DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

APPLICATION OF FRY-DRY TECHNOLOGY ON MUNICIPAL TREATMENT SLUDGES

by
Gülsün Durak

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İZMİR

APPLICATION OF FRY-DRY TECHNOLOGY ON MUNICIPAL TREATMENT SLUDGES

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by
Gülsün DURAK

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"APPLICATION of FRY-DRY TECHNOLOGY on MUNICIPAL TREATMENT SLUDGES"** completed by **GÜLSÜN DURAK** under supervision of **ASSOC.PROF.DR. AZİZE AYOL** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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APPLICATION OF FRY-DRY TECHNOLOGY ON MUNICIPAL TREATMENT SLUDGES

ABSTRACT

Sludge, generated throughout the water and wastewater treatment plants (WWTPs), is considered as a waste material. The production of sludge has continuously been increased. It’s a huge problem regarding its increasing production amounts, organic contents and also final disposal.

Land filling has been widely applied, however it has major problems due to sludge’s unsteady characteristics, transportation costs, odor and gas emissions. The European directive 86-278-EEC (Council Directive, 1986) intends to control all potential harmful effects of sewage sludge on soil, vegetation, animals and human. As a result of strictly limited land application of sewage sludge, incineration has become an increasing disposal method. For the incineration method, thermal drying is positioned as an intermediate unit operation.

Thermal drying is a process that reduces the volume and increases the heating value of sludge, by removing the water and achieving dry solids content more than 90 percent. In addition to the available sludge drying technology, fry-drying process has been recently considered as an alternative process with its many advantages for sludge drying purpose. This process is an attractive method for energy recovery as a result of combining two waste materials (sludge and waste oil) into a valuable product (bio-fuel). Also, the Turkish waste oil directive (2005) intends to control, collect and reuse waste oils.

This research study conducted in Department of Environmental Engineering at Dokuz Eylul University aimed to investigate the fry-drying technology as an alternative approach to typical sludge drying methods. The wastewater sludge used in this study was taken from a Municipal Wastewater Treatment Plant located in

Çiğli, Izmir, Turkey. Dewatered sludge cake characteristics were determined based on the pH, temperature, total solids content, volatile solids content, and heating value parameters. Experimental studies were designed by using the Box Wilson experimental statistical method. Experimental studies were done as two series by using: waste engine oil (WEO) and waste cooking oil (WCO) for the fry-drying process. In the experimental studies, sludge used as cylindrical samples at five different diameters between 1cm and 3 cm (1.0 cm., 1.5 cm, 2.0 cm., 2.5 cm., 3.0 cm.), at five different oil temperatures ranged between 100 degree Celcius and 180 degree Celcius (100 degree Celcius, 120 degree Celcius,140 degree Celcius,160 degree Celcius,180 degree Celcius) and at five different frying times ranged between 2min. and 20min. (2min., 6min.,11min.,16min.,20min.). Experimental results showed that the increasing of time and temperature increased the both dry solid contents and heating value of the final sludge product.

This thesis presents the detailed research results on fry-drying of sludge and debugs them for full-scale applications.

Keywords: Sludge, fry-drying, waste oil, drying, heating value

KENTSEL NİTELİKLİ ARITMA ÇAMURLARINA KIZARTMA-KURUTMA TEKNOLOJİSİNİN UYGULANMASI

ÖZ

Su ve atıksu arıtma tesislerinden elde edilen arıtma çamuru bir atık olarak değerlendirilmektedir. Atık çamurunun üretimi sürekli olarak artış göstermektedir. Artan çamur miktarı, sahip olduğu yüksek organik madde içeriği ve nihai olarak bertaraf edilmesi gibi konular ele alındığında uygulamada bu konu büyük bir problem olarak dikkat çekmektedir.

Arıtma çamurunun katı atık depolama sahalarında depolanması yaygın ve kolay bir uygulamadır; ancak, çamur özellikleri, nakliye maliyetleri, koku ve gaz salınımı gibi sebeplerden ötürü büyük sorunlar yaratabilmektedir. Avrupa Birliği'nin çamurun toprakta uygulanabilmesine ilişkin yönetmeliği 86-278-EEC arıtma çamurunun olumsuz etkilerininin insan ve çevre sağlığı açısından en aza indirilmesini hedeflemektedir. Depolamada yaşanan problemlerden dolayı son dönemlerde yakma yöntemine yönelinmiştir. Yakma yöntemi için, termal kurutma bir ara-ön işlem olarak konumlandırılmıştır.

Termal kurutma işlemi çamurun sahip olduğu suyu yok ederek ve kuru madde içeriğini yüzde 90'dan fazla tutarak hacmi azaltan ve atık çamurunun daha düşük ısı değerini artıran bir süreçtir. Mevcut atık çamur kurutma teknolojisine ek olarak, yağda kızartma süreci atık çamurunu kurutma maksadıyla sahip olduğu pek çok avantajıyla birlikte yeni alternatif bir yöntem olarak değerlendirilmeye başlamıştır. Bu süreç, iki atık materyalin (çamur ve atık yağ) değerli bir ürün (bio-yakıt) elde edilmesi için birleştirilmesinin bir sonucu olarak enerji geri dönüşümünde cazip bir yöntemdir. Ayrıca, Türk atık yağ direktifi (2005) atık yağların kontrol edilmesi, toplanması ve yeniden düzenlenmesini amaçlamaktadır.

Dokuz Eylül Üniversitesi Çevre Mühendisliği Bölümü'nde yürütülmüş olan bu araştırma çalışmasında, tipik atık çamuru kurutma yöntemlerine bir alternatif olarak arıtma çamurları için yağda kızartma teknolojisinin uygulanabilirliği incelenmiştir. İzmir Büyükşehir Belediyesi, İzmir Su ve Kanalizasyon İdaresi Genel Müdürülüğü (İZSU) sorumluluğunda işletilen Çiğli Kentsel Atıksu Arıtma Tesisi'nden alınan çamur keki örnekleri ile çalışılmıştır. Çamur keki karakterizasyonunun belirlenmesinde, pH, sıcaklık, çamur katı madde miktarı, organik madde miktarı, kalorifik (ısıl) değer analizlenmiştir. Deneysel çalışmanın tasarımında ve elde edilen verilerin değerlendirilmesinde Box Wilson İstatiksel Deney Yöntemi uygulanmıştır. Deneysel çalışmalarda bu uygulama, atık mutfak yağı (WCO) ve atık trafo-madeni yağ (WEO) ile iki seri olarak gerçekleştirilmiştir. Silindirik olarak şekillendirilen örneklerde 1cm ile 3 cm arasında beş farklı çap (1.0 cm., 1.5 cm, 2.0 cm., 2.5 cm., 3.0 cm.), 100 derece ile 180 derece arasında (100 derece,120 derece,140 derece,160 derece,180 derece) beş farklı yağ sıcaklığı ve 2 dk. ile 20 dk. arasında beş farklı süresi (2min., 6min.,11min.,16min.,20min.) yağda kızartma uygulamasında kullanılmıştır. Deneysel çalışmaların sonuçları, artan sıcaklık ve alıkonma süreleri için hem çamurun katı madde içeriğinin hem de son ürünün ısıl değerinin arttığını göstermektedir. Kullanılan yağların çamurun sahip olduğu ısıl değeri arttırdığı bulunmuştur.

Bu tez çalışmasında, arıtma çamurlarının yağda kızartma yöntemiyle kurutulmasına ilişkin elde edilen deneysel veriler detaylı olarak sunulmakta ve tam ölçekli uygulamalara yönelik sonuçlar tartışılmaktadır.

Anahtar sözcükler: Arıtma çamuru, kızartma-kurutma, atık yağ, kurutma, ısıl değer

CONTENTS

CHAPTER ONE
INTRODUCTION

1.1 Introduction

Sludge generated throughout the water and wastewater treatment plants (WWTPs) is considered as a waste material. However, it consists of microorganisms, extracellular polymeric substances (EPS), inorganic particles, cations, and large quantities of water (Ayol, 2005). EPS is the largest organic constituent in sludge includes carbohydrates, proteins, humic compounds, uronic acids, nucleic acids (DNA), and other organic macromolecules (Ayol, 2005). Regarding these constituents, sludge can also be used for beneficial purpose like energy recovery.

Sludge is a huge problem regarding its increasing production volume, organic content and final disposal. The disposal route of sludge depends on the limitations of the given city or country. The production of sludge has continuously been increased. The sludge production in all 27 European countries is predicted more than 10 millions of tonnes-dried solids (DS)/year, while it is expected about 13 millions of t-DS/year for 2020. Sludge is an important problem to be managed for Turkey as well. The annual amount of sludge in Turkey was approximately 0.5 millions of t-DS/year in 2008 (TUIK, 2008).

Sewage sludge is landfilled in nearly 40% of European Union countries (Fytili and Zabaniotou,2008; Werther and Ogada, 1999). Landfilling has major problems due to sludge unsteady characteristics, transportation costs, odor and gas emissions. The European directive 86/278/EEC (Council Directive, 1986) intends to control all potential harmful effects of sewage sludge on soil, vegetation, animals and human. Also, Turkey is developing environmental policy based on European Directives. In Turkey, the produced sludges have been processed using auxiliary sludge treatment processes: thickening (gravity thickening, flotation thickening, and centrifuge) and dewatering (sludge drying beds, belt press filters, centrifuges, and plate press filters). Regarding the WWTPs has a wastewater treatment capacity above 10000 m^3/day, the number of stabilization units are 49. Most of them are aerobic and anaerobic stabilization units; however, lime stabilization method is applied in some treatment plants successive dewatering units. Some treatment plants those are really good experiences with anaerobic digester units like Ankara MWWTP, Kayseri MWWTP, Malatya MWWTP, Tuzla/Istanbul MWWTP (Filibeli and Ayol, 2011). The tender for the construction of anaerobic digesters and drying facility in City of Izmir has recently been done. The most common disposal alternative in Turkey is landfilling for processed sludges either in special areas or in municipal solid waste disposal area. Other alternatives of beneficial usage of sludge like energy recovery from sludges are still under research by universities, governmental institutions, and the administrations of the plants (Filibeli and Ayol, 2011).

