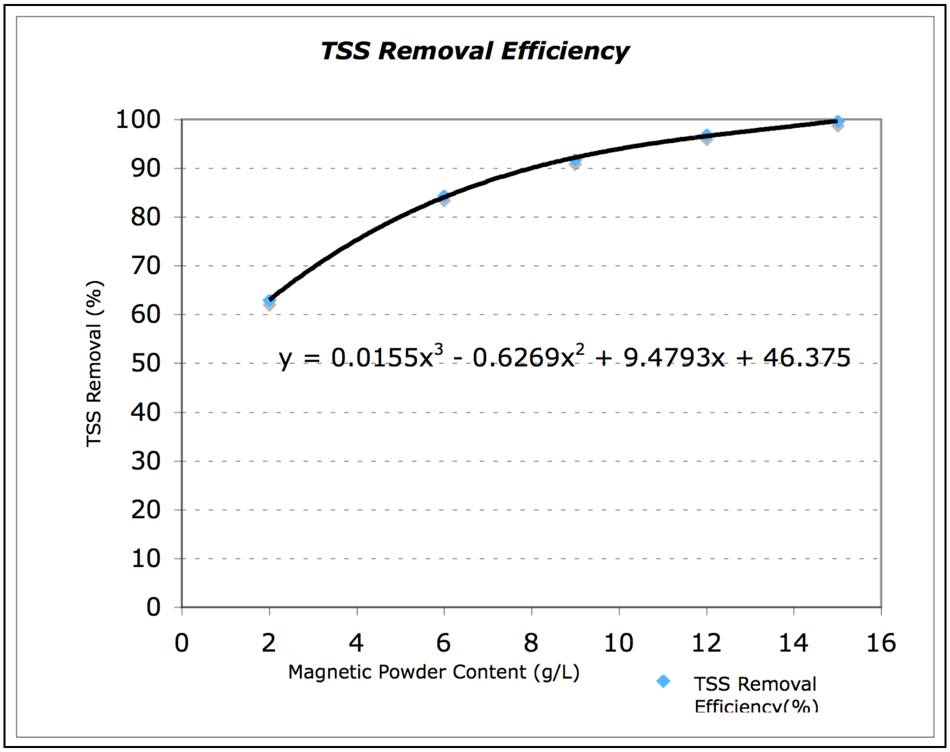


Figure 4.8 TSS removal efficiency

Figure 4.8 presents the average TSS removal for a range of magnetic powder dosages and the equation that best describes the FOG removal as a function of magnetic powder:

$$Y = 0.0155X^3 - 0.6269X^2 + 9.4793X + 46.375 \quad [4.2]$$

$$R^2 = 0.9995$$

The TSS removal figures also reveal that the powder dosage increase led to a more effective removal of TSS. Figure 4.8 also shows that addition of 15 g/L of magnetic powder to the mixture removes 99.6 % of TSS. Also, the R^2 value indicates that the obtained equation and trendline are a good fit for the plotted data.

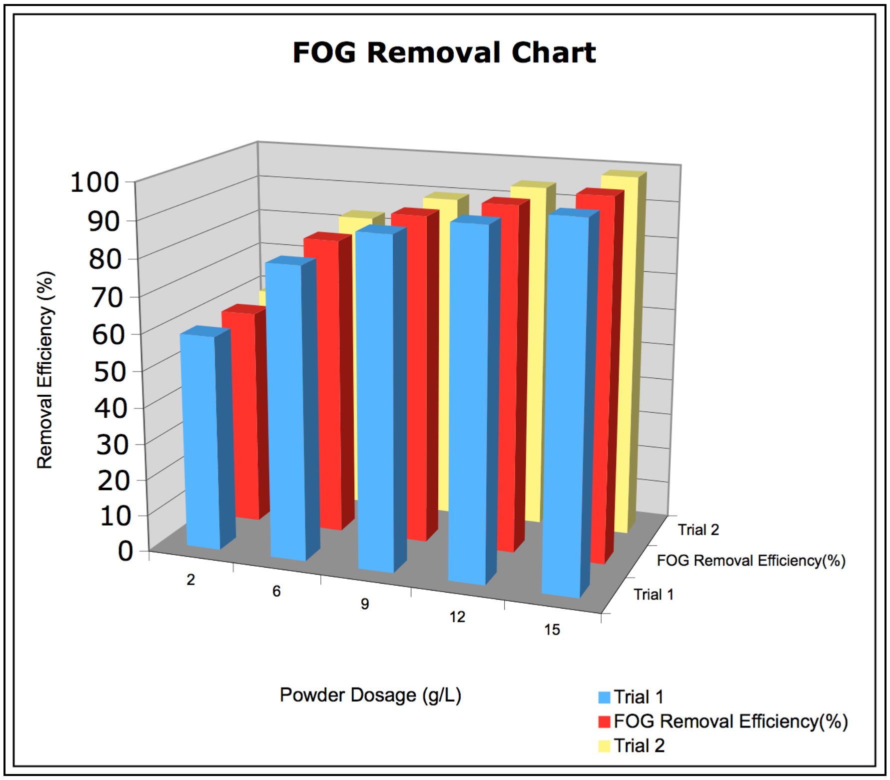


Figure 4.9 The FOG removal Chart

During the jar test, the FOG concentration tests were performed in duplicates, as shown in Figure 4.9, and the average was recorded as the final value. Due to the fair accuracy of the FOG measurement procedure, stated in section 3.4, the FOG values did not fluctuate. However, the use of soap was eliminated since it caused some inaccuracy to the procedure and instead bleach was used as the instance of cleaning product material present in the oily wastewater. Also, the FOG reduction with the increase of magnetic powder dosage is evident in all three series. The reduction in all FOG concentrations is as a result of combination of various powder dosages and PHAS as coagulator.

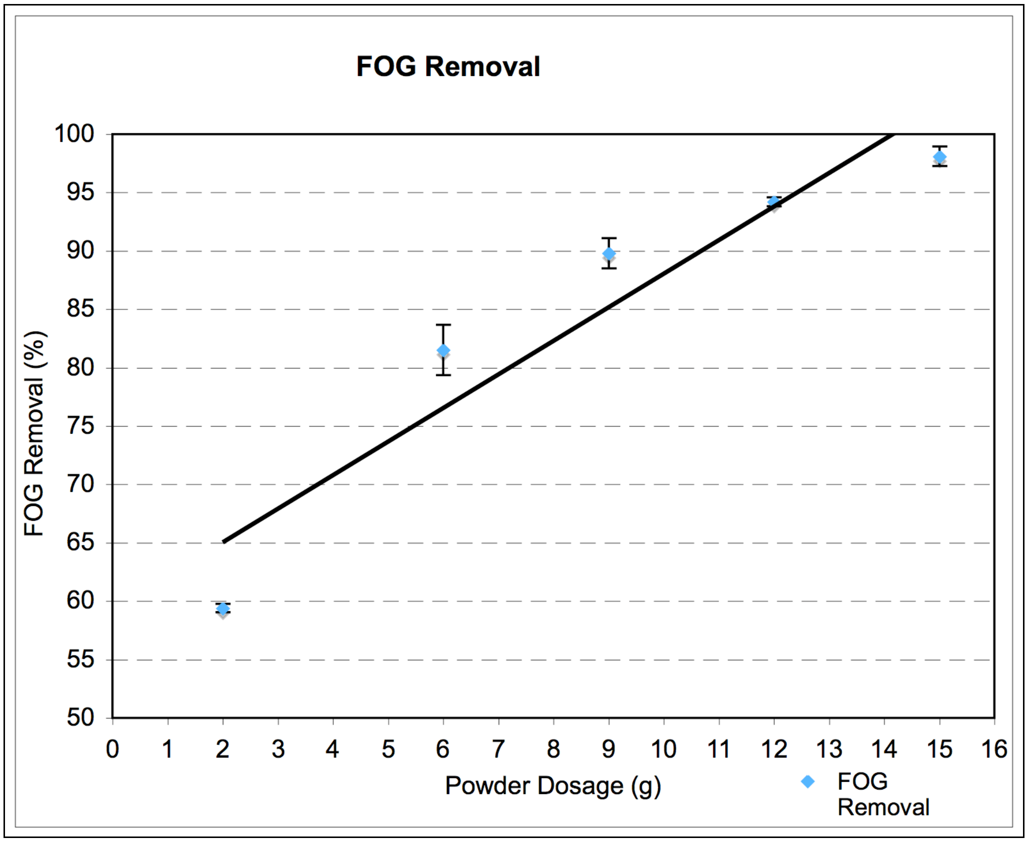


Figure 4.10 FOG removal graph

Figure 4.10 demonstrates the FOG removal values with blue points indicating the mean value of FOG removal for corresponding dosage. The vertical lines on each side of the blue points illustrate the highest and lowest FOG removal values and the range of experimental results. Since the FOG values were measured in duplicates, the number of observations was low and in some instances the level of uncertainty appears to be slightly higher for the linear trend line.

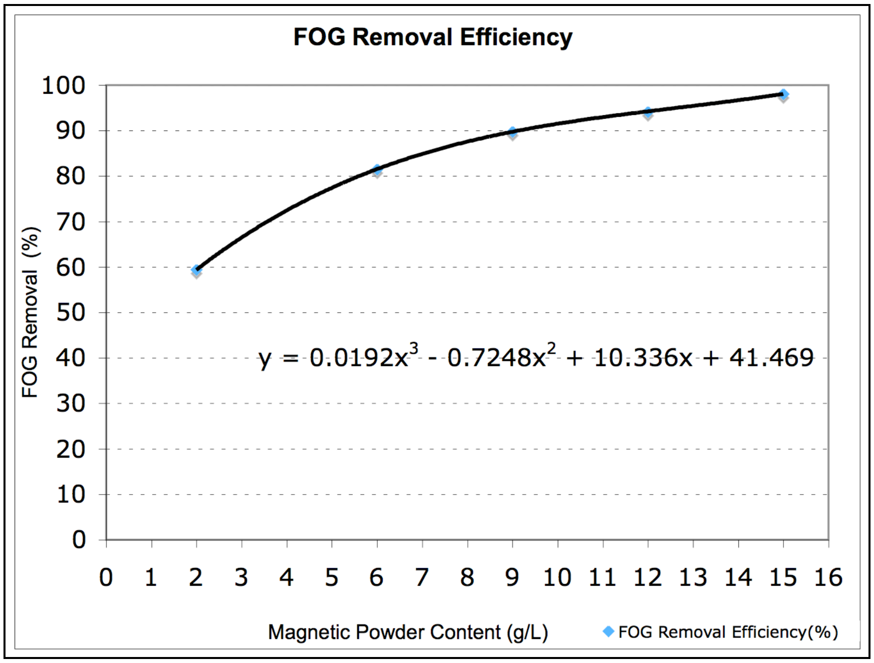


Figure 4.11 FOG removal efficiency

The FOG removal figure demonstrates that the powder dosage increase led to a more effective removal of FOG. The Figure 4.11 also shows that addition of 15 g/L of magnetic powder to the mixture removes 98.1% of TSS. Based on the trend line that fits the plotted data best, the FOG removal equation is the following:

$$Y = 0.0192X^3 - 0.7248X^2 + 10.336X + 41.469 \qquad [4.3]$$

$$R^2 = 1$$

The R^2 value shows that the trendline and equation 4.3 are in approximation of plotted data. The Table 4.13 presents different types of coagulants and its corresponding FOG removal. The coagulants are arranged from mediocre to best results. Also, a control test was performed with 12g/L magnetic powder as the singular oil adsorption and coagulant. While the addition of 0.05mL/L of PHAS could remove 94.2 % of FOG, the FOG removal without any other coagulant could only reach to 81.6%. The coagulation was magnetically enhanced with placement of 6 bar magnets.

Table 4.18 The FOG removal and corresponding coagulants

Coagulant*	FOG Removal (%)
Control	81.6
Alum	82.4
Ferrous Chloride	92.7
PHAS**	94.2

* The corresponding powder dosage was 12g/L
**Poly-Hydroxy-Alluminum-Sulfate

Among the coagulants employed in the procedure, the alum solution was deemed to be the less effective. Several dosages of 1-10 mL/L were added to the artificial wastewater to improve the coagulation. However, the best result was recorded at 0.05mL/L when the FOG removal increased to 82.4%. The addition of more alum solution to the mixture afterwards, did not alter the FOG concentration.

Ferrous chloride was added to the mixture in dosages of 0.5, 1 and 2g/L where the addition of 2g/L of ferrous chloride yields the best results. Since an exceeding amount of ferrous chloride could contaminate the water sources, the dosage remained minimal and was not increased.