The legislations have strict limitations for landfilling of sludge in order to ensure protection of soil and the ground water. As a result of strictly limiting land application of sewage sludge, incineration become an increasing disposal method. For the incineration method, thermal drying is positioned as an intermediate unit operation, allowing volume reduction, stabilization (inactivation of pathogenic biological organisms) and increase the energy value of sludge (Grueter, H., et al.,1990; Hasserbrauck et al.,1995). Thermal drying is a process that reduces the volume of sludges, by removing the water and achieving dry solids content more than 90%. During the process, heat should be applied to evaporate the water of sludge. In practice, there are different types of dryers to be used for sludge processing. The dryers are classified depending on three typical heat transfer methods: convective (direct) dryers, conductive (indirect) dryers, and mixed or combined dryers. All thermal dryers have technical difficulties as volatile organic compounds in produced vapor, odor, and risk of explosion and plastic phase of sludge, etc. Therefore, installation and operation of the drying units should be carefully done.

The sludge water content need to be reduced from 70-90% to below 10% during the drying process for increased the lower heating value of sludge. This requires large amount of energy and according to reference (Furness et al., 2000) the solid content in the sludge should be considerably reinforced to be auto-thermal. In addition to the available sludge drying technology, fry-drying process has been recently considered as an alternative process with its many advantages for sludge drying purpose.

Frying, one of the oldest processes of the food industry consists of drying by contact with hot oil and involves simultaneous heat and mass transfer (Moreira et al., 1999). Sludge heating value increases after fry-drying application and can be used as a solid fuel. This process is an attractive method for energy recovery as s result of combining sludge and recycled oil into a bio-fuel. At the same time, two waste materials (sludge and waste oil) have been used to produce a valuable product. Also, the Turkish waste oil directive (2005) intends to control, collect and reuse waste oils.

In food industry frying used with oil temperature between 120°C and 180°C.The high heat transfer rate in frying allows the moist surface of the product to be dried in a few seconds. With adequate temperature conditions in the oil bath, an evaporative front migrates towards the centre of the product, with the formation of an outer layer of dried crust, partial impregnation of the oil and a number of chemical reactions (Saguy et al., 1998). Limited research studies used this technology for sludge drying are available in the literature. However, more information about the fry-drying of sludge is necessary.

This research study carried out in the Department of Environmental Engineering at Dokuz Eylul University aimed to investigate the efficiency of the fry-drying process of sludges under the different operational conditions. This thesis presents the detailed research results on the sludge’s fry-dry applications.

1.2 Scope And Research Objectives Of The Thesis

In the field of sludge reuse and energy recovery, the production of valuable material from sludge has an important issue because organic matter accumulated in sludge represents big quantum of energy. The enhancement of thermal processing of sludges will improve production and quality of deriving products for material and/or energy utilization (Brester et al., 1997). The importance of the energy recovery from sludge pushes forward to research studies so that the thermal processes are optimized. Drying is an essential step if followed by a thermal treatment process. The more research studies for enhancing the drying ability of sludge and energy recovery from its organic fraction are required. Frying of sludge is considered to be of great concern for waste-to-energy recovery. This application involves chemical, physical and biological alterations in the sludge structure. This research study aimed to determine the most aspects affecting physical and thermal properties of sludge during fry-dry application, which are the mass transfer, mainly represented by water loss and oil uptake, and heat transfer. The research objectives of this thesis are therefore:

- to review the current drying technologies applied to sludges and the applicability of fry-dry technology in sludge management field,
- to combine two waste materials (sludge and waste oil) into a valuable product (bio-fuel).
- to investigate the effects of operational conditions (time, temperature, sludge’s depth) on sludge drying performance,
- to determine the heating (calorific) values of sludge after fry-drying process.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

This chapter gives information about the sludge treatment methods and sludge thermal drying technology.

In this chapter, in addition, the background information about thermal sludge drying technologies and dryer types has been summarized. The detailed information including the research studies on fry-drying of sludges has been reported in the following chapter.

2.2 Sludge Treatments And Disposal

The management of sludge produced at WWTPs is one of the most difficult problems to be solved in all over the World. That's because sludge produced by WWTPs amounts to only a few percent by volume of the processed wastewater, but its handling accounts for up to 50% of total operating costs. The sustainable sludge management strategy has become of greater concern. Due to the strict limits for some recycling options like agricultural usage and land application, innovative systems to maximize recovery of useful materials and/or energy has been promoted (Brester et al., 1997). There are a auxiliary treatment methods throughout the sludge processing including *(1) Pretreatment, during which sludge characteristics are altered to enhance subsequent process performance; (2) dewatering, for separating moisture from the sludge body; (3) post-treatment, for stabilizing or deoxidizing the sludge, and (4) final disposal, which aims to achieve safe and economically feasible disposal* (Wang et al., 2005). The sludge treatment methods providing mass and volume reductions in sludge are summarized in Table 2.1.

Table 2.1 Sludge processing methods providing the volume and mass reduction (Metcalf & Eddy, 2003)

Unit operation, unit process, or treatment method	**Function**
Thickening:	
Gravity thickening	Volume reduction
Flotation thickening	Volume reduction
Centrifugation	Volume reduction
Gravity – belt thickening	Volume reduction
Rotary – drum thickening	Volume reduction
Stabilization:	Stabilization
Alkaline stabilization	Stabilization, mass reduction
Anaerobic digestion	Stabilization, mass reduction
Aerobic digestion	Stabilization, mass reduction
Autothermal aerobic digestion (ATAD)	Stabilization, product recovery
Composting	
Dewatering:	
Centrifuge	Volume reduction
Belt – filter press	Volume reduction
Filter press	Volume reduction
Sludge drying beds	Volume reduction
Reed beds, Lagoons	Storage, volume reduction
Heat drying:	
Direct dryers	Weight and volume reduction
Indirect dryers	Weight and volume reduction
Incineration:	Volume reduction, resource recovery
Multiple – hearth incineration	
Fluidized – bed incineration	Volume reduction
Co-incineration with solid waste	Volume reduction

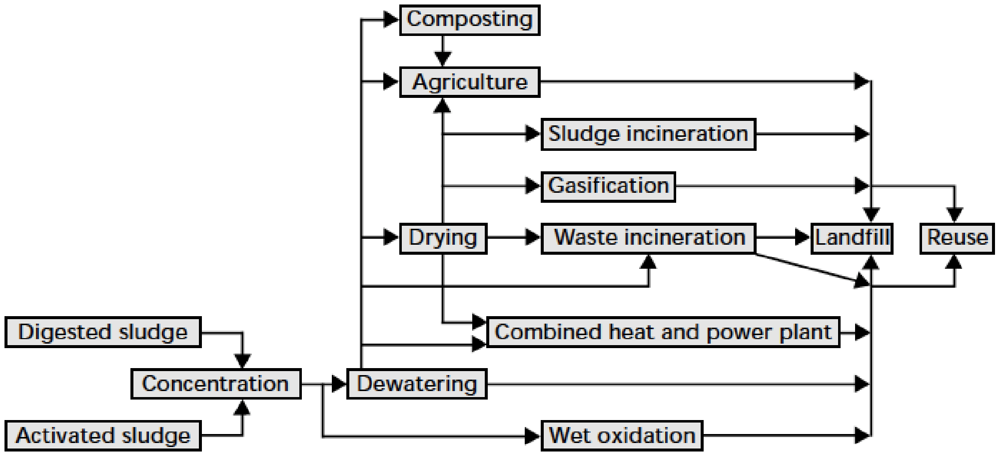

Figure 2.1 A sludge treatment net-work (Bresters et al.,1997)

Whatever the chosen disposal route, drying is often included as a final stage in sludge treatment (Arlabosse et al., 2001; Chen et al., 2002). Sludge drying is positioned after dewatering units, which is thermal energy applied to sludge. Thermal drying allows the volume reduction, stabilization (inactivation of pathogenic biological organisms) and increase in energy value of sludge (Grueter, H., et al., 1990; Hasserbrauck et al., 1996).

Land application appears presently as the most economical alternative in developed countries with approximately 40% in the European Union (Fytili and Zaba- niotou, 2008; Werther and Ogada, 1999). In coastal areas, sludge dumping into the deep sea is very problematic and London dumping convention will be prohibited by the year 2012 (Ohm et al., 2009). Also, the European Directive 86/278/EEC (Council Directive, 1986) intends to control all potential harmful effects of sewage sludge on soil, vegetation, animals, and human. In order to reduce final waste disposal, the European Union made a strategy following the prevention of waste, waste recovery through, reuse, recycling and energy recovery, improved treatment conditions, and regulation of the transport (Fytili and Zabaniotou, 2008). As a result of strict limits for land application of sewage sludge, incineration becomes an increasing disposal method. Potential advantages of thermal processes include reduction of volume and weight, destruction of toxic organic compounds, and recovery of energy, but economics need to be carefully evaluated. Sewage sludge has a heating value as in coal. Even if one ton of sludge dry matter is approximately equivalent to 700 kg of hard coal, the material has to be dewatered/dried prior to be used for thermal processing (Brester et al., 1997). Table 2.2 shows the typical heating values of different kinds of sludge. However, incineration of sewage sludge requires additional energy during thermal drying step as it contains a large volume of water (60 to 80%) (Werther and Ogada, 1999). After drying process water content must be reduced to 20% (Tae-In Ohm et al., 2009).

Table 2.2 Typical heating values for different types of sewage sludge (Fytili, D. & Zabaniotou, A., 2008)

Type of sludge	**Heating Value (MJ/ kgDS)**	
	Range Typical	
Raw sludge	23-29	25.5
Activated sludge	16-23	21
Anaerobically digested primary sludge	9-13	11
Raw chemically precipitated primary sludge	14-18	16
Biological filter sludge	16-23	19.5

To achieve a significant dry mass content in the sludge, the water fractions available in the sludge structure should be considered. The gain in dryness obtained by dewatering and drying is connected to the water types in it. The water fractions of the sludge will be explained in the subsection 2.3.

2.3 Water Classification In Sludge

Water presented in sludge is categorized as: free water, surface water, capillary water, and bound water (Vesilind et al., 1994). Figure 2.1 shows the moisture distribution of sludge (Chen et al., 2002).

- **Free w ater:** water not attached with solid particles plus void water not affected by capillary force and can be easily removed by gravitational settling (thickening). Sludge thickening units as gravity thickeners, belt thickeners or centrifuges used for achieve up to 10% DS content. **Capillary (interstitial) water**, trapped within crevices and interstitial spaces of flocs and organisms. The water can be removed by mechanical forces.

- **Floc or particle (surface) water,** held on to the surface of solid particles by adsorption and adhesion. **Bound water,**

  -Biologically - in *intracellular form, it is a part of the cells of living organisms present in sludge, bound by molecular forces to the constant phase of sludge;*

  - Chemically - in intercellular form, it is a part of the crystal lattice of molecules of the constant phase of sludge;

  - Physically – in colloids, bound by the surface tension present on the border of phases (Flaga, A.,2009).

The bound water content can be determined by methods such as dilatometric determination, vacuum filtration, expression, drying, and thermal analysis (Chen, et al., 2002). The free water and surface water in sludge are evaporated at 95-105 ^{o}C; but capillary and bound water require the temperature up to 400 ^{o}C (Ohm et al., 2009).

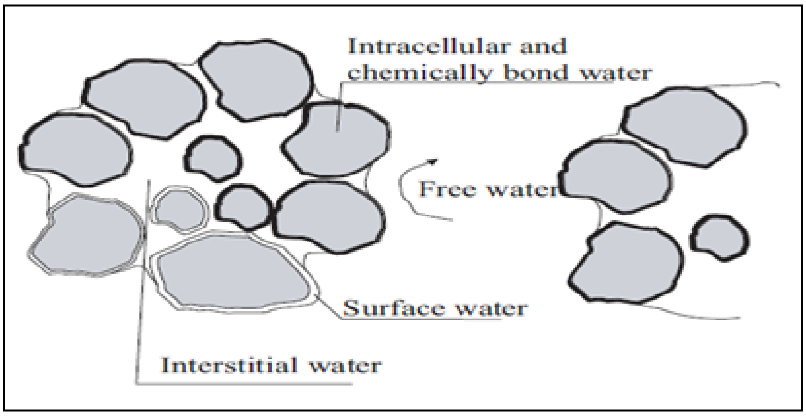

Figure 2.2 Water Distributions in Sludge (Chen et al., 2002)

2.4 Thermal Drying

Sludge drying processes were adapted from other industries like food, chemical, pharmaceutical, and mineral processing. Thermal drying of sludge can be defined the technology which is based on removal of water from dewatered solids (WEF-RBC-BTS, 2004). This application led to the both volume and weight reduction of sludge. The number of sludge drying plants is progressively increasing worldwide reaching about 1,500 lines, due to the drastic reduction of the sludge amount, and the production of a material with significant energy and nutrient value, and high quality from the hygienic point of view (Chabrier, 2008; Brester et al., 1997). Thermal drying of sludge can be positioned as an intermediate unit before the final disposal methods - land filling, land spreading, and other thermal applications like incineration, pyrolysis and gasification– which providing volume reduction, stabilization and increase the energy value (Peregrina et al., 2001). Depending on the heat transferring method, current drying technologies used in sludge management field are categorized as four main classes: convective (direct drying), conductive (indirect drying), combined (mixed), and radiation (infrared drying).

2.4.1 Heat Transfer Methods

Heat is the transfer of energy between particles. Energy is a property possessed by particles of the matter. Heat transfers from a high temperature to a lower temperature by using one or combination of these methods: conduction, convection, and radiation. These methods are briefly explained in the following subsections.

2.4.1.1 Conduction

This method is an atomic or molecular activity that transfers thermal energy from a region with higher temperature to a region with lower temperature. The mechanism of the conduction varies for different substances. For an electrically non-conducting solid, conduction is attributed to atomic activity in the form of lattice vibrational waves (or phonons) while it is a combination of lattice vibration and translational motion of electrons for an electrically conducting solid. Heat conduction in a liquid or gas is due to the random motion and interaction of the molecules (Faghri et al., 2010).

2.4.1.2 Convection

Convection is the transfer of heat and mass through a fluid flow. *Convective heat and mass transfer describe momentum, energy, and/or mass transfer between a surface and a fluid in contact with that surface. Convective heat and mass transfer caused by bulk fluid motion (advection) and the random motion of fluid molecules (conduction and diffusion).* This transport mechanism can be occurred by two ways: forced or natural. A convective force can be induced by the help of an external source like a fan or pump. Natural convection transport can be induced by the fluid motion caused by the body forces resulting from properties such as density and mass concentration variation (Faghri et al., 2010).

2.4.1.3 Radiation

Radioactive energy is carried by electromagnetic waves, which require no medium for their dissemination. This energy can be transferred through a vacuum, for example allowing us to receive solar energy through the vacuum of space (Faghri et al., 2010).

The movements of atoms and molecules in a material induce thermal radiation. Their movement results in the emission of electromagnetic radiation, which carries energy away from the surface, which is continually bombarded by radiation from the surroundings, resulting in the transfer of energy to the surface. Depending on the increases in the amount of emitted radiation, a net transfer of energy from higher temperatures to lower temperatures occurs (Faghri et al., 2010).

2.4.1.4 Mass Transfer

Because of the concentration differences in a multi component mixture, mass transfer occurs as in two modes: diffusion and convection (Faghri et al., 2010).

2.5 Dryer Types

Depending on the predominant heat transfer methods, dryer types can be generally categorized into four types:

- Direct drying systems (convective dryers)
- Indirect drying systems (conduct dryers)
- Combined systems (mixed convective-contact dryers)
- Infrared dryers (with the use of infrared radiation or high frequency currents).

2.5.1 Direct Dryer

In the direct dryer systems, convective heat transfer method is applied. Hot gas or air used as a heat source contacts directly particles of wet solids. The contact between hot gas/air and wet material leads to an increase in the solid temperature and so the water in the sludge evaporates (WEF-RBC-BTS, 2004; Flaga.A, nd). Rotary drum dryers, flash dryers, belt dryers, and fluidized-bed dryers are common types of the direct dryers.

2.5.1.1 Rotary Drum Dryer

The dewatered sludge cake is fed into the dryer at one point and rotation transports the cake mixture through the drum where mixture contacted to the hot gases directly. End of the drying process, the dried sludge product has more than 90% dry solid content. Also back feeding is necessary to achieve more than 65% dry solid content before fed the sludge (Bresters et al., 1997; Water Siemens, 30.08.2011). Figure 2.3 shows a schematic view of a rotary-drum dryer.

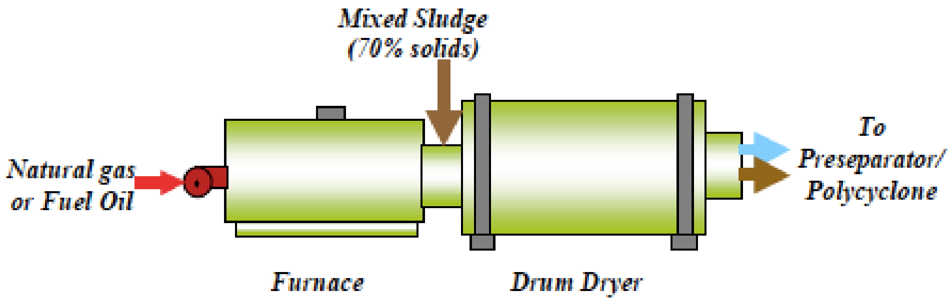

Figure 2.3 Drying System Grup Water Siemens (2011).

2.5.1.2 Flash Dryer

The flash drying is a hot gas stream and sludge mixing system by spraying or injecting. A flash drying system is shown in Figure 2.4.

2.5.1.3 Belt Dryer

Belt dryers have been designed as a belt conveyor onto wet sludge contact with hot air. The wet sludge is slowly conveyed through the several drying chambers and the moisture of the material released into the air. The operating temperatures are approximately 150 °C (300 °F) at the belt entry and 100 °C (210 °F) at the end. The low operating temperature is achieved less odor and safe operation. Dried sludge is shaped with 1 to 10 mm and dust formation reduced whereas the granulate bed acts as a filter media to prevent dust generation inside the dryer. The schematic view of a belt dryer is given in Figure 2.5 (Idswater, 30.08.2011; Lowe, 1995; Westernwakepartners, 30.08.2011).

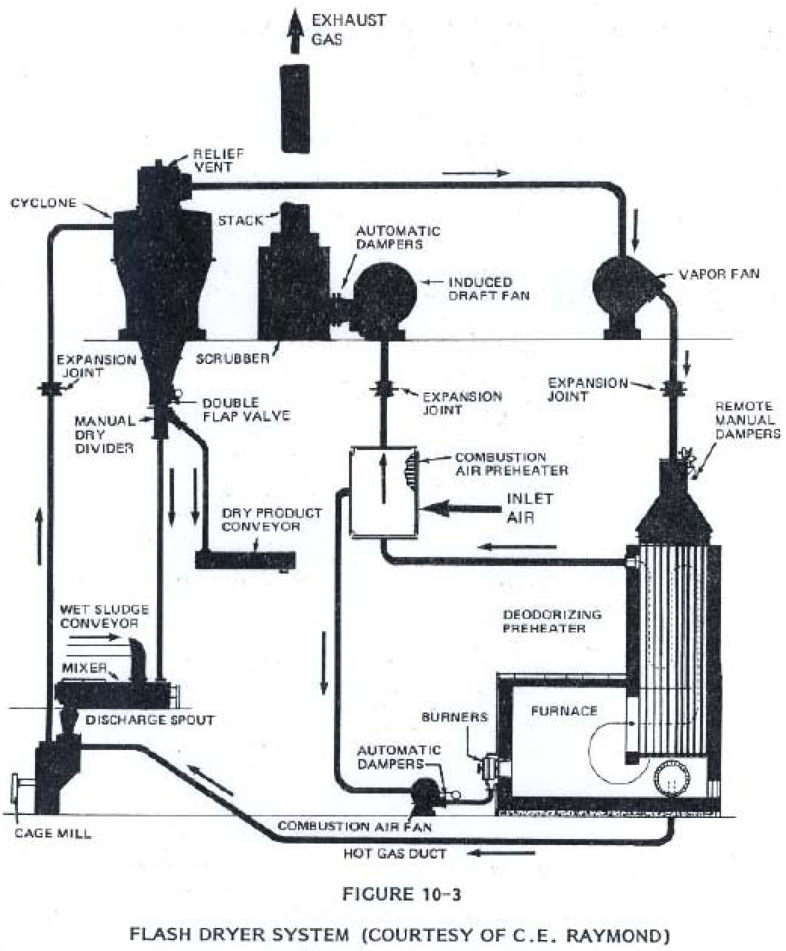

Figure 2.4 Flash dryer system.