The best result was achieved with the combination of 12g/L magnetic powder and 0.05 mL/L of PHAS, where more that 95% of FOG concentration was removed. Due to importance of FOG concentration as oil removal indicator, the jar test trials was performed and reported based on the FOG removal potential of the coagulants.

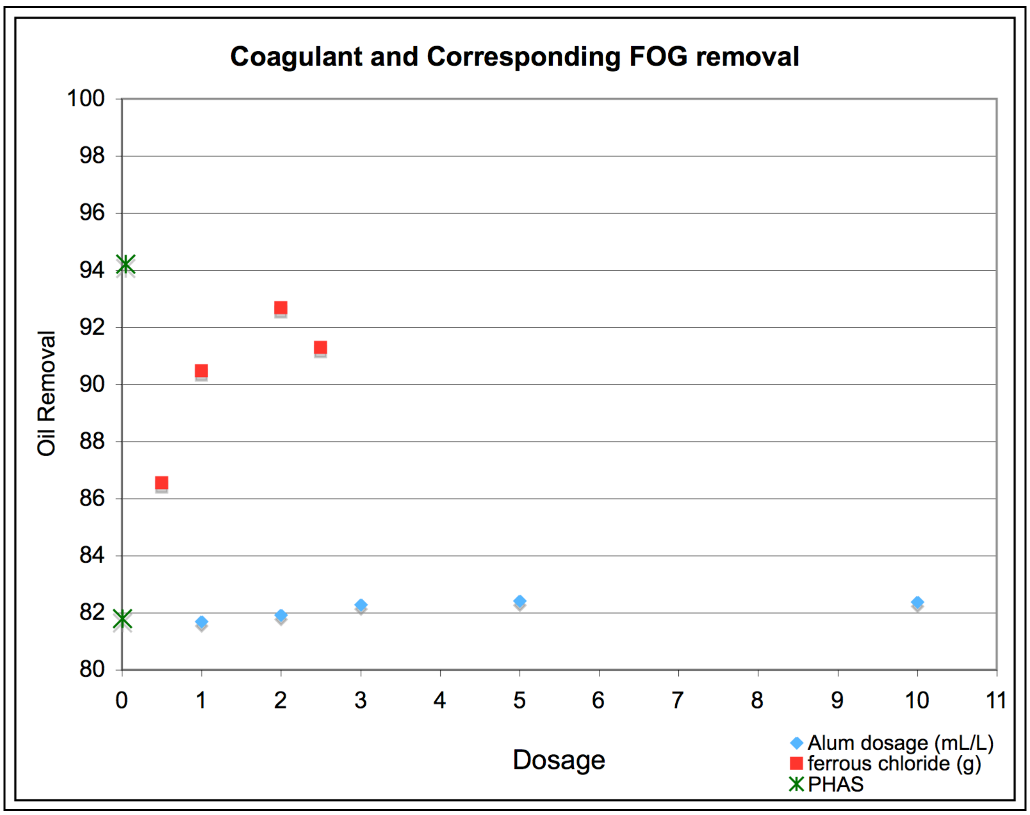


Figure 4.12 Various coagulants and corresponding FOG removal efficiencies

Figure 4.12 illustrates the various dosages of applied coagulants and corresponding oil removal. Clearly, PHAS, even in minimal dosages, is capable of enhancing the oil removal procedure during oily wastewater treatment by magnetic coagulation. PHAS is a polymer of aluminum sulphate is a pre-polymerized aluminum chemical with formula of [$Al_4(OH)_3O(SO_4)_3.H_2O5$]. Based on the results, the use of polymers, as a cationic charged particle was highly effective in coagulation process.

5. Discussion

5.1 Contribution of Artificial Wastewater

The concept of artificial wastewater as an alternative to the original wastewater was declared to be acceptable in the laboratory trials. In order to carry out a precise experiment, the wastewater as the primary component should display the identical physical and chemical features as the real wastewater influent to sewer system. Therefore, the best option while operating in the laboratory was to employ artificial wastewater freshly made to preserve the physical and chemical features.

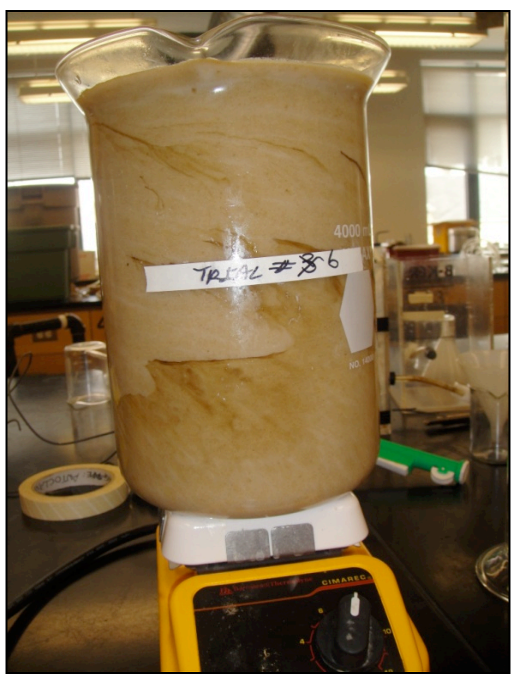


Figure 5.1 Mixture of ultimate artificial wastewater

Since the optimal artificial wastewater, generated in this experiment, presents FOG, TSS and COD in the same range as typical wastewater, as demonstrated in Table 4.12, it is expected that the artificial wastewater would be an acceptable representation of regular food industry wastewater.

5.2 Contribution of Microscopic Investigation

The goal of microscopic investigations was to readily verify the size of oil droplet and state of the oil/water mixture. Several conclusions were reached as the result of microscopic examinations. The following section discusses the overall conclusions of observations of pure oil, artificial wastewater and magnetic powder. Magnetic powder exhibited oleophilic tendencies toward oil both with the aid of a magnetic field and in absence of it. Magnetic powder attached itself to the fringes and outer boundaries of oil. Pure oil did not form any smaller oil droplets and only appeared as one whole drop of oil.

In pure form and without the aid of any coagulant or emulsifier, magnetic powder did not coagulate the oil but only attached itself to the oil. In other words, this examination was a confirmation of oleophilic capabilities of magnetic powder in microscopic capacity. The oil droplets in artificial wastewater were observed with several various sizes.

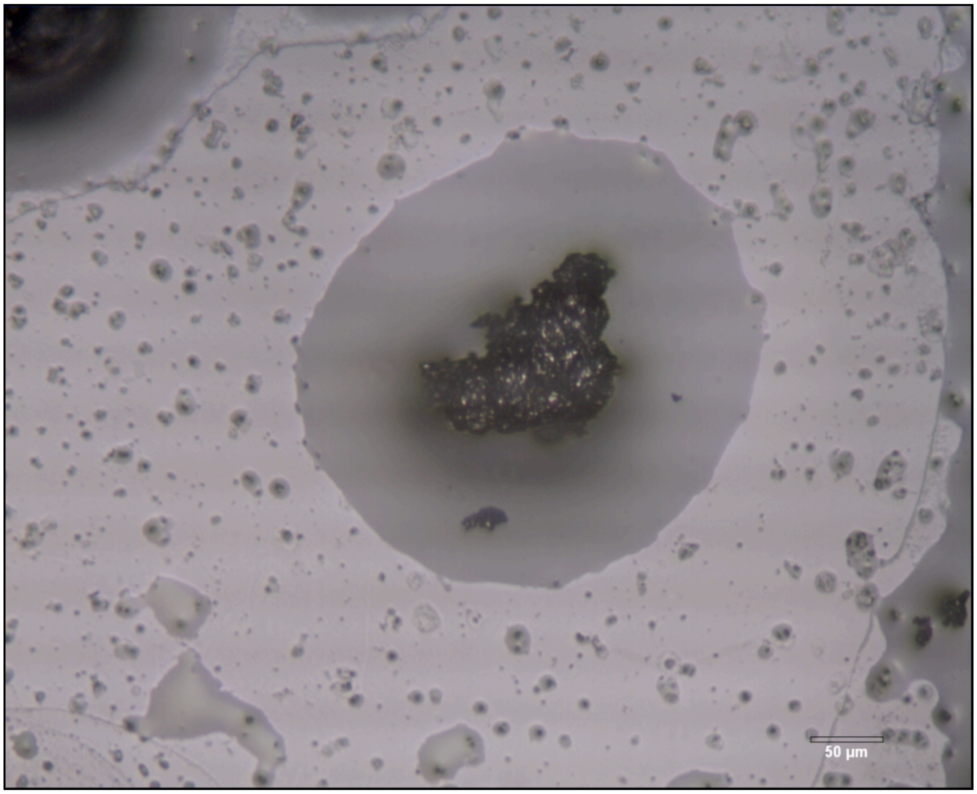


Figure 5.2 Oil droplet surrounding magnetic powder (100x)

Bleach as emulsifier evidently broke down the oil in smaller oil droplets. This experiment affirmed the presence of oil droplets in 50-100 μm sizes and therefore verified that the artificial wastewater contains emulsified oil. The magnetic powder attachment to the oil droplets, in presence of magnetic field and in absence of it, further confirmed the oleophilic character of magnetic powder. Also, the network of magnetic powders, improved by magnetic field, could absorb more oil based on formation of their structure. As illustrated in Figure 5.2, the irregular shape of magnetic powder enhanced the creation of flocs and led to more oil absorption.

5.3 Contribution of the Vial Test

Magnetic powder gradation proved to be an influential factor on oil adsorption. Based on microscopic results, oil droplets of several sizes are present in the artificial wastewater. Therefore, the right gradation would allow an improved coagulation. Magnetic powders of various sizes were attached to oil droplets of relevant size and formed flocs. The vial test proved that sole use of one gradation could not contain the oil droplets especially the very fine (45 μm) magnetic powder. On the other hand the combination of 150 μm and finer magnetic powder 150-75 μm effectively coagulated and removed the suspended oil droplets.

The vial test confirmed the successful removal of oil by application of various magnetic powder gradations. As evident in Figure 5.3, oil removal can be accomplished with application of an adequate oil/magnetic powder ratio. Also, it was revealed that higher ratio that contains more magnetic powder ratio did not improve the oil removal. It was observed that in the 1:1 oil/powder ratio the oil was replaced by more magnetic powder. The scenario was repeated when magnetic field was made more powerful by addition of supplementary bar magnets.

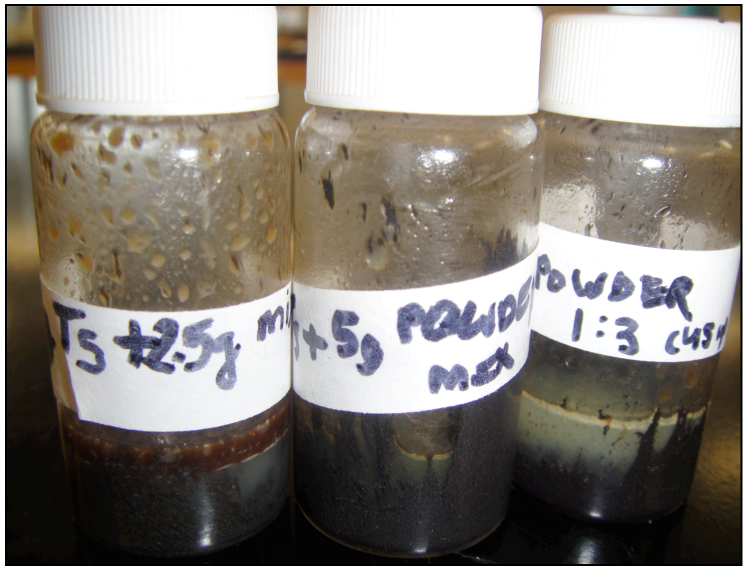


Figure 5.3 Vial tests

The magnetic powder dosage was one of the most significant characters of the investigation. From the vial test, it was concluded that enough magnetic powder should be dispensed to target the oil droplets and overcome the VanderWaals forces. Then, the bonded oil-magnetic powder would form flocs and coagulate.

On the other hand, the excessive magnetic powder of any size would disturb the balance of the bond and replace the oil droplets. The evidence of oil being “squeezed out”, as a result of excessive magnetic powder, was observed during the vial tests. Also, as a major factor of magnetic separation mechanism, it is economical to arrive at an efficient oil removal process with minimal magnetic powder dosage that could present the magnetic coagulation method as an effective and cost efficient oil removal mechanism.

Magnetic enhancement unquestionably improved the sedimentation of magnetic powder/oil flocs. While, the microscopic observation confirms the attachment of magnetic powder to oil droplets, the presence of magnet bars demonstrated that suspended flocs would quickly sediment in presence of magnetic field. The deposited flocs then would not interfere with further coagulation and sedimentation of the remaining suspended oil droplets.