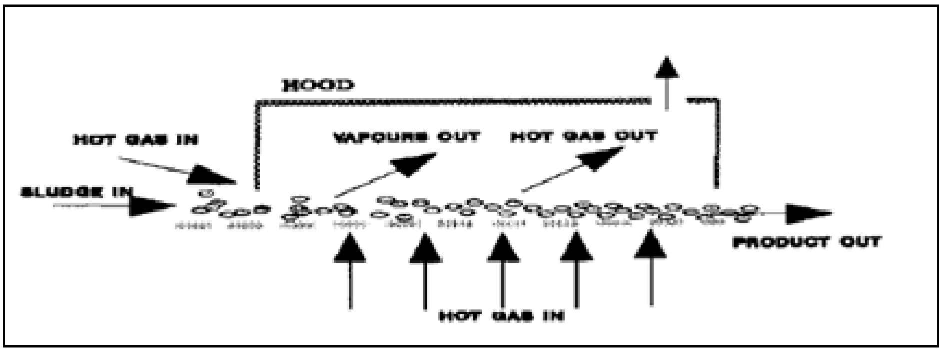

Figure 2.5 Belt Dryer (Lowe, 1995).

2.5.2 Indirect Dryers

In the indirect dryer systems, heat is transferred from the metal surface to the wet sludge cake. Heating medium (usually steam or oil) transfers the thermal energy onto the metal wall. Heating medium is separated by a metal wall. The solids particles have never come in direct contact with the heating medium (WEF-RBC-BTS, 2004; Bresters et al., 1997). The drying rate in the indirect dryer systems may be lower than that in the direct dryers due to the direct systems can operate at much higher temperatures (Chen et al., 2002).

The indirect dryers can be operated without air and produce less gas; most of their designs are done as a closed loop system with either heat recovery and/or odor removal units. The DS content of the dewatered sludge fed to the dryer should be around 25% DS. Therefore, mechanical agitation is important in the designing step since there is no airflow provided to disperse or disintegrate the sludge cake. Horizontal indirect dryers (paddle dryer, hollow-flight dryer and disk dryer) and vertical indirect dryers are used for sludge drying purpose. Depending on the requirement of the final water content of the dried sludge, single or two-stage indirect drying systems can be used (Chen et al., 2002; Bresters et al., 1997). Figure 2.6 shows the schematic diagram of a horizontal indirect dryer (Turovskiy and Mathai, ,2006) .

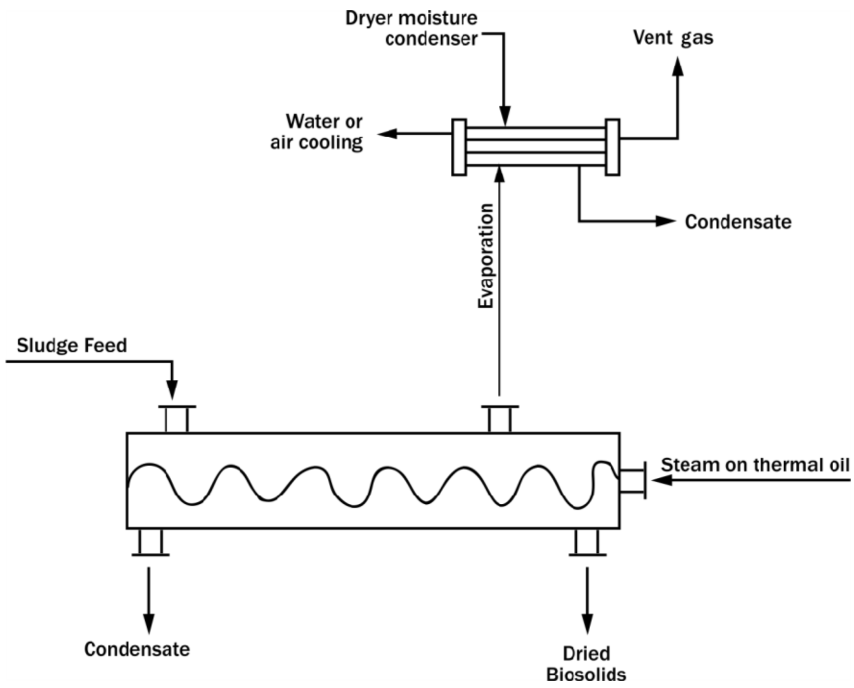

Figure 2.6 Schematic flow of horizontal indirect dryer system (Book of Wastewater Sludge Processing, Turovskiy and Mathai, 2006).

2.5.2.1 Horizontal Indirect Dryers

Horizontal indirect dryers consists of a horizontal jacked vessel with one or two rotating shafts fitted with paddles, flights, or disks, which agitate and transport the sludge through the dryer. The heat transfer medium (usually steam or oil) circulates through the jacketed shell and through the hollow-core shafts and hollow agitators (paddles, flights, or disks). Feed sludge moisture content can be reduced to 40-50% when it’s mixed with recycled-dried sludge. The dryers are able to get dried sludge with moisture contents down to less than 10%. Figure 2.7 shows the jacketed hollow-flight dryer (Turovskiy and Mathai, 2006; Chen et al., 2002; Process design manual,U.S ,1979).

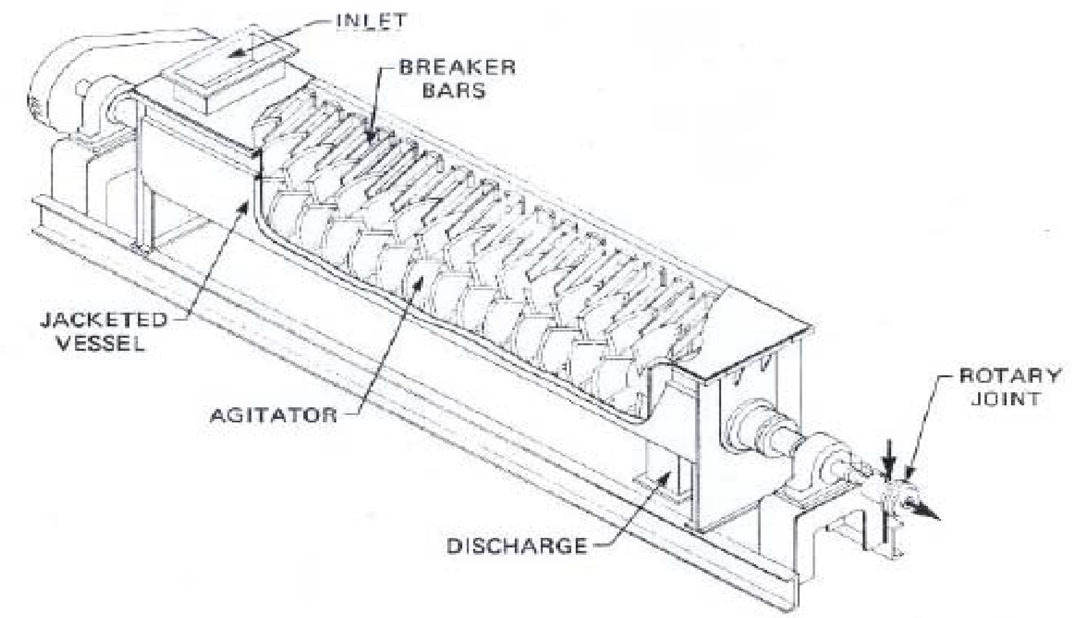

Figure 2.7 Jacketed hollow-flight dryer (Courtesy Bethlem Coporation) .

2.5.2.2 Vertical Indirect Dryers

A vertical indirect dryer simultaneously dries and pelletizes sludge material. It is a multi-stage tray dryer, which is oriented vertically shown in Figure 2.8. The sludge is fed into the top and moved between heated trays. The trays are heated by steam or thermal oil in a cloosed loop system to achive moisture content 10% or less (Turovskiy and Mathai,2006; Chen te al., 2002).

2.5.3 Combined Dryer Systems

Combined dryer systems are used as a combination of conduction and convection heat transfer methods together or use different drying mediums. The most common and important combined dryer type is fluidized bed dryer.

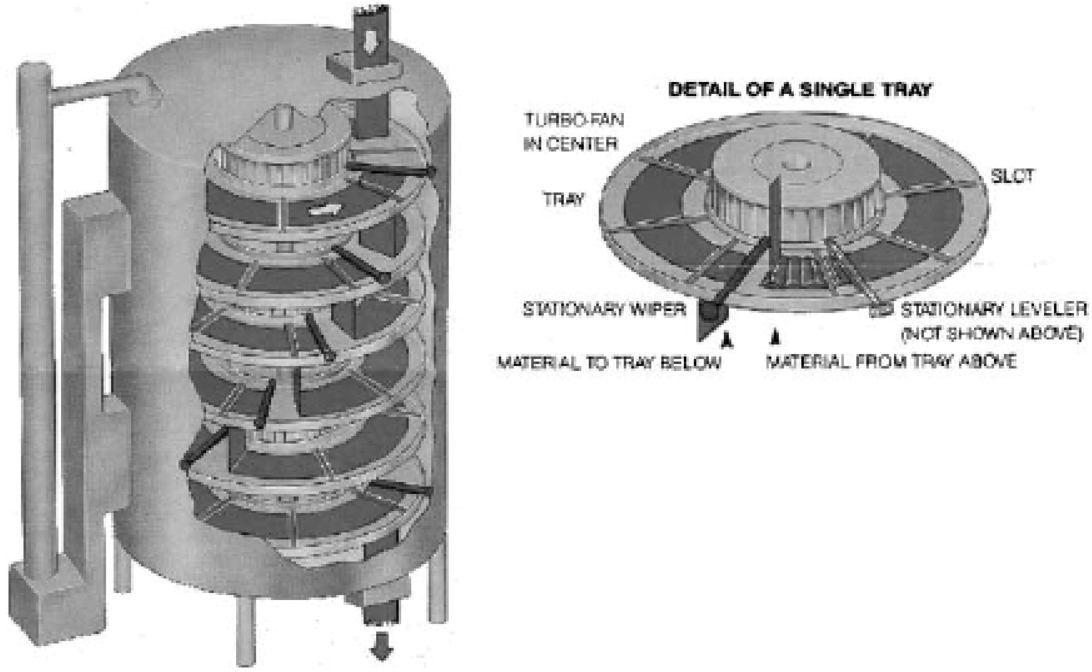

Figure 2.8 Vertical multi-tray dryer (Courtesy of Wyssmont Co. Inc., Chen et al., 2002).