Furthermore, it was concluded that sufficient number of bars should be applied so that sedimentation process be successful. A more powerful magnetic field would change the balance of the flocs in favor of magnetic powder. The trapped and coagulated oil flocs were released as result of a very strong magnetic field. On the other hand, less adequate number of bar magnets would fail to collect and sediment the suspended and less heavy flocs. Consequently the settling velocity decreases and the oil removal process is interrupted. Even though the coagulation capability of magnetic powder was observed during the vial test, it was concluded that an external coagulant would improve the sedimentation process.

The flocs solely formed by aid of magnetic powder may not be large enough. Therefore, an alternative coagulant in small doses would aid the process. During the vial test, several coagulant including the traditional coagulants such as alum and modern choices such as

PHAS were put to test and subsequently, the coagulants that were deemed to improve the magnetic coagulation process were selected for the jar test.

5.4 Contribution of the Magnetic Coagulation Jar Test

Magnetic powder proved to be the most influential factor of magnetic coagulation. Based on the jar tests, any dosage of magnetic powder can lead to partial magnetic coagulation. Also, it was concluded as the magnetic powder dosage was increased, the oil removal process was improved. The jar tests, as well as vial tests, demonstrated that excessive amount of magnetic powder can effectively decline the oil removal and disturb the process. Therefore, the application of excessive magnetic powder dosage was not only more costly but also could lead to a less efficient oil removal.

The FOG and TSS showed more successful result than COD tests. According to COD tests, the organic matter contained in wastewater was removed less effectively compare to suspended solids and FOG content. It was concluded that there was some form of organic matter which magnetic powder could not target.

Based on TSS results, it can be concluded that sedimentation of magnetic aided flocs not only removed the suspended oils but also any other deposited solids was removed during the process. The use of magnetic field at the bottom and sedimentation, as means of separation, therefore was more desirable.

According to the results of vial, it was concluded that magnetic enhancement is beneficial to the oil removal process. The magnetic field arrangement in circular shape was decided based on those tests and confirmation of other papers, (Luk et al. 2005) which demonstrated that circular arrangement is more successful than the parallel arrangement. The bar magnets provide a constant magnetic field which improved the settling velocity and reduced the oil suspension.

Both vial tests and jars test confirmed that although magnetic coagulation is successful, it could be further improved by addition of other coagulants. Based on Table 4.12, magnetic powder as the sole coagulant can remove up to 81.6% of oil and combination of magnetic powder and PHAS removed 94.2% of the FOG content. Therefore, these coagulants promoted the break-up of the emulsified oil by reducing the superficial charges of the oil droplets and coalescing the flocs and subsequent separation of flocs from aqueous phase by means of magnetic settling.

Also, the use of polymeric coagulant such as PHAS led to accomplishment of better results. These results can be attributed to the structure of the polymer. The polymeric coagulant also can be administered in smaller dosages and therefore remain the more economic option for the procedure.

6. Conclusions

6.1 Implications of the Magnetic Coagulation Technology

The first objective of this research was to develop a formula for artificial wastewater that closely follows the primary features of regular food industry wastewater. The artificial wastewater consisted of the ingredients most likely to be in the oily wastewater including: used fryer oil, oils of animal origin, olive oil and water. The optimal artificial wastewater was composed of 68% water, which concluded that water remained the main component of artificial wastewater, similar to regular wastewater.

The oily component of optimal artificial wastewater, consisted of used vegetable oil, olive oil, animal fat and bacon oil, only occupied 28% of the total volume of wastewater. The remaining constituents were apple juice and bleach with 20% volume. It was also concluded that bleach is not only an active ingredient and representation of all cleaning products, but also, particularly in this research assisted with enhancement and stabilization of oil/ water emulsion. Maintaining the oil/water emulsion was one the goals of this research, since the emulsified oil was the main target of magnetic coagulation procedure. The resulting TSS, COD and FOG were found to be 3100, 3758 and 2208 mg/L respectively, which indicates that standard parameters of artificial wastewater are very similar to same parameters from food industry wastewater.

The second objective of this study was to compare and contrast the current oil removal technology with magnetic coagulation and verify advantages and disadvantages of each mechanism. This research has reviewed existing oil removal procedure, both traditional and innovative methods, at length in their appropriate categories. Furthermore, these procedures included all treatments that target all forms of oil: free and emulsified. While some merits of these treatments were reported during the investigation, it was also reported that each treatment has few disadvantages where high concentrations of oil is concerned.

The growth of oily flocs due to high FOG concentrations, while harmful and inefficient for DAF and IAF treatment systems due to reduction in oxygen transfer rate, clogging the aeration tank and increasing maintenance cost, is a constructive factor for the magnetic coagulation. The magnetic powder adsorbs the flocs, grows larger and precipitates with the simultaneous aid of gravity and magnetic field.

While anaerobic and aerobic treatment systems deal with oily wastewater in a more comprehensive method, several obstacles were discovered during the review of these methods. Anaerobic treatment is capable of removing and degrading oil to a point where it can cause less damage to the environment. However, sufficient removal of oil for a long term is not possible with anaerobic treatment. Also, biodegradability of oil requires use of expensive biosurfactants that is capable of solubilizing high concentrations of FOG.

Membrane filtration can achieve destabilization of water/oil emulsification and high COD removal efficiency without the use of chemicals. However, among the existing oil removal treatments, the magnetic coagulation procedure proved to target a wider range of oil droplets than membrane filtration. Also, membrane filtration particularly ultra filtration is an expensive treatment system. Membrane filtration is designed to remove specific sizes of oil and treating wastewater with high oil concentration would lead to growth of oily film that block the filters. Membrane cleaning and maintenance is costly and requires certain amount of time that is not a desired factor for treating food industry wastewater.

Electrocoagulation process has confirmed to possess high efficiency in the course of treating oily wastewater under laboratory conditions. Metal ions such as aluminum generated by electric current act as coagulant and attract and absorb emulsified oil. The coagulated oil droplets are then removed by either flotation or sedimentation, which is beneficial for both oil spill removal and wastewater treatment.

However, the anode, which provides metal ions, consumption rate is reported to be high. This drawback could present an even bigger predicament during long-term treatment of oily wastewater. Also, the quantity of ions cannot be controlled accurately when presented with fluctuating concentrations of FOG.

By meticulous monitoring of influent wastewater, magnetic powder can be adjusted to avoid excess usage of magnetic powder or reduce oil absorption efficiency. Additionally, recycled powder may also be introduced to the system multiple times as another economical benefit of magnetic coagulation. The fact that besides oily content and suspended solids, any traces of heavy metals will be removed is another advantage of magnetic coagulation.

Another main objective of this research was to study the oil absorption capacity of magnetic powder and identify the decisive factors that enhance the magnetic coagulation procedure and the degree of their effect on the oil removal. The nature and appearance of magnetic powder was concluded to be the primary factor in oil absorption process. It was demonstrated that the magnetic powder was more attracted to oil in microscopic and vial capacity.

The gradation of magnetic powder and application magnetic field were also found to be effective in oil absorption process. It was concluded that the larger magnetic particles are capable of attracting and trapping more oil droplets. In addition, a magnetic field with appropriate intensity enhanced the settling velocity of the oil/powder flocs.

Finally, the use of magnetic powder as separator and coagulator of oil in oil removal treatment was demonstrated by a series of microscopic, vial and jar test investigations. Generally, magnetic separation as an oil removal method was proved to be effective. This study demonstrated that magnetic coagulation at 15g/L is capable of removing 98.1% of oil from artificial wastewater. A simultaneous removal of 92.9% COD and 99.6% TSS is also achieved at this dosage. For wastewaters of lower oil content the magnetic powder dosage could be reduced to 12 g/L, which is more economical. On the other hand, for lower powder dosages, the detention time should be higher to allow a proper settling velocity of the coagulated oil.

This trial also showed the significant role of surfactant in the oil removal. The magnetic powder with the various gradations was applied to target all oil-droplet sizes, while the emulsion’s establishment was credited to the presence of surfactants in the wastewater. Since many sources confirmed that detergents and cleaning supply act as surfactants in the formation of emulsified oil, the addition of an external surfactant was deemed unnecessary.

Finally, magnetic coagulation procedure turned out to be a rapid and competent procedure. Upon mixing, the magnetic powder was almost instantly attracted to oil; however, the floc growth and precipitation of flocs were more time-consuming factors. Nevertheless, these factors could be controlled by use of external coagulant and a more appropriately tuned magnetic field to facilitate the precipitation.

6.2 Future Recommendations

Based on the results from TSS, COD and FOG tests, the magnetic coagulation procedure in treating the artificial wastewater, as a representation of food industry wastewater, was successful in removal of oil and suspended contents of the oil/water emulsion. Furthermore, oil adsorption in microscopic stage was observed and recorded. Also, among the external coagulants tested both in vial and jar tests, the PHAS proved to be more efficient in aiding with coagulation process for oil removal treatment.

Based on the experiments performed with magnetic coagulation, some recommendation to improve the pilot model, previously employed to treat DAF sludge, is illustrated in Figure 6.1. In order to keep emulsified oil at stabilized state before entering the system, constant stirring is recommended. The magnetic field can be replaced by an electric magnetic field with fluctuating power that can be adjusted according to magnetic powder dosage. The coagulant and magnetic powder simultaneously are introduced to the mixture in main magnetic coagulator tank.

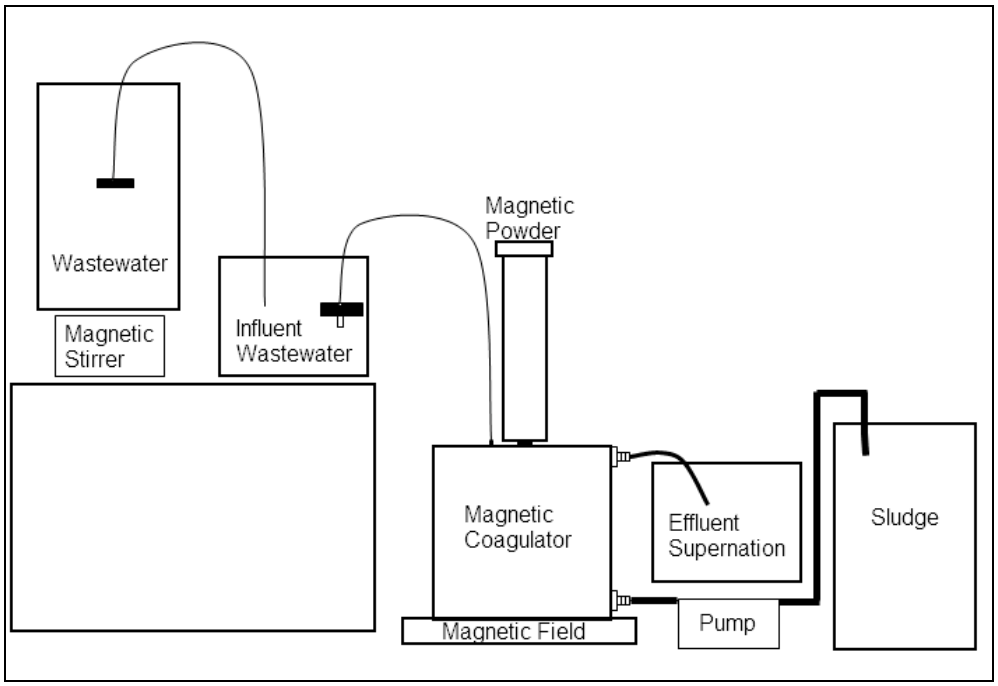


Figure 6.1 Recommended configuration for the pilot model test

The following recommendations are based on the observations and results of the study:

1.According to the results, the application of magnetic coagulation as an effective oil removal treatment is an adequate option for food industry wastewater. On the other hand, the application of magnetic coagulation process for oil removal from petroleum industry wastewater, according to the results of this study, is more likely. Also, magnetic powder with finer gradation can focus on removing smaller oil droplets and soluble oils which are more frequent in refinery wastewater.

2.The microscopic study demonstrated that magnetic powder, due to its oleophilic tendencies, could be applied as an oil removal agent in oil spill operations. However, since oil spills rarely produce any other form of suspended solids than oil droplets, for oil spill removal the flotation process is deemed to be more efficient.

3.The magnetic powder is more effective on emulsified oil. As a result, for practical implication it is recommended that wastewater be instantly introduced to oil removal treatment system to avoid formation of free oil; or appropriate surfactant in small and proper dosage should be added to preserve the emulsion. Furthermore, the installation of a simple skimmer device as a primary procedure to magnetic coagulation could remove the free oil.