2.5.3.1 Fluidized Bed Dryer

Fluized bed dryers can be characterized by an upward flow of hot gases carring the sludge particles. Resulting of a turbulent gas flow, the granules become a free-floating and mixed, simultaneously. Depending on sludge characteristics, more than 90% DS can be achived.An example of the fluized bed dryers is shown in Figure 2.9 (Bresters et al., 1997; Turovskiy and Mathai., 2006 Wastewater Sludge Processing; Chen et al., 2002; Idswater, 30.08.2011).

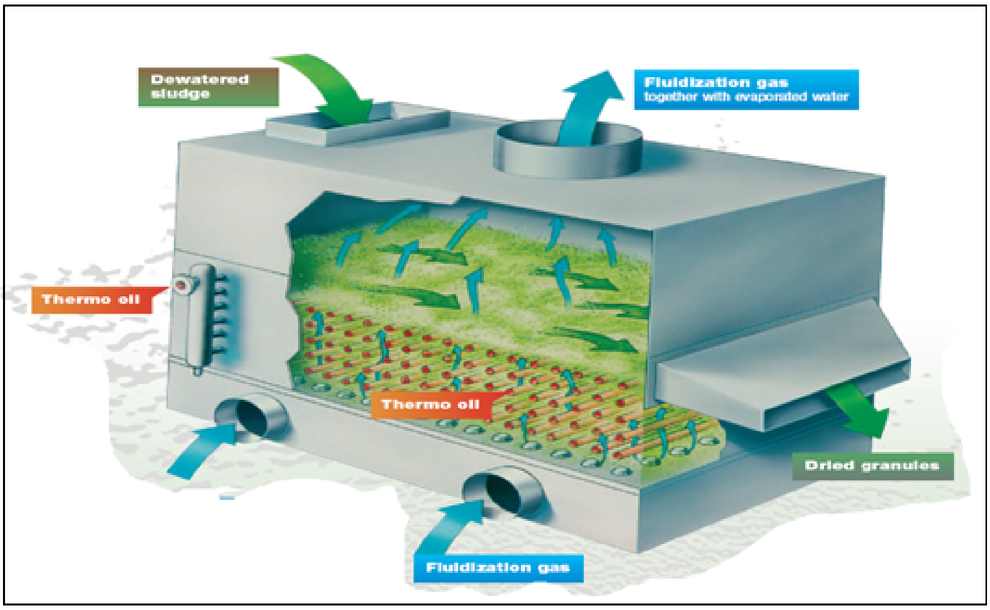

Figure 2.9 Fluid Bed Dryer System (By Andritz Technology, http://www.andritz.com/ep-thermal-brochure-fds-e.pdf).

2.5.4 Solar Drying

Solar drying is a cost-efficient option using freely available solar energy. These systems can be open air as in sludge drying beds and/or sludge lagoons and closed system as in the greenhouses.

Figure 2.10 shows a drying process of the greenhouse systems. The drying occurs difference between the partial vapor pressure inside the sludge and the ambient air. Open-air drying beds are ventilated by wind and it affects drying rate. The efficient ventilation systems developed for the greenhouses.

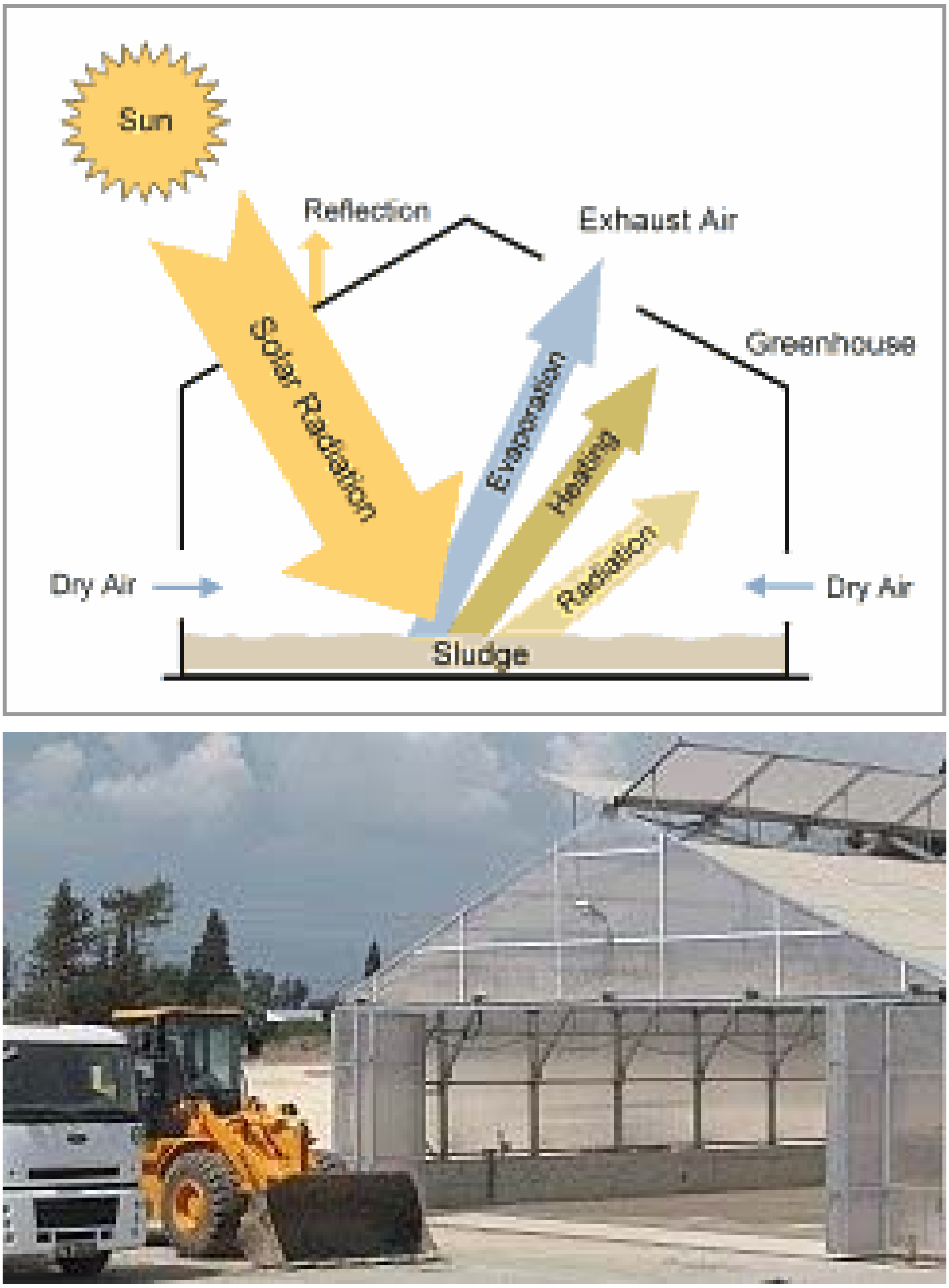

Figure 2.10 (a) greenhouse drying process; (b) greenhouse facility in Mugla, Turkey. (Wendewolf, 2011).

CHAPTER THREE
LITERATURE BACKGROUND ON FRY-DRYING TECHNOLOGY

3.1 Introduction

This chapter gives information about fry-drying technology, which is an alternative process to thermal drying of sewage sludge.

3.2 Fry-Drying Studies

Frying is one of the oldest processes used in the food industry. In this process, the material contacts with hot oil and simultaneous heat and mass transfer occur (Moreira et al., 1999). In food industry, frying is applied with oil in the temperature range between 120°C and 180°C. The high heat transfer rate during frying allows the moist surface of the product to be dried in a few seconds. With adequate temperature conditions in the oil bath, an evaporative front migrates towards the centre of the product, with the formation of an outer layer of dried crust, partial impregnation of the oil and a number of chemical reactions (Saguy et al., 1998.)

Silva et al. (2003, 2005) used frying technique with fresh and used oil. This was the first reported systematic work about drying sewage sludge with frying technology. These experimental tests were carried out by immersing the cylindrical shaped sludge (20-26mm diameter and 40 mm length) using the 5 L commercial fryer in the heated oil ranged from 190 °C to 215 °C. In their work, after 600 s of frying sludge reached less than 5% moisture and the heating value increased to 24 MJ/kg DS (5736 cal/g DS). Figure 3.1 shows heat combustion values of samples, which fried different time periods at the same temperature (180°C). The point time zero shows air-dried sample in an oven at 110°C for 24 hours. The heating value of the fried sludge increased with the frying time due to the loss of moisture and the incorporation of oil Silva et al. (2005).

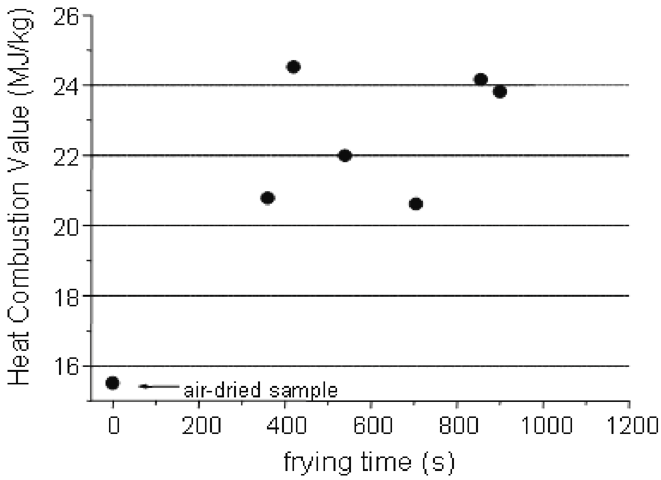

Figure 3.1 Heat of combustion of the sludge samples fried for different lengths of times. Toil = 180ºC.