4.Since the wastewater effluent could contain various FOG concentrations from time to time, different powder dosages may be introduced in the procedure, therefore the application of electric current as magnetic field inducer is recommended for the pilot model. The electric current can be tuned to accommodate various number of dosages accumulated and improve the settling velocity for any set of changes that may be applied to the procedure.

5.The results of the research demonstrated that the contact time for powder and oil is very significant for oil removal. Sufficient time is required for dispersed oil drops to attract and bond with magnetic powder. Therefore for the practical use of magnetic coagulation, further study is required to determine a suitable flow rate that allows the introduction of wastewater influent for oil removal while coagulated oil is removed from the bottom without disturbing the settling velocity.

6.While it has been reported that recycled magnetic powder has oleophilic characteristics, the extent of recovered magnetic powder oil absorption capability for reuse in oil removal should be tested. It is recommended to examine the use of recycled magnetic powder in combination with new magnetic powder. Further study could lead to providing the industry with even more economical option for oil removal.

7.The removal of other pollutants such as heavy metals, odor producing compositions and organic matters, which may be found in wastewater effluents by magnetic coagulation should be examined. The heavy metals and organic matter have previously been removed by magnetic coagulation. Therefore, it is recommended to perform the appropriate tests to study the changes in heavy metal content during pilot model test.

8.Based on effective application of polymeric coagulant as an external coagulant that facilitated for magnetic powder coagulation. The use of PHAS or any polymeric coagulator is recommended for the pilot model to enhance the coagulation and improve the settling velocity.

9.The role of surfactant in creating and controlling the oil/water emulsion is undeniable. For the purpose of maintaining the artificial wastewater features similar to the original one, the use of surfactant or emulsifying agent was limited to bleach that was applied in a minor quantity since traces of bleach as cleaning material was observed in wastewater. However, there are several anionic and ionic surfactants that could be introduced to stabilize the emulsion prior to magnetic coagulation process. It is recommended to test the option of external surfactant when no clear account of the dosage of bleach, or other common surfactants such as soap, is not available.

10.Finally, several researchers have investigated the extent of magnetic separation and magnetic coagulation in scope of laboratory conditions. Additionally, the prototype known as pilot model has been created previously and certain alterations were recommended as a result of these investigations. The final proposal is to select a type of food industry establishment, preferably a restaurant, and examine the procedure on site by employing pilot model to perform magnetic coagulation procedure.

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APPENDIX A

DATA & TABLES

Table A:

Source	FOG (mg/L)	FOG Limit (mg/L)
Restaurant 1	3200	150
Restaurant 2	4480	150
Restaurant 3	1970	150
Bakery	1512	150
Paint company	1624	150

First Trial:		Content	Source	%
Water	40%	Tap Water	Lab	40
Fats and oils	40%	Vegetable Oil	Harveys	25
		Bacon Oil	Store	6.25
		Olive Oil	Store	6.25
		Motor Oil	Store	1.25
		Animal Fat	Fryer	1.25
Other	20%	Cream	Store	6.25
		Sour Cream	Store	2.5
		Salad Dressing	Store	2.5
		Frozen Dinner*	Store	
		Cooked Rice	Store	
		Beef Stew	Store	8.75
		Coffee Grinds	Store	

PH	1st Sample	2nd Sample	3rd sample
	4.92	4.94	4.92

TSS	1st Sample	2nd Sample	3rd sample
W(dish+fillter)	1.405	1.407	1.424
W(dish+fillter+residue)	1.427	1.411	1.456
Volume of sample	5mL	5mL	5mL
Calculated TSS (mg/L)	4400	800	6400
	24400	3200	25600

*sample diluted 4 times

FOG	1st Sample	2nd Sample
W(empty sample bottle+cap)g	475.635	472.78
W(filled sample bottle+cap)g	720.4	721.13
W(Empty Beaker)mg	102.631	102.554
W(Beaker+residue)mg	109.105	108.297
FOG mgL-1	26,450	21,897

COD	1st Sample	2nd Sample	3rd sample
Reading*	1.012	1.237	1.211
Actual Measurement**	11014	13422	13144

**Y = 10705x + 180.5
Y = COD , X = A600

Second Trial:

		Content	Source	%
Water	55%	Tap Water	Lab	55
Fats and oils	35%	Vegetable Oil	Harveys	25
		Olive Oil	Store	6.25
		Bacon Oil	Store	2.5
		Motor Oil	Store	1.25
Other	10%	Apple Juice	Store	6.25
		Cream	Store	1.25
		Oily Tuna Juice	Store	1.25
		Coffee Grinds	Store	1.25

PH	1st Sample	2nd Sample	3rd sample
	5.3	5.67	5.52

FOG	1st Sample	2nd Sample
W(empty sample bottle+cap)g	477.52	477.011
W(filled sample bottle+cap)g	709.98	713.252
W(Empty Beaker)mg	104.997	105.486
W(Beaker+residue)mg	108.823	109.443
FOG mgL-1	16,459	16,750

TSS	1st Sample	2nd Sample	3rd sample
W(dish+fillter)	1.403	1.4	1.403
W(dish+fillter+residue)	1.415	1.414	1.419
Volume of sample	5mL	5mL	5mL
Calculated TSS (mg/L)	2,400	2,800	3,200
	9,600	11,200	12,800

COD	1st Sample	2nd Sample	3rd sample
Reading*	0.895	0.883	0.829
Actual Measurement**	9761	9633	9059

**Y = 10705x + 180.5
Y = COD , X = A600

THIRD TRIAL:

		Content	Source	%
Water	65%	Tap Water	Lab	65
Fats and oils	25%	Vegetable Oil	Harvey's	15
		Olive Oil	Store	6.25
		Bacon Oil	Store	1.25
		Motor Oil	Store	2.5
Other	10%	Apple Juice	Store	5
		Cream	Store	2.5
		Oily Tuna Juice	Store	1.25
		Diluted Industrial Cleaner	Store	1.25

	1st Sample	2nd Sample	3rd sample
PH	5.06	4.95	5.13

FOG	1st Sample	2nd Sample
W(empty sample bottle+cap)g	474.652	473.809
W(filled sample bottle+cap)g	719.96	718.86
W(Empty Beaker)mg	101.831	102.584
W(Beaker+residue)mg	103.104	103.553
FOG mgL-1	4,011	3,954

TSS	1st Sample	2nd Sample	3rd sample
W(dish+fillter)	1.496	1.496	1.498
W(dish+fillter+residue)	1.504	1.503	1.509
Volume of sample	5mL	5mL	5mL
Calculated TSS (mg/L)	1,600	1,400	2,200
	6,400	5,600	8,800

COD	1st Sample	2nd Sample	3rd sample
Reading*	0.616	0.603	0.606
Actual Measurement**	6775	6636	6668

**Y = 10705x + 180.5
Y = COD , X = A600

FOURTH TRIAL:

		Content	Source	%
Water	75%	Tap Water	Lab	75
Fats and oils	15%	Vegetable Oil	Harveys	10
		Olive Oil	Store	2.5
		Motor Oil	Store	2.5
Other	10%	Apple Juice	Store	6.25
		Diluted Industrial Cleaner	Store	3.75

PH	1st Sample	2nd Sample	3rd sample
	5.37	5.23	5.39

FOG	1st Sample	2nd Sample
W(empty sample bottle+cap)g	475.921	473.225
W(filled sample bottle+cap)g	725.31	722.04
W(Empty Beaker)mg	103.227	102.569
W(Beaker+residue)mg	103.512	102.347
FOG mgL-1	1143	892

TSS	1st Sample	2nd Sample	3rd sample
W(dish+fillter)	1.325	1.342	1.388
W(dish+fillter+residue)	1.329	1.344	1.391
Volume of sample	5mL	5mL	5mL
Calculated TSS (mg/L)	800	400	600
	3200	1600	1800

COD	1st Sample	2nd Sample	3rd sample
Reading*	0.375	0.364	0.369
Actual Measurement**	4195	4077	4131

**Y = 10705x + 180.5
Y = COD , X = A600

Fifth Trial:		Content	Source	%
Water	68%	Tap Water	Lab	68
Fats and oils	17%	Vegetable Oil	Harveys	12
		Olive Oil	Store	2.5
		Motor Oil	Store	2.5
Other	15%	Apple Juice	Store	10
		Diluted Industrial Cleaner	Store	2.5
		Cream	Store	2.5

FOG	1st Sample	2nd Sample
W(empty sample bottle+cap)g	475.921	473.225
W(filled sample bottle+cap)g	725.31	722.04
W(Empty Beaker)mg	103.227	102.569
W(Beaker+residue)mg	103.512	102.347
FOG mgL-1	1908	1994

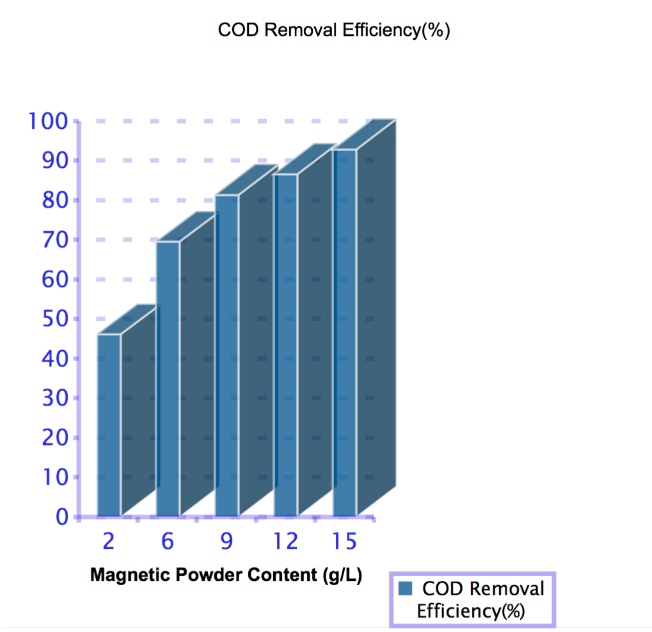
COD	1st Sample	2nd Sample	3rd sample
Reading*	0.531	0.538	0.532
Actual Measurement**	5502	5581	5519

**Y = 10705x + 180.5
Y = COD , X = A600

TSS	1st Sample	2nd Sample	3rd sample
W(dish+fillter)g	1.441	1.419	1.391
W(dish+fillter+residue)g	1.444	1.423	1.394
Volume of sample	5mL	5mL	5mL
Calculated TSS (mg/L)	700	800	775
	2800	3200	3100

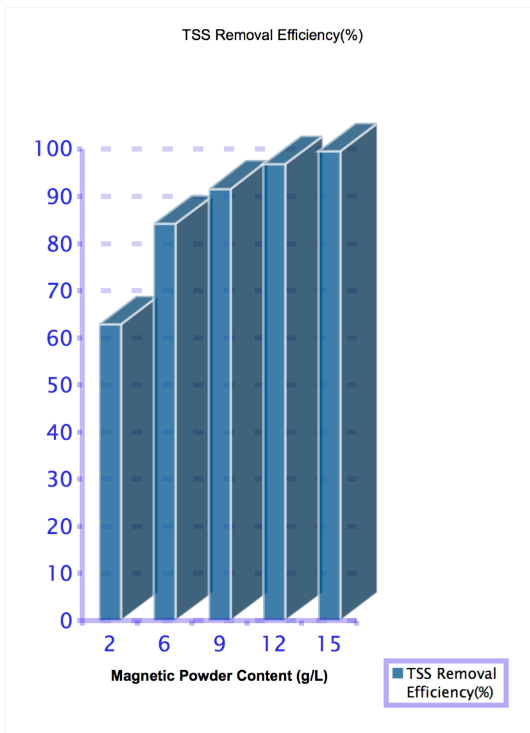
Powder Dosage(g/L)	COD Removal Efficiency(%)
2	46.2
6	69.6
9	81.4
12	86.7
15	92.9

Where: COD Removal= COD (optimum wastewater)-COD (after treatment)