Peregrina et al. (2006) worked on fry drying with recycled cooking oils (RCO) and cylindrical shaped sludge (diameter 15mm -25mm). They used immersion fry-dryer with a maximum capacity 5L and temperature between 120°C and 180°C. Experimental test were carried out with a customized household fryer, which can online weight measuring. Continuous measurement method performed by online weighing fryer that measured the moisture loss due to water evaporation. Figure 3.2 shows the experimental setup details for obtaining the mass and temperature data to analyze the heat and mass transfer. The selected fry-drying conditions were evaluated (i.e., oil temperature, initial moisture content, and diameter of the sample) in order to understand their influence on the fry-drying kinetics. Experimental results from this work showed that the fry-drying was affected only for a range of temperature (i.e., 120 to 160 °C); beyond this limit heat transfer was mainly controlled by internal conduction phenomena. They found that the optimal frying temperature was comprised between 140 and 160 °C. It was also observed that a reduction from 5.8 to 4.7 kg water/ kg of original total dry solids does not significantly reduce the fry-drying time. However, it was reported that the transition between the different fry-drying periods occurred at different critical moisture contents. Regions as an image and schematized regions within the cross section of a partially fry-dried sample are given Figure 3.3. It was concluded that the fry-drying of sewage sludge was sensitive to the thickness of the sample during the first part of the process. On the other hand, the bound moisture was not sensitive to the geometric conditions. This work recommended that the technologically smallest sample diameter should be used during fry-drying of sludges (Peregrina et al., 2006).

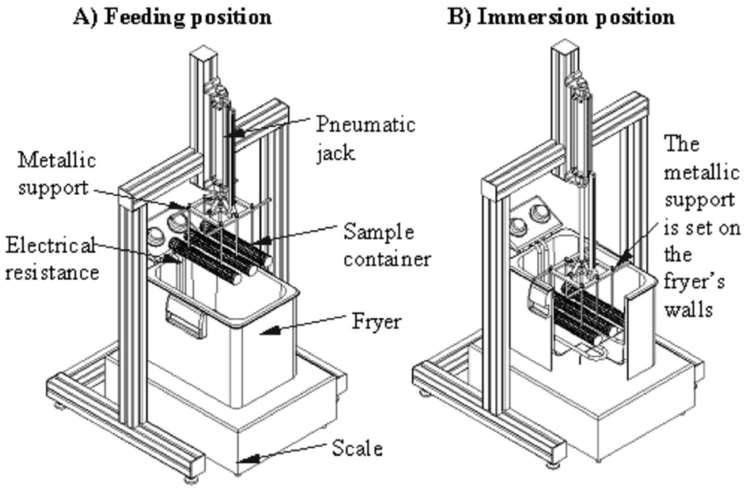

Figure 3.2 Experimental setup details. (Peregrina et al., 2006).

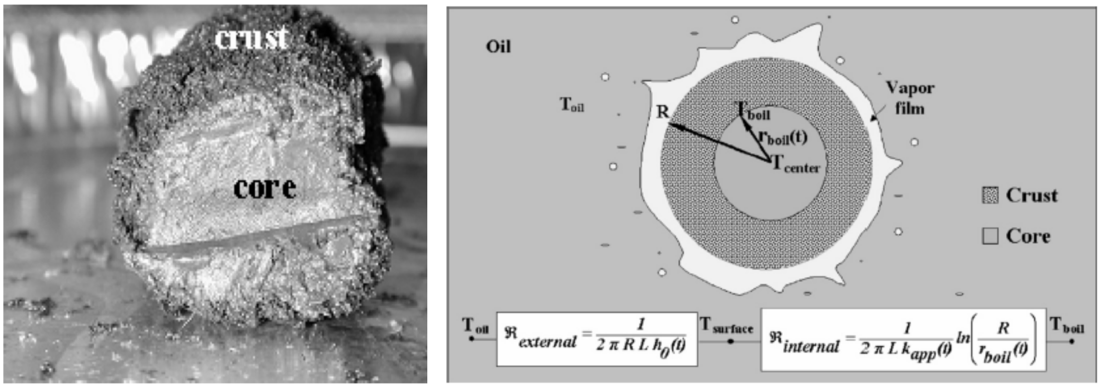

Figure 3.3 Regions as an image and schematized regions within the cross section of a partially fry-dried sample (Peregrina et al., 2006).

Ohm et al. (2009) worked with three kind of industrial wastewater sludge at oil temperature between120°C and 170°C for 10 min. Figure 3.4 shows the fry-drying system used for the experimental tests. This system is divided into three parts: the first part consists of sludge feeding equipment, which inputs sludge to the evaporative drying tank. Sludge fed by a sludge injector, which pushes the sludge through 10mm. diameter, five holes. The second part is the fry-drying tank. The tank is 1.8 m in length, 1.2 m in height, and 1.0 m width and also a round screw drum attached. Screw drum feeder controls the sludge fry-drying time. Third part is the condenser where steam, oil and volatile organic compounds (VOCs) are separated into condensed liquids and VOCs. The equipment can treat 50-100 kg sludge in 1h with regarding to process takes 10 min. from feeding to outputting of the dried sludge. The water contents of sludge samples from chemical, leather and plating plants were reduced from 80.0 to 5.5%, 81.6 to 1.0%, and 65.4 to 0.8%, respectively. The analyses results from this work are summarized in Table 3.1.

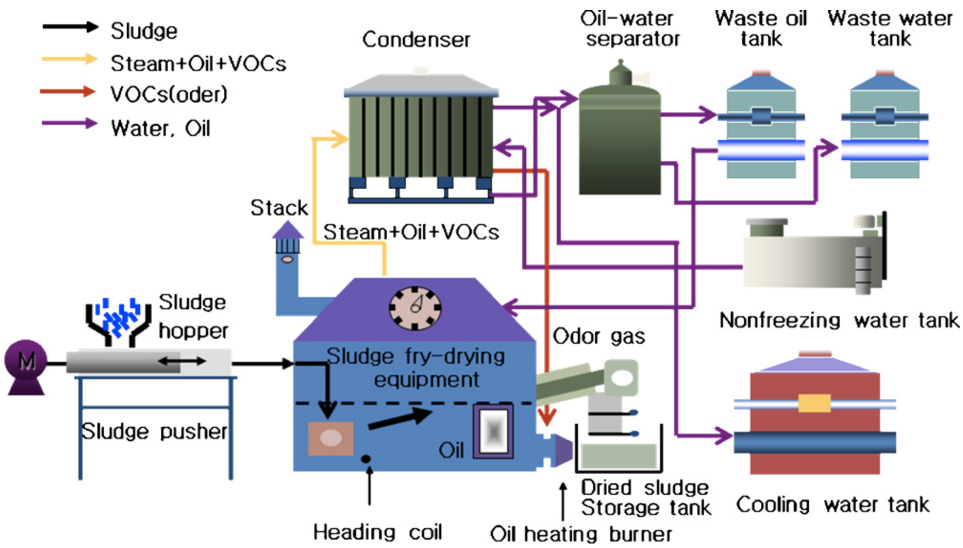

Figure 3.4 Fry-drying system (Ohm et al., 2009).

Table 3.1 Analysis of industrial sludge (Ohm et al., 2009).

Sludge	Item	Moisture (wt.%)	Ash (wt.%)	Fixed carbon (wt.%)	Volatile matter (wt.%)
Chemical plant	Before drying	80.0	7.8	2.3	9.9
	After drying	5.5	22.5	38.0	34.0
Leather plant	Before drying	81.6	8.1	1.5	8.8
	After drying	1.0	21.0	51.3	26.7
Plating plant	Before drying	65.4	15.0	3.6	16.0
	After drying	0.8	20.5	51.7	27.0

As a result of the high heating value analysis, these values increased from 217 to 428 kcal/kg before drying to 5317–6031 kcal/kg DS after drying. Figure 3.5 shows the drying curve of the moisture content 78% sludge in the frying equipment with the 140°C heated waste oil. It shows that the constant rate period is relatively longer and falling rate period is shorter than other drying technologies. The dried sludge water content is 2.0% for 8 min. of the drying time.

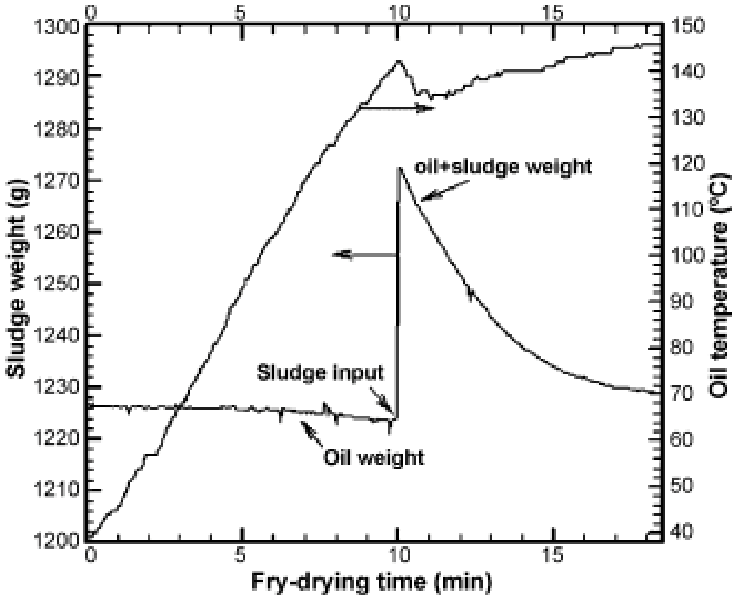

Figure 3.5 Drying curve of sludge in fry-drying equipment (Ohm et al., 2009).

The other work of Ohm et al. (2010) is oil type and temperature effects on the sludge fry-drying process. In this work, sewage and leather plant sludge were fry-dried for 10 min. using four different oils (waste engine oil, waste cooking oil, refined waste oil, and B-C heavy oil.) at three different temperatures (140°C, 150°C, and 160°C). The water content of sewage sludge fry-dried for 10 min at 150 ◦C was reduced from 78.9% to 3.8% with waste engine oil, 1.5% with waste cooking oil, 1.7% with refined waste oil, and 1.6% with B-C heavy oil.. For leather plant sludge dried under similar conditions, the reduction in water content was from 81.6% to 2.7% with waste engine oil, 1.0% with waste cooking oil, 6.5% with refined waste oil, and 1.6% with B-C heavy oil. Also they found the drying constant rate period length chances oil as: refined waste oil > waste engine oil > B-C heavy oil > waste cooking oil.

Table 3.2 Analysis of sewage sludge (oil temperature at 150°C) (Ohm et al., 2010).

Component:Frying oils	Moisture (wt.%)	Ash (wt.%)	Fixed carbon (wt.%)	Volatile matter (wt.%)	Low heating value (kcal/kg)
Raw sludge	78.9	8.5	3.4	9.2	626
Waste engine oil	6.0	24.2	5.0	64.8	5501
Refined waste oil	5.5	24.0	5.1	65.4	5795
Heavy oil (B-C)	5.1	23.6	5.4	65.9	5875
Waste edible oil	4.8	24.1	4.9	66.2	5459

Romdhana et al. (2009) investigated the energy enhances of sewage sludge using a batch fry-drying process. Experimental tests were carried out with cylindrical samples with diameters 4mm, 8mm, and 12mm and recycled cooking oil at temperatures 110°C, 120°C, 130°C, and 140°C. Moisture loss and oil uptake mass transfer took place during frying sewage sludge. Oil uptake improved the heating value of fry-dried sludge. Sludge heating value rose from 6 MJ/ kg DS (1424 cal/g DS) to 24 MJ/ kg DS (5736 cal/g DS) after fry-drying process. Figure 3.6 shows sludge lower heating values during the process.

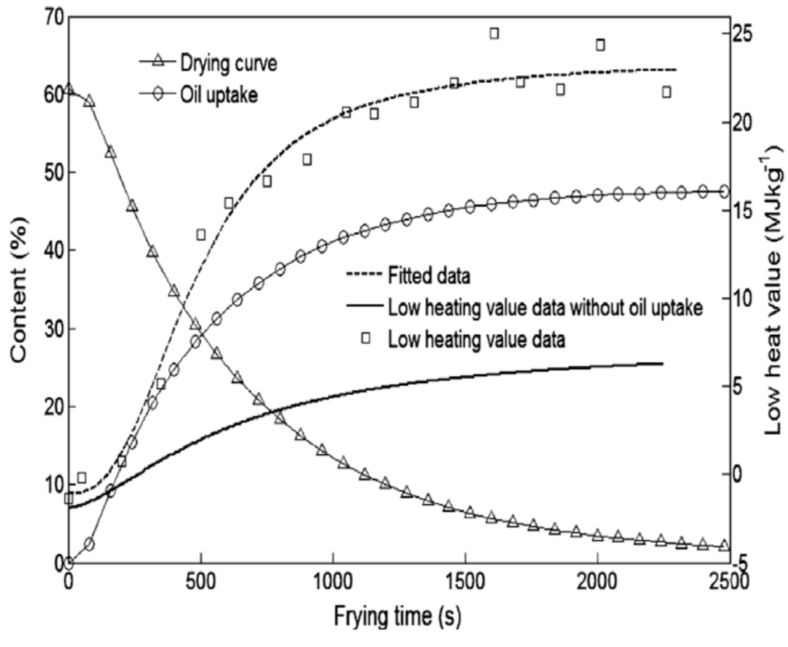

Figure 3.6 Lower heating values in process time (Romdhana et al., 2009).

Park et al. (2010) performed the laboratory tests using vacuum evaporation and fry-drying technology in a batch-type rotary evaporator. Figure 3.7 shows the laboratory-scale batch-type evaporator consisting of a vacuum evaporator, rotary mixing system, and temperature controller. They chose the optimal operating conditions for drying sludge is 450 mmHg of vacuum, a temperature of 100°C, a drying time of 90 min, and a sludge/oil ratio of 1:1. Experimental results showed the moisture content reduced from 80% to less than 5%; volatile matter increased from 12.4% to 64.7%, and lower heating value (LHV) dramatically increased from −54.8 kcal/kg to 4044.7 kcal/kg as given in Figure 3.8.

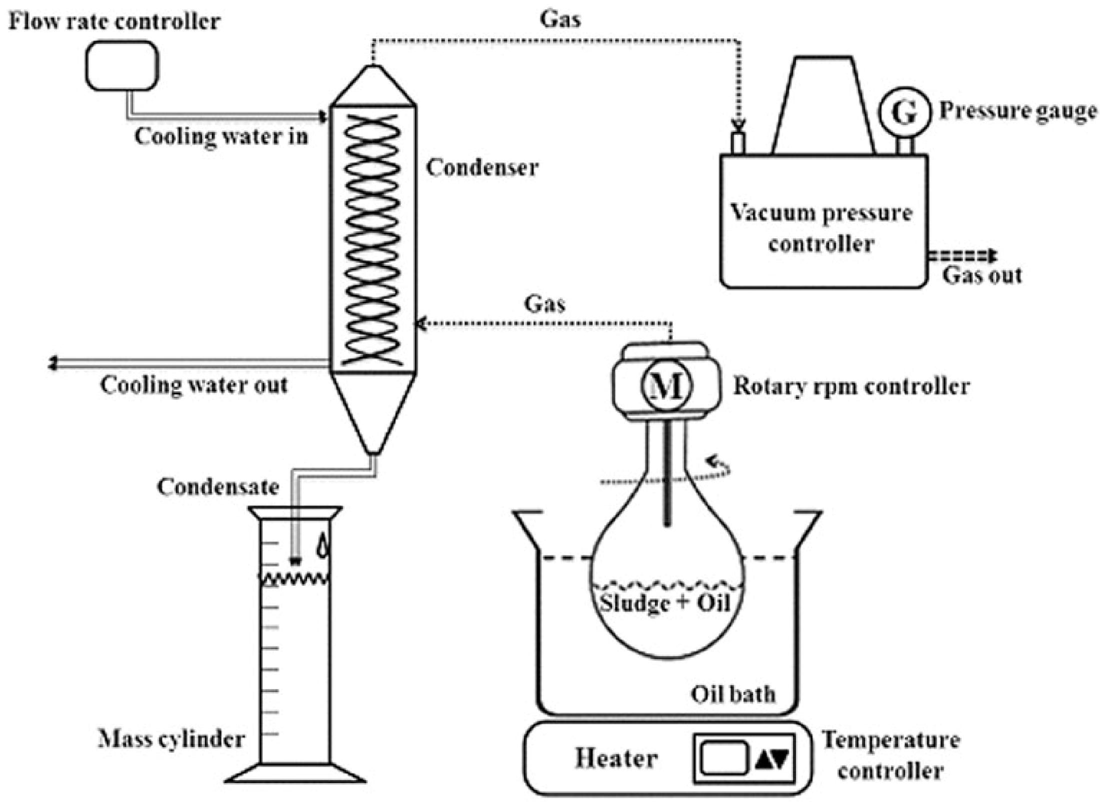

Figure 3.7 Batch type experimental set up (Park et al., 2010).

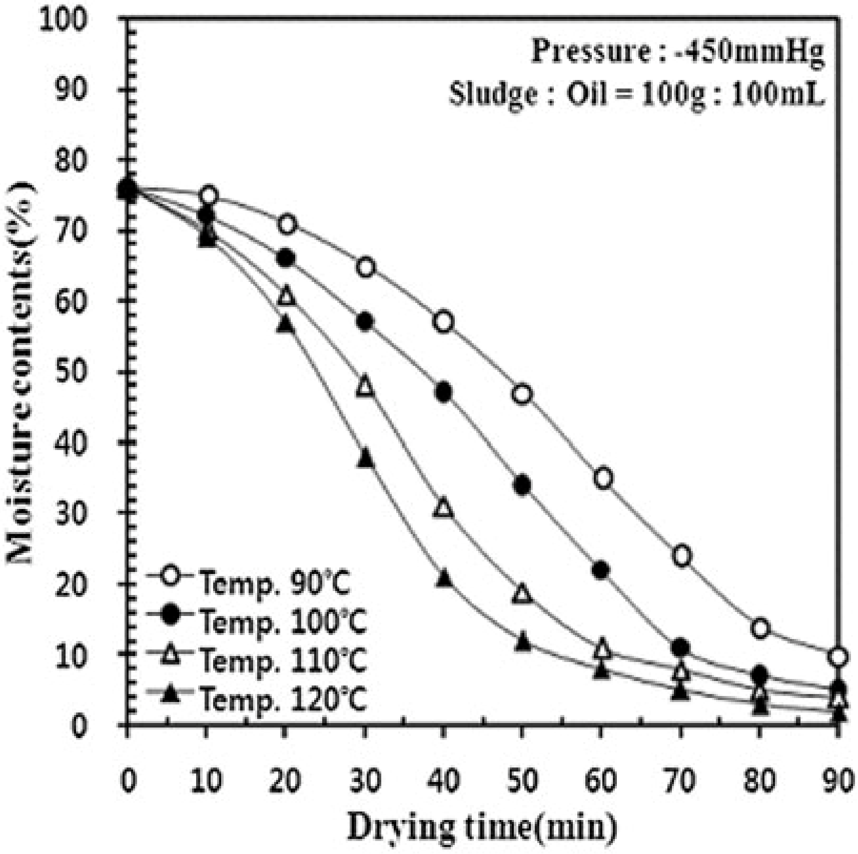

Figure 3.8 Drying behavior with oil temperature (Park et al., 2010).

CHAPTER FOUR
MATERIALS AND METHODS

4.1 Introduction

This chapter gives the information on the materials and methods used in this thesis. For sludge fry-drying experiments, the effects of drying time, temperature, and diameter of the sludge shaped as cylindrical were evaluated. In order to determine the effects of time, temperature, and diameter applied during fry-drying process, Box Wilson statistical experimental method was used for the optimization purpose.

4.2 Materials

4.2.1 Sludge Samples

Dewatered sludge cake samples used in this study was collected from Cigli Municipal WWTP, located in-Izmir, Turkey. The administration on water and sewage systems in City of Izmir (IZSU) is responsible for the operation of this plant. Cigli WWTP has advanced biological treatment units for nutrient removal and its treatment capacity is 7 m^3/sec. Approximately daily sludge cake production is 600 tons. Sludge are dewatered by 7 centrifuge decanters, which have120m^3/h capacity of dewatering and 150m^3/h thickening capacity. The sludge cakes are stabilized with lime and disposed in a special land-fill area (İzmir Waterworks Autority,28.02.2011). However, the binder for anaerobic sludge digesters and drying facility has recently been opened.

The sludge cake characterization studies were first done at the beginning of each experimental trial. pH, temperature, total dried solids content (DS) and volatile solids content (VS), heating (calorific) value were analyzed according to Standard Methods (APHA, 2005).

4.2.2 Oils

Two types of oil were used for fry-drying studies. The experimental series were performed with waste engine oil (WEO) and waste cooking oil (WCO). WEO was supplied from KIMTAS Inc., Izmir, while WCO was taken from the university restaurant of DEU. Figure 4.1 shows the WEO used in this study.

Figure 4.1 Waste engine oil.