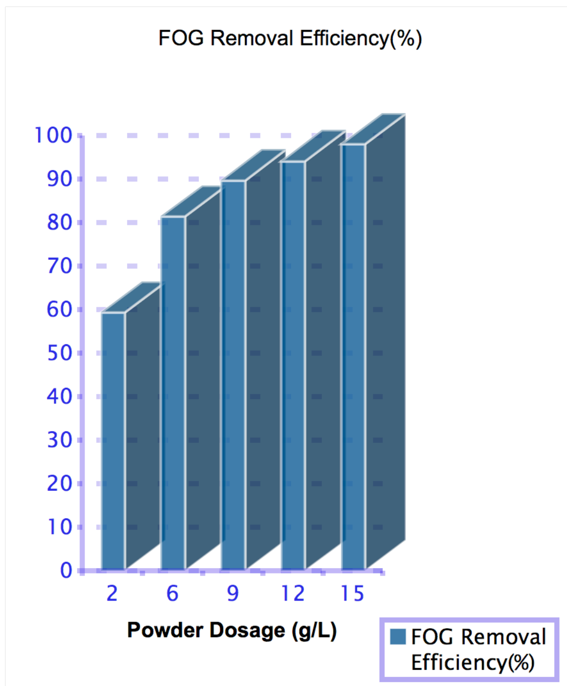
Powder Dosage (g/L)	Trial 1	TSS Removal Efficiency (%)	Trial 2
2	61.7	62.9	64.1
6	83.9	84.3	84.7
9	91.4	91.7	92
12	96.9	96.9	97
15	99.4	99.6	99.4

Where: TSS Removal= TSS (optimum wastewater)-TSS (after treatment)



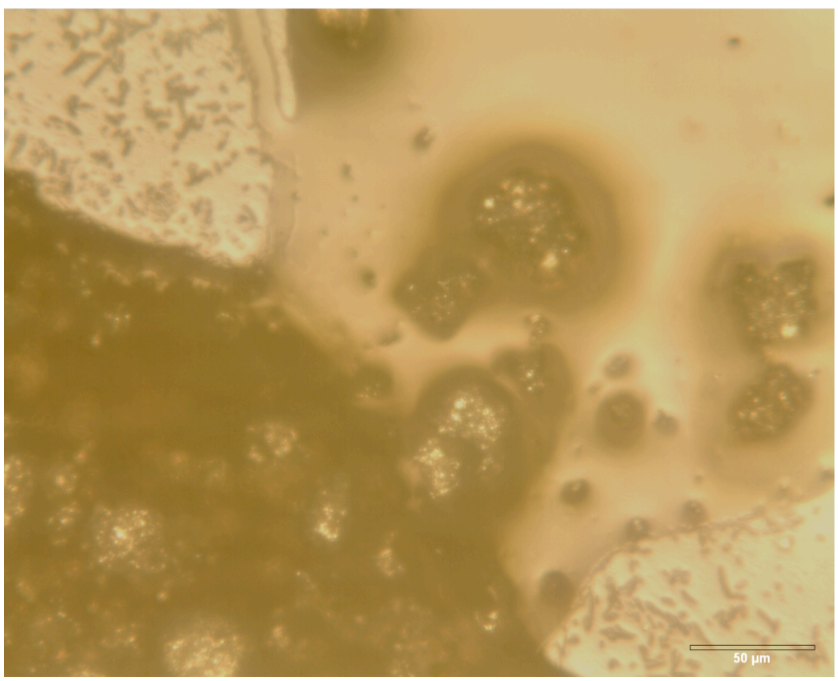
Powder Dosage (g/L)	Trial 1	FOG Removal Efficiency (%)	Trial 2
2	59	59.4	59.8
6	79.9	81.5	83.1
9	89.7	89.8	89.9
12	93.8	94.2	94.6
15	97.2	98.1	98.9

Where: FOG Removal= FOG (optimum wastewater)-FOG (after treatment)

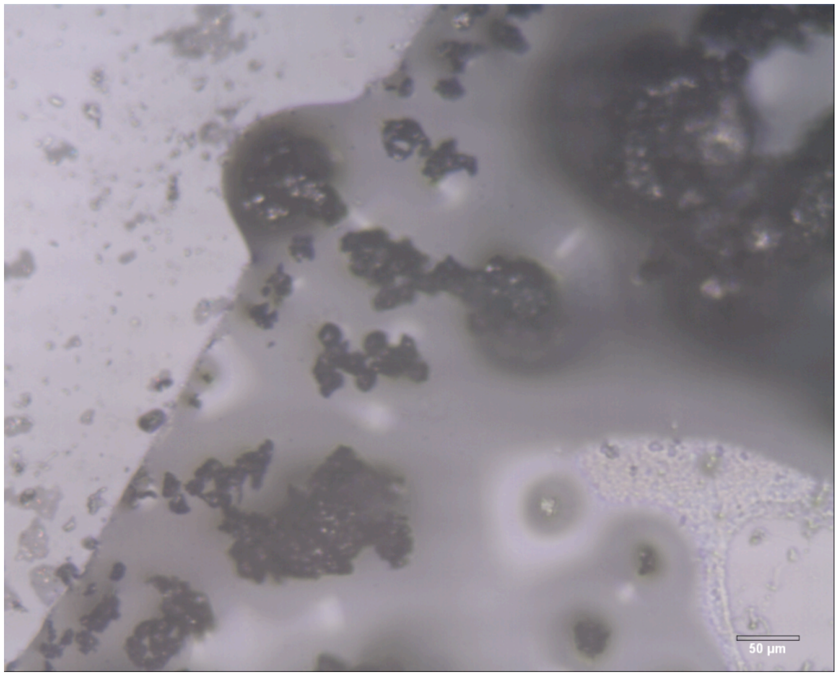


APPENDIX B

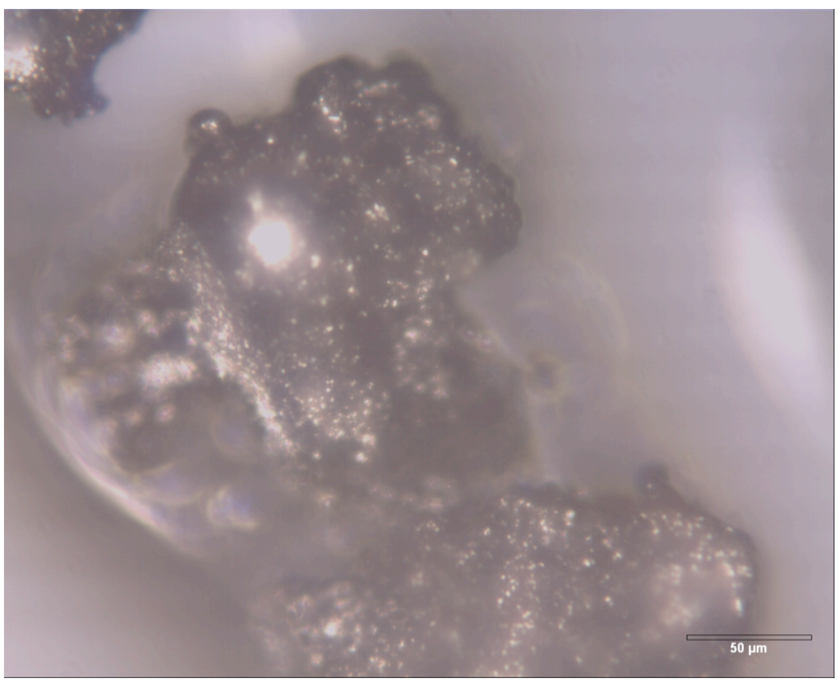
PHOTOGRAPHS



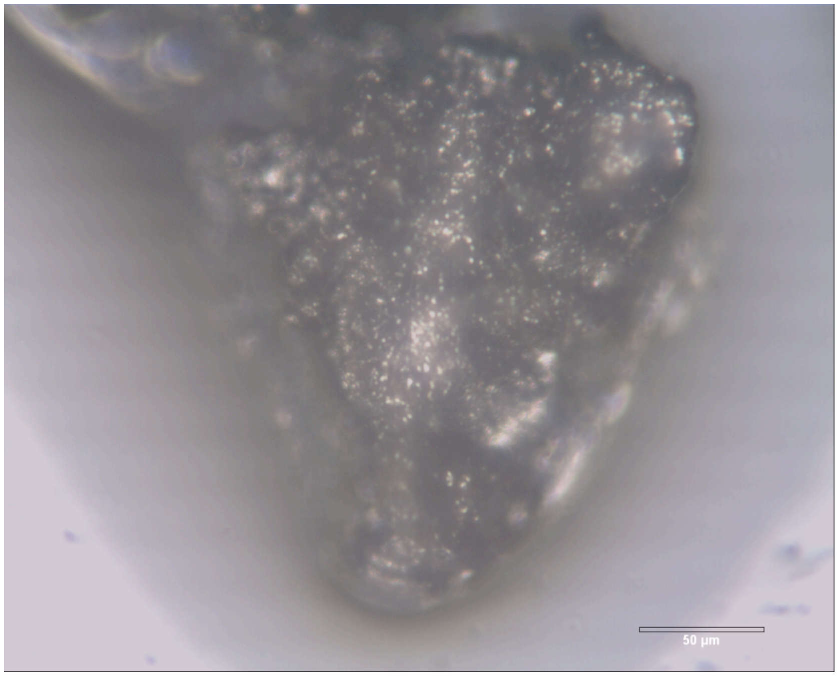
45 μm Magnetic Powder in Artificial Wastewater Magnified 200x



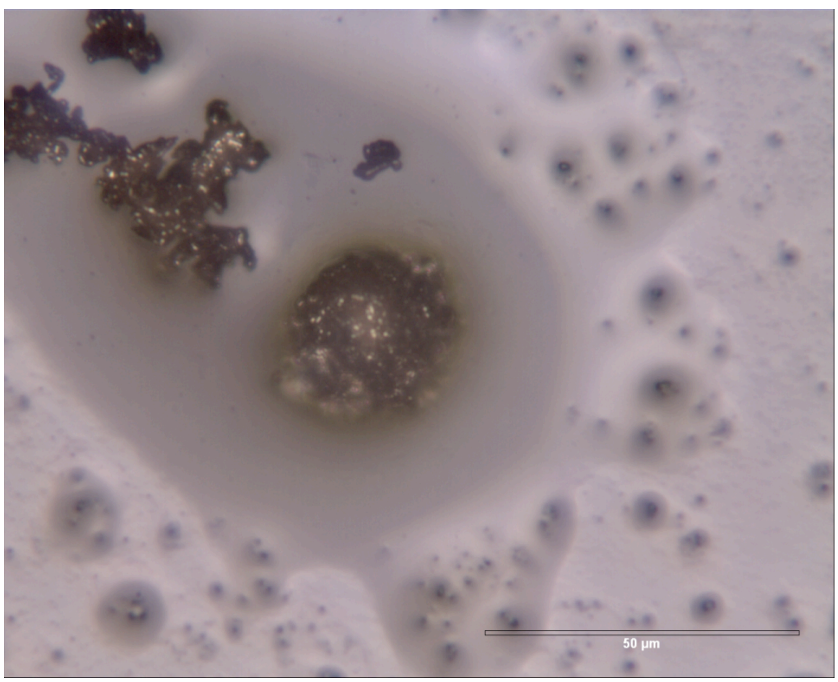
150 µm Magnetic Powder in Olive Oil 100x



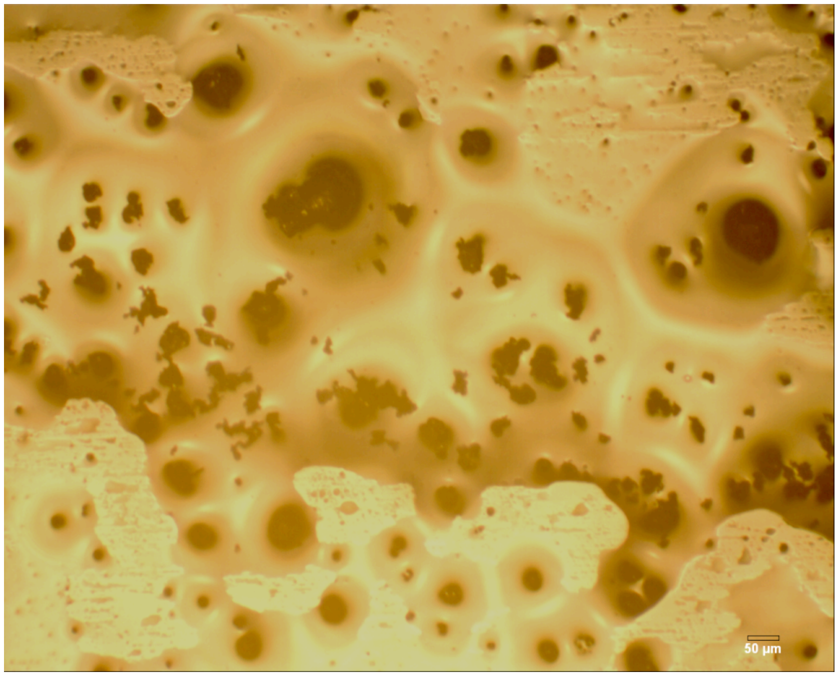
150 µm Magnetic Powder in Olive Oil Magnified 200x



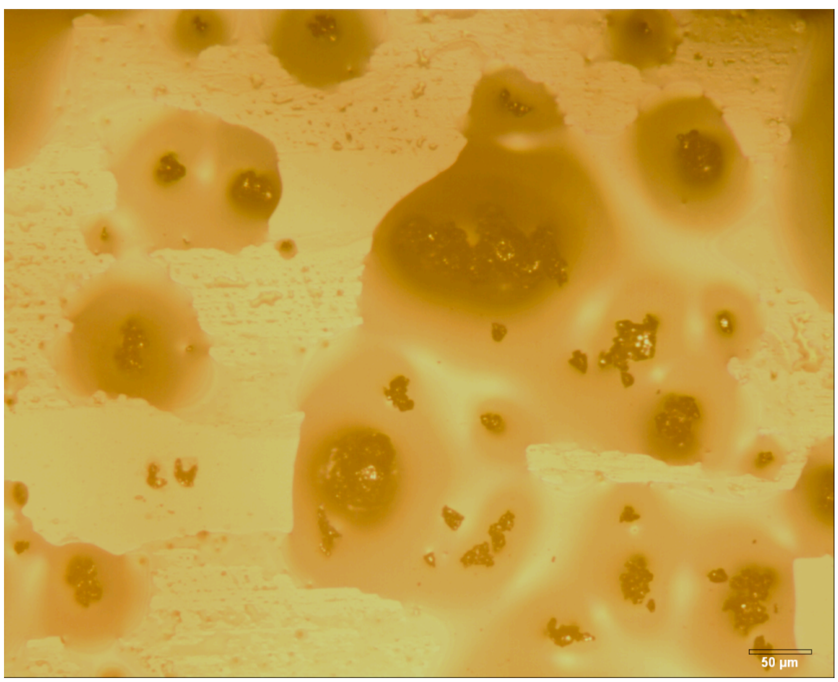
150 µm Magnetic Powder in Olive Oil Magnified 200x



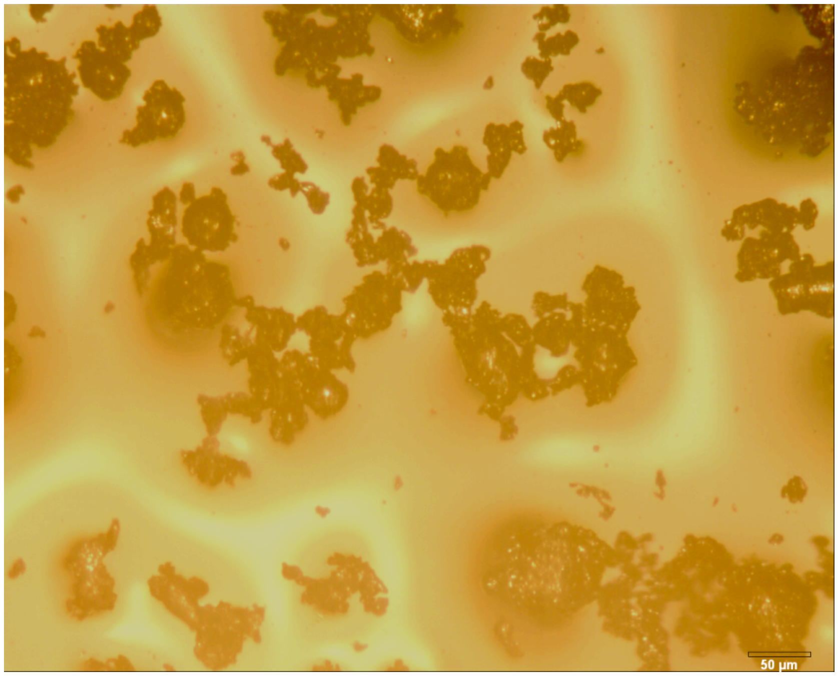
150 µm Magnetic Powder in Olive Oil Magnified 500x



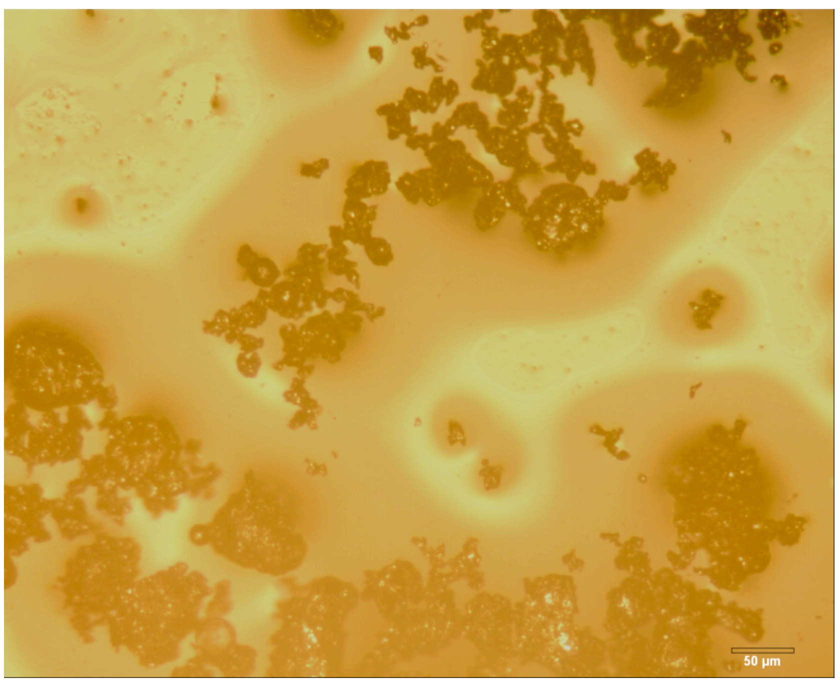
150 µm Magnetic Powder in Artificial Wastewater Magnified 50x



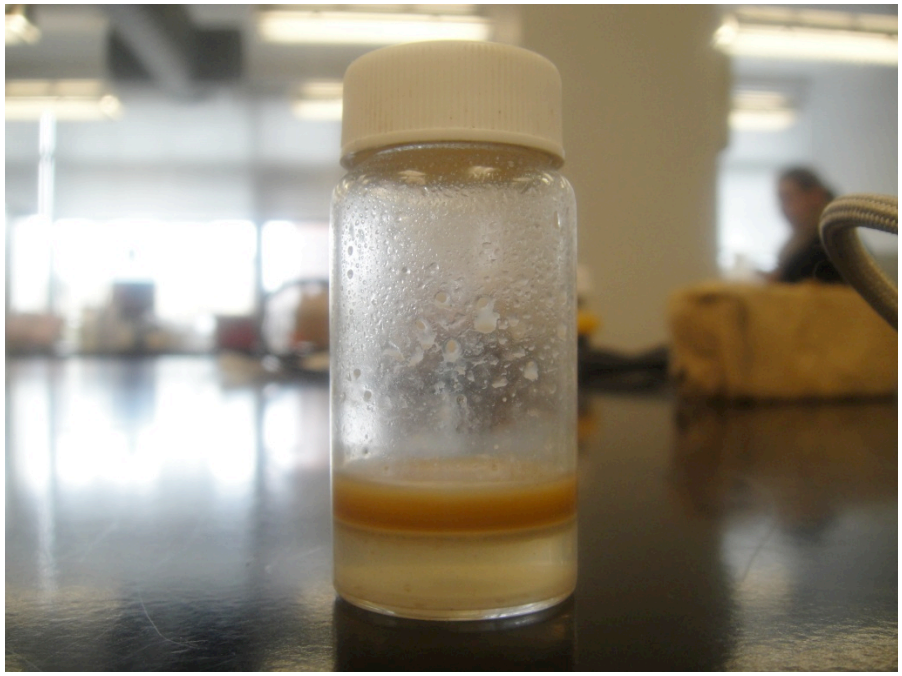
150 µm Magnetic Powder in Artificial Wastewater Magnified 100x



150 µm Magnetic Powder in Artificial Wastewater magnified100x



150 µm Magnetic Powder in Artificial Wastewater Magnified 100x



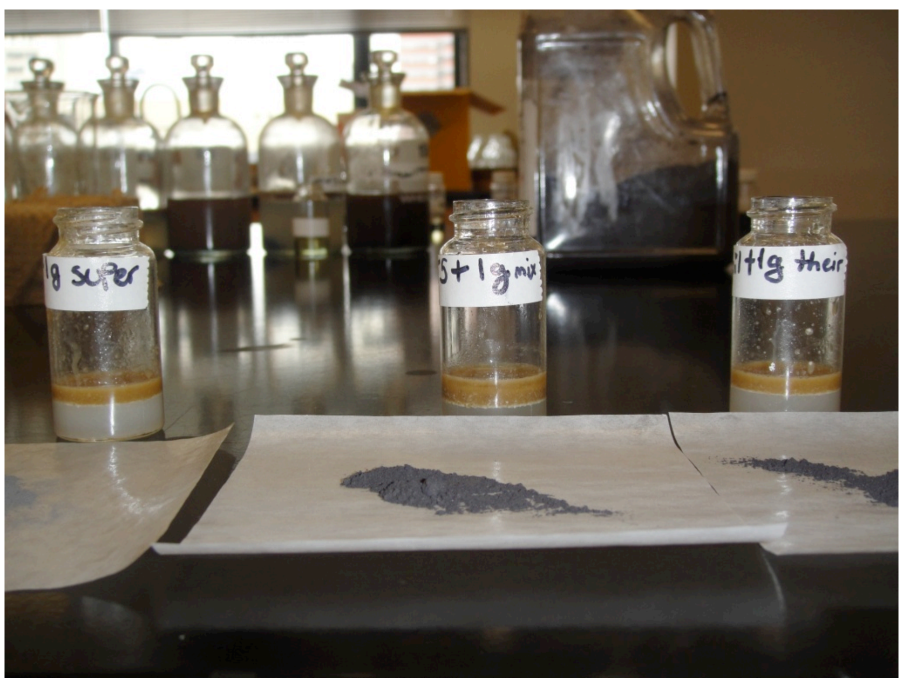
Blank Artificial Wastewater Vial Test

Vial Test Magnetic Powder Dosage Trial

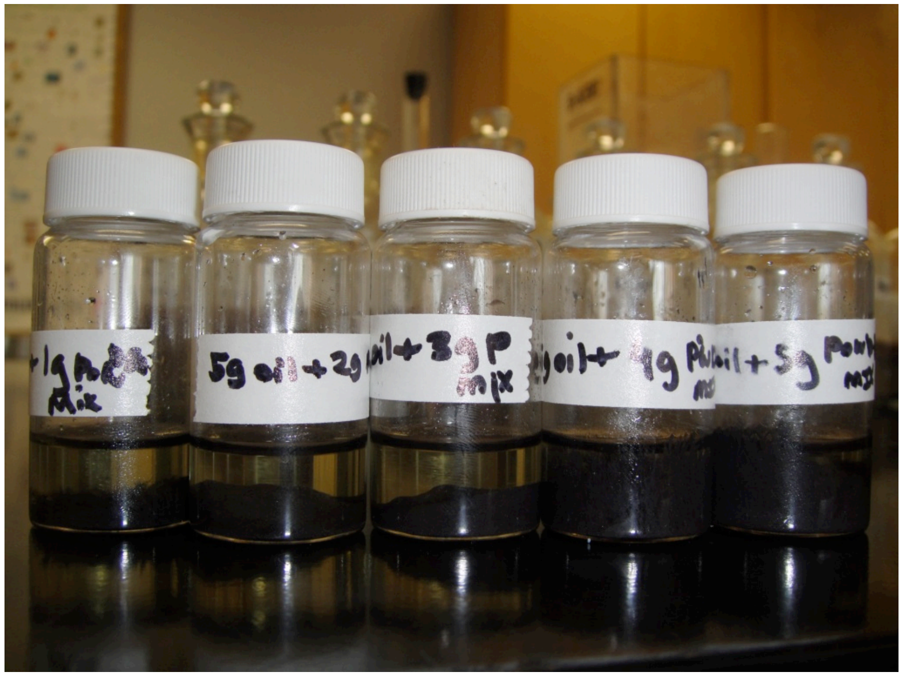
Vial Test Different Magnetic Powder Ratios Trial

Vial Test Different Magnetic Powder Ratio Trial

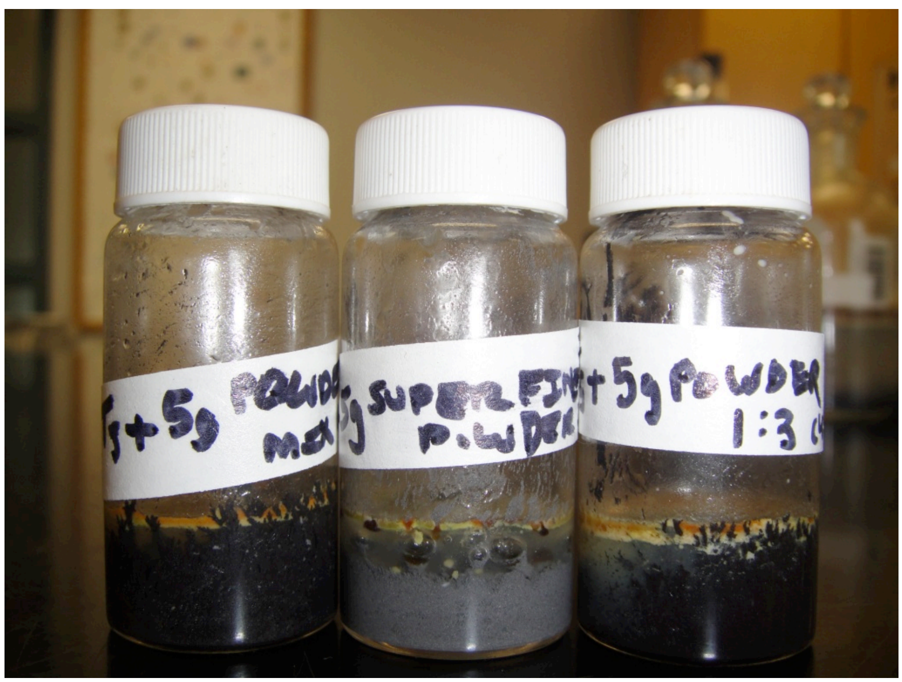
Vial Test with Different Grades of Magnetic Powder



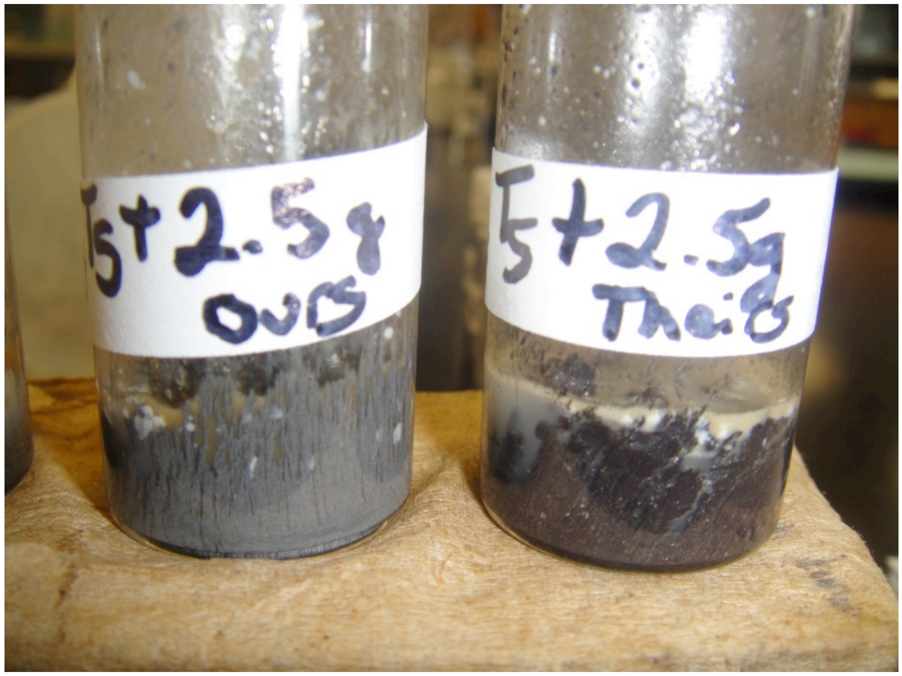
Vial Test Preparation



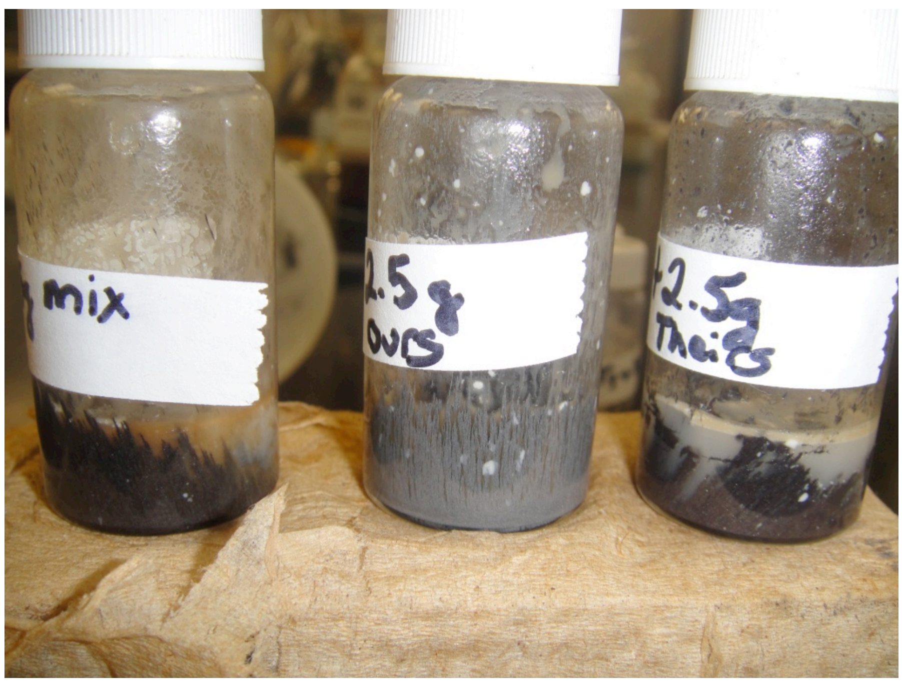
Vial Test Trial with Olive Oil



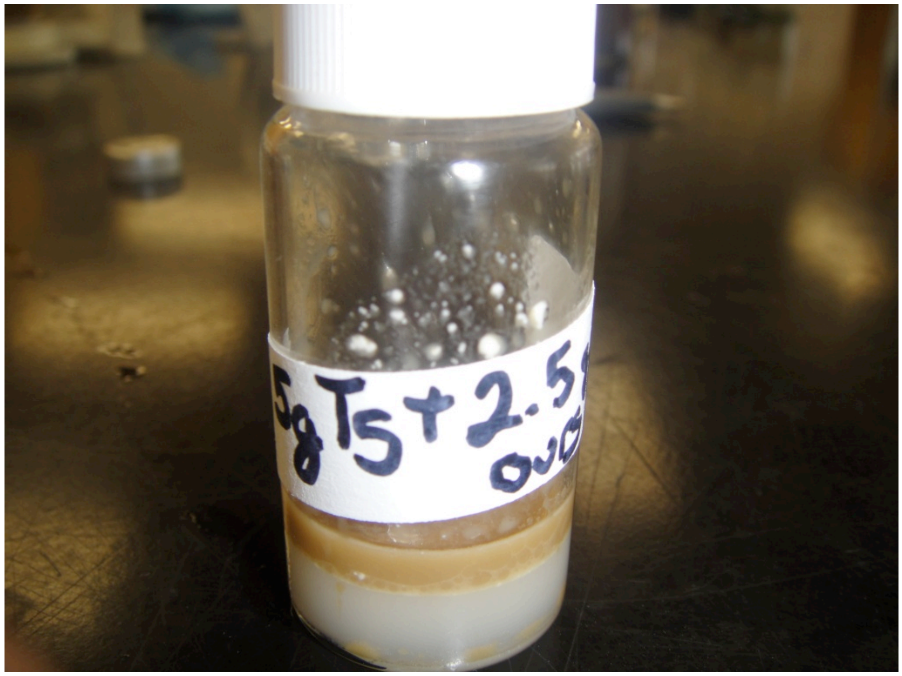
Vial Test with Optimum Artificial Wastewater



Vial Test with Magnetic Field and Artificial Wastewater



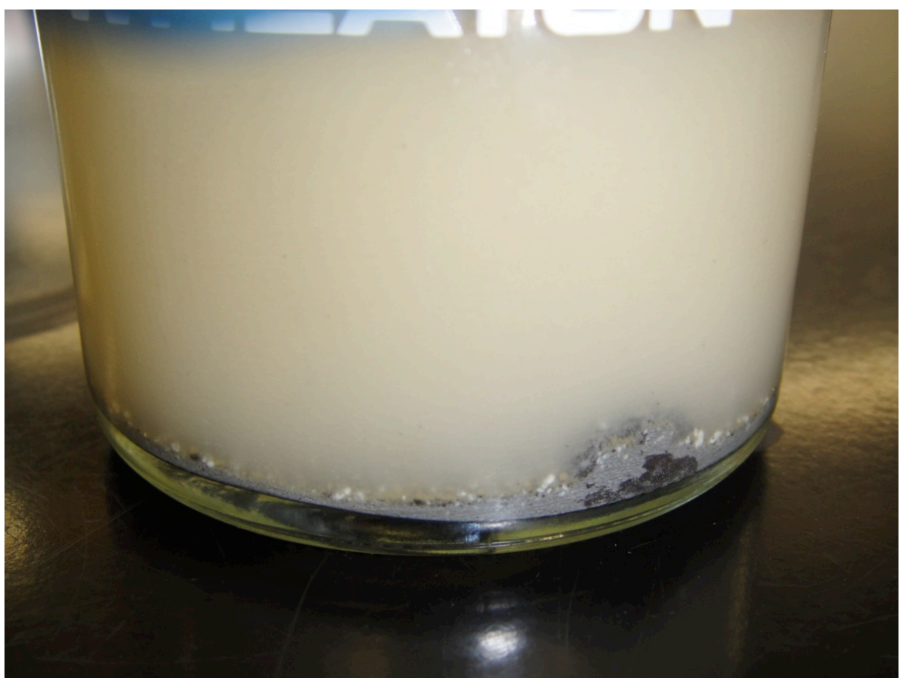
Vial Test with magnetic Field and Artificial Wastewater



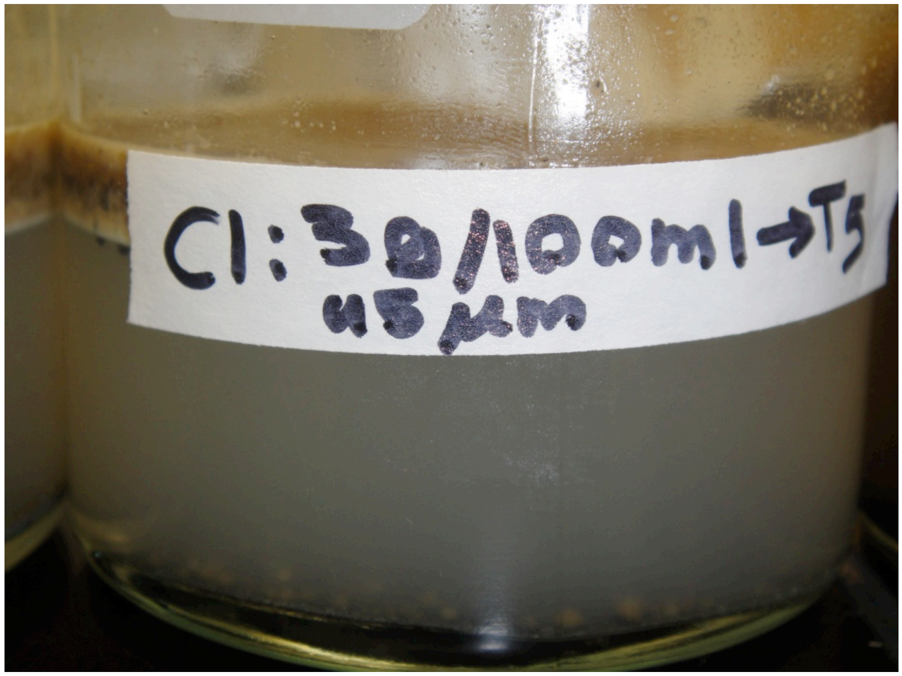
Vial Test with Super Fine Magnetic Powder

Vial Test with Various Powder Sizes

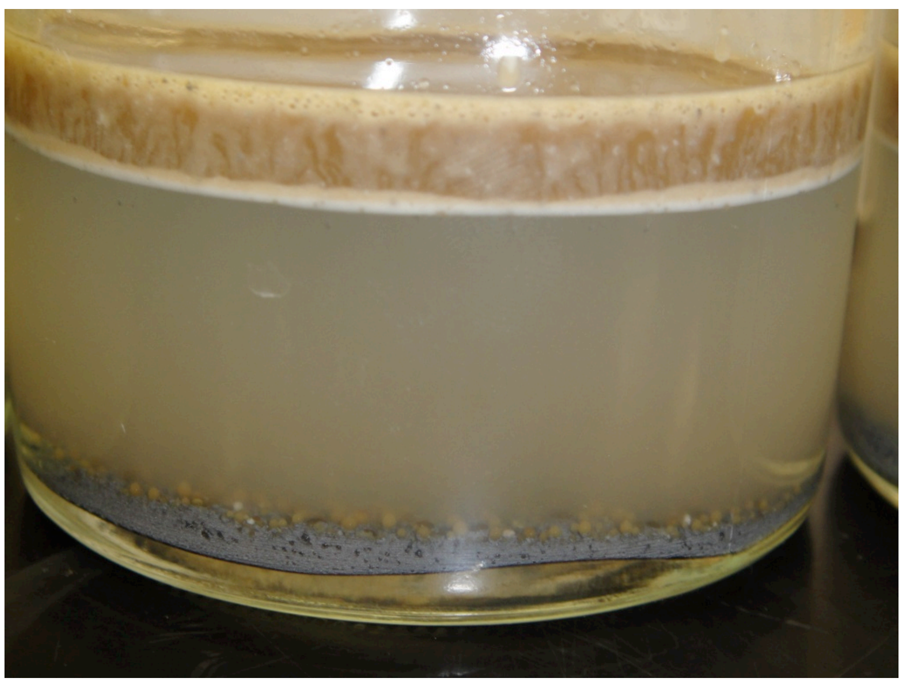
Oil/Powder Flocs in Vial Test (Larger Scale)



Oil/Powder Flocs in Vial Test (Larger Scale)



Vial Test and Visible Oil Droplets at the Bottom

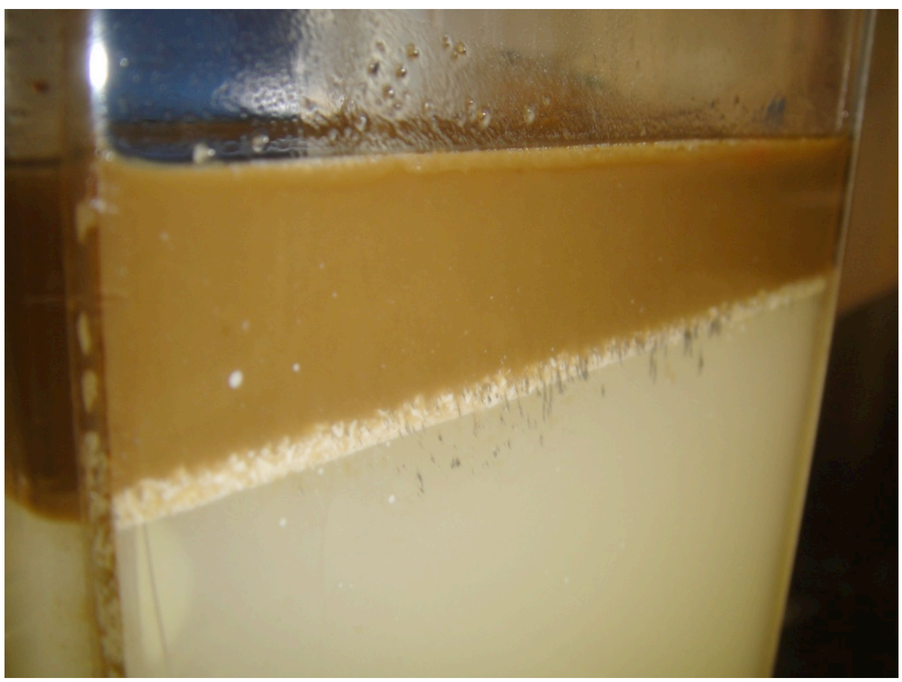


Visible Oil/Powder Flocs in Vial Test (Larger Scale)

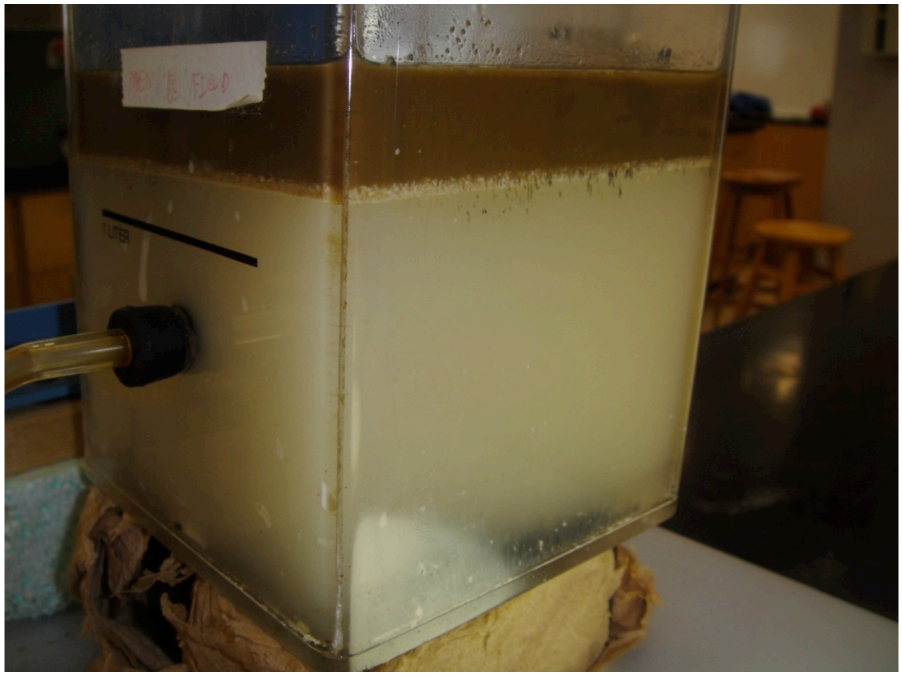
Vial Test (Larger Scale) with Magnetic Field

Vial Test (Larger Scale) with Low Magnetic Powder Ratio

Vial Test (Larger Scale) with Various Powder Ratios



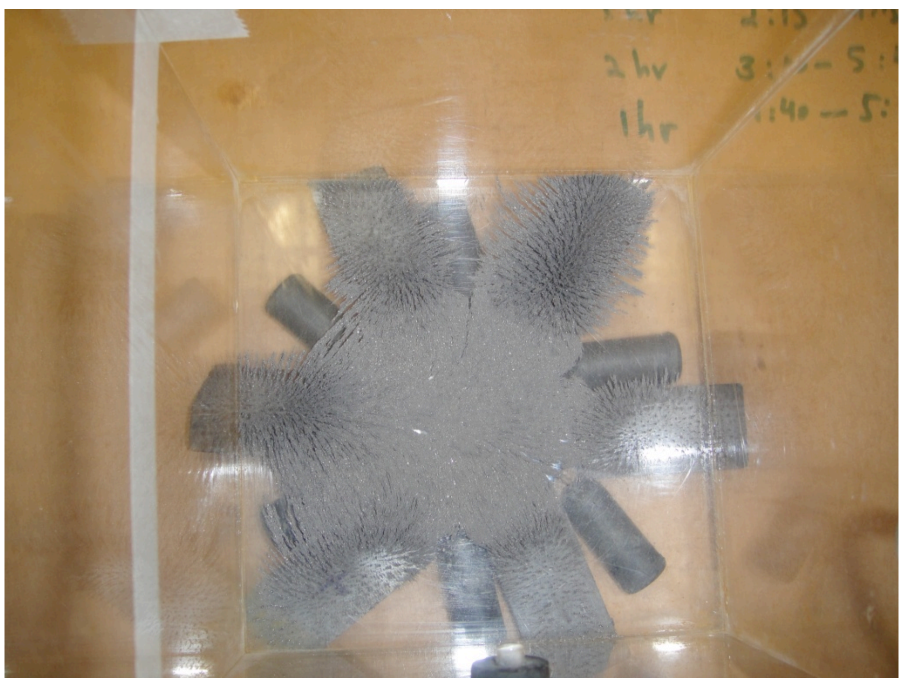
Jar Test First Trial



Jar Test First Trial

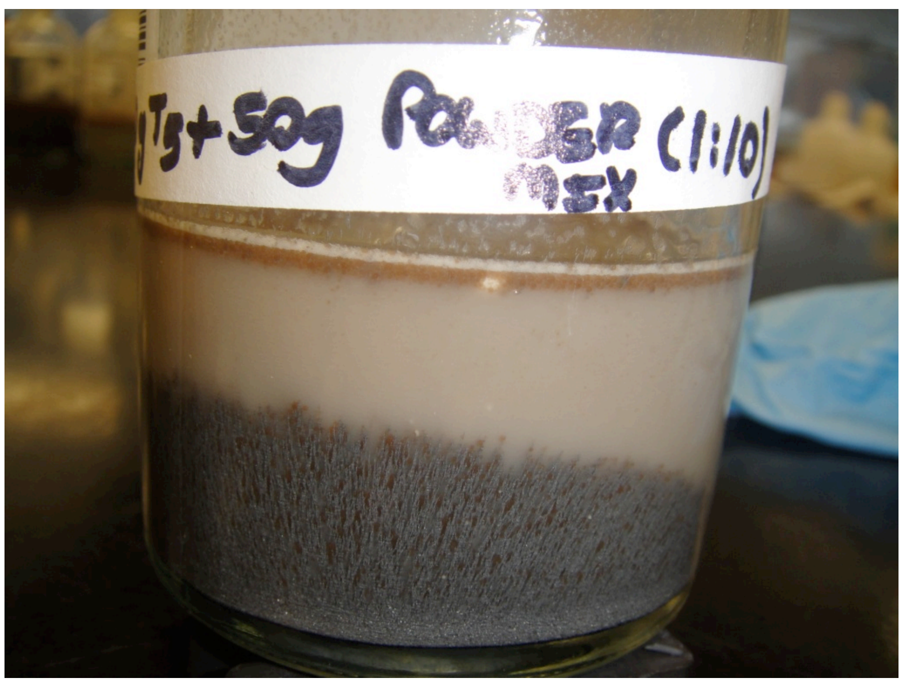
Jar Test First Trial

Jar Test Trials



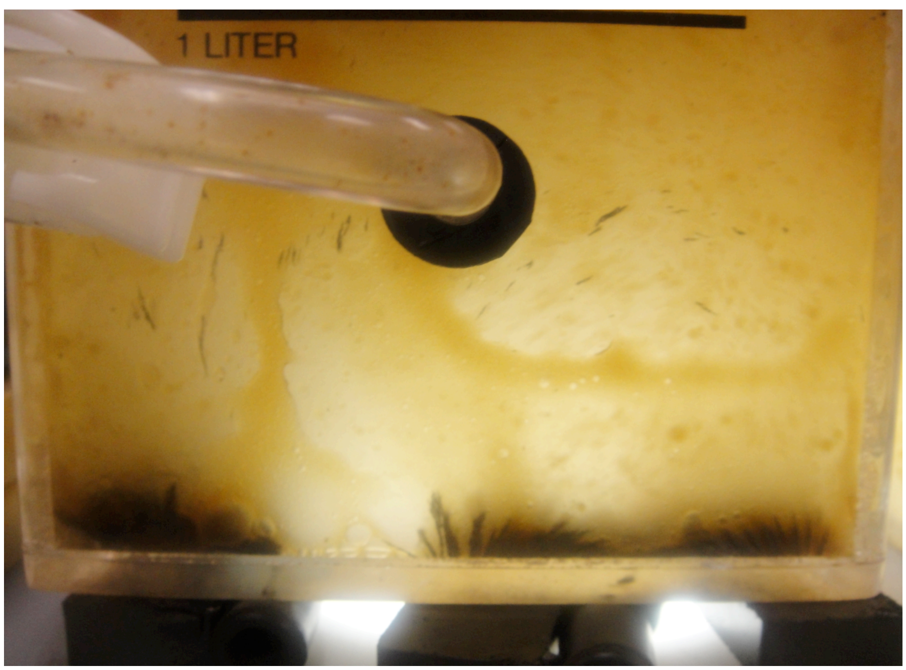
Magnetic Field Distribution

Vial Test (Larger Scale)



Vial Test (Larger Scale) After Few Hours

Vial Test (Larger Scale) with Magnetic Field



Jar Test Oil Captured by Magnetic Powder Settled at the Bottom

Settled Oil Droplets in Jar Test