4.3 Experimental Approach For Fry-Drying Procedure

The main experiment set up is a household fryer (Sinbo -SDF-3804 model) with a maximum capacity 1L (Figure 4.2). The deep fryer can run at 80 °C and 190 °C and heated with a 900W electrical resistance element. An American Weigh SM-501 Digital Pocket Scale was used to weigh the samples with and without oil before and after fry-drying experiments (Figure 4.3). The experimental set up also includes the modified cream pump, which was used for forming the raw sludge cakes as cylindrical samples (Figure 4.4). Raw sludge cake samples were first shaped as cylindrical samples, which those diameters ranged from 1mm to 3 mm. They were fried at different temperatures ranged between 100 °C and 180 °C at for different drying times between 2 min to 20 min. Also samples were weighted before and after fry-drying process by using sensitive tare. For the optimization of the process, drying temperatures, sample diameters, and fry-drying times were applied depending on the experimental statistical analysis-Box Wilson. After frying studies, the fry-dried products were subjected to the further analysis to determine the drying potential of the sludge cake samples using this process based on DS, VS, and lower heating value (LHV) analysis.

Figure 4.2 Sinbo SDF-3804 deep fryer.

Figure 4.3 American Weigh SM-501 Digital Pocket Scale.

Figure 4.4 Cream pump.

4.4 Methods Used In The Experimental Studies

4.4.1 Analytical Methods

The measured parameters of raw sludge were dry solids content (DS), water content (WC), volatile solids content (VS), pH, temperature, low heating value (LHV). Fry-dried samples were analyzed based on DS, VS, and LHV. All analyses as triplicates were done according to Standard Methods (APHA, 2005). In addition, oil uptake of the samples was determined.

4.4.1.1 Temperature and pH Measurements

WTW model 340i multi analyzer shown in Figure 4.5 was used for temperature and pH measurements.

Figure 4.5 WTW model 340i multi analyzer.

4.4.1.2 Dry Solids Content (DS), Water Content (WC), and Volatile Solids Content (VS) Analysis

Dry solids (DS) and water contents (WC) were analyzed by using an oven- Nuve FN 400 model (Figure 4.6). The dry solids content of raw sludge cake and fry-dried sludge samples were determined at 105±3 °C. In order to determine the dry solid contents of sludge cake and dried sludge samples, a method that depends on the gravimetric measurement was used as detailed in Standard Methods (APHA, 2005). The volatile solids content of the samples were determined by using a muffle oven - Nuve MF 120 model at 550 °C (Figure 4.7) . The gravimetric measurements of the sludge samples were done by a sensitive tare shown in Figure 4.8

Figure 4.6 FN 400 Nuve oven used in experimental studies.

Figure 4.7 Nuve MF120 muffle oven used in experimental studies.

Figure 4.8 Sensitive tare used in experimental studies.

4.4.1.3 Heating Value Analysis

IKA brand C200 model calorimeter (Figure 4.9) was used for determining the heating values of chosen samples, which were first dried and grinded before the measurements. This calorimeter is available in the coal laboratory of the Department of Mining Engineering at DEU.

Figure 4.9 Calorimeter IKA C200 used in experimental studies.

Approximately 0,5 g ground sample was weighted and placed in to the calorimeter's container. Oxygen was exposed 45 sec. as shown in Figure 4.9 after closing the lid of the container. Container was placed into the analyzer and read high heating value in dry base. High heating value in dry base was used for calculating high heating value in original base, low heating value in original base and low heating value in dry base. Statistica 7 software (Statistical program) was used for examine the results correlation among time, temperature, and diameter effects on the dryness and heating values.

The formulas for the calculating of low heating value in original base, high heating value in original base and low heating value in dry base are given below.

- *Low heating value in original base:*

$LHV_{original}$=(100-(A+B)/100)*X)-(6*A)
X=((C+6*D)*100)/(100-(D+E))

A: Moisture content in original base
B: Ash content in original base
C: Low heating value in dry base
D: Hygroscopic moisture content
E: Ash content in dry base

- *The low heating value in dry base*

LHV_{dry}=F-5,85*(9*((100-(D+E))/100)*5+D

F: High heating value in dry base

- *For the high heating value in original base:*

$HHV_{original}$= G+5,85*(9*((100-(A+B)/100)*5+A)

G:Low heating value in original base

4.5 Statistical Methods Used

The Box–Wilson statistical experimental design was employed to determine the effects of operating variables on water removal from the sludge. Time, temperature, and diameter were selected as operating parameters. Box Wilson statistical method was used to examine what extend these parameters effect the efficiency of the dry solid content and volatile solid content, and also heating value of sludge. Minimum and maximum points of the parameters were chosen to do the experimental design using Box Wilson method. The coded table for the method is arranged for the experimental studies (Table 4.1). The formulas of Box Wilson experimental design are given below.

Table 4.1 Coded Form.

Trial Number	X_1	X_2	X_3
1	+1	0	0
2	-1	0	0
3	0	+1	0
4	0	-1	0
5	0	0	+1
6	0	0	-1
7	+k	+k	+k
8	+k	+k	-k
9	+k	-k	+k
10	+k	-k	-k
11	-k	+k	+k
12	-k	-k	+k
13	-k	+k	-k
14	-k	-k	-k
15	0	0	0
16	0	0	0
17	0	0	0

n = variable number

0 = center point

+1 = maximum point

-1 = minimum point

$$\mp k = centerpo\text{int} \mp \left(\frac{\max - \min}{2\sqrt{n}} \right)$$

$$\text{Center point} = \left(\frac{\max + \min}{2} \right)$$

X1: time

X2: temperature

X3: diameter

Experiments were performed according to design k values and centre points. For results utilization STATISTICA 7 software was employed for the determination of the response function of non-linear estimation. The predicted and residual values ‘‘b’’ coefficients and regression value calculated by the program. The estimated (response) function that used by program was:

$$y=b_o + b_1X_1 + b_2X_2 + b_3X_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2$$

The experiments run as two sets by using WEO and WCO. Three important operating parameters: fry-drying time (X_1), temperature (X_2), and diameter (X_3) were chosen as independent variables as mentioned above. Fry-drying time (X_1) was changed between 2 and 20 minutes; temperature (X_2) was varied between 100 and 180 °C; and diameter (X_3) was from 1 to 3 cm. Experimental points for Box–Wilson statistical design were determined depending on the ranges of the operating parameters. Both experimental series for WEO and WCO used the same ranges. Experimental results and their evaluations are discussed in the following chapter.

CHAPTER FIVE
RESULTS AND DISCUSSION

5.1 Introduction

Application of fry-drying technology for the sewage sludge processing was investigated in this thesis. Experimental studies were carried out using dewatered sewage sludge cake and two kinds of waste oil: waste engine oil and waste cooking oil. To examine the fry-drying time, temperature, and diameter effects on sludge dryness and heating value; experimental test series were designed by Box Wilson statistical method. In the experimental studies, the fry-drying time range of 2-20 minutes, the temperature range of 100-180 °C, and the diameter range of 1-3 cm were selected for the operating parameters. This chapter presents the experiment results obtained from the both series.

5.2 Dewatered Sludge Cake Characteristics

Before starting experimentation, dewatered sludge cake characteristics were determined based on the pH, temperature, total solids content, volatile solids content, and heating value parameters. The characteristics of the dewatered sludge cake samples are given in Table 5.1. The image of the cake sample taken from Cigli MWWTP is shown in Figure 5.1.

Table 5.1 Dewatered sludge cake characteristics.

	pH	**Temperature, ◦C**	**Heating (Calorific) value, cal/gDS**	**DS, %**	**VS, %**
Experimental Study- I (WEO)	6.30	25 ◦C	2900	24.63	53.18
				25.27	53.36
				24.28	53.94
Experimental Study- II (WCO)	6.83	25 ◦C	3100	22.87	49.83
				23.07	56.78
				23.03	56.52

Figure 5.1 Dewatered sludge cake sample taken from outlet of the centrifuge decantor.

5.3 Results of the Fry-Drying With Waste Engine Oil

Three operating parameters: fry-drying time (X_1) ranged between 2-20 minutes, frying temperature (X_2) ranged between 100-180 °C, and sludge sample's diameter (X_3) ranged between 1-3 cm were chosen as independent variables: frying time (X_1) between 2-20 minutes, frying temperature (X_2) between 100 -180 °C and sludge samples diameter (X_3) 1-3 cm. Experimental data points used in Box-Wilson were given in Table 5.2. The experiments consisted of six axial (A), eight factorial (F) and one centre (C) point. The centre point was repeated three times to predict the experimental error.

Table 5.2 Experimental data points used in Box-Wilson.

Trial Number	Data points (A/F/C)	Time (X_1), min	Temperature (X_2), °C	Diameter (X_3), cm
1	A1	20	140	2
2	A2	2	140	2
3	A3	11	180	2
4	A4	11	100	2
5	A5	11	140	3
6	A6	11	140	1
7	F1	16	160	2.5
8	F2	16	160	1.5
9	F3	16	120	2.5
10	F4	16	120	1.5
11	F5	6	160	2.5
12	F6	6	120	2.5
13	F7	6	160	1.5
14	F8	6	120	1.5
15	C	11	140	2
16	C	11	140	2
17	C	11	140	2

The performance of the fry-drying process was described by the following response function:

$$Y=b_o + b_1X_1 + b_2X_2 + b_3X_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2$$

Where; Y is the predicted response function (percent DS,VS or heating value), b_0 is the offset term. b_1 ,b_2 ,b_3 are the linear coefficients; b_{12} ,b_{13} ,b_{23} are the cross product coefficients; b_{11} ,b_{22} ,b_{33} are the quadratic coefficients.

A STATISTICA computer program (Statistica 7.0) was employed for the determination of the coefficients of the response functions by regression analysis of the experimental data. The response functions with the determined coefficients were used in calculating the predicted values of percent DS, percent VS, and heating value. The results are given in the following subsections.

5.3.1 Dry Solids Content Results of the Fry-drying Process with Waste Engine Oil

Experiments regarding the DS contents of dewatered sludge cake and fry-dried sludges were done according to the experimental data points determined by Box–Wilson statistical design as shown in Table 5.2.

The obtained DS results are given in Table 5.3. It is clear from this table, DS values increased with the increasing frying time and temperature and the decreasing cylinder diameter of the samples. For 2 cm sample diameter, the highest DS content was obtained as 93.60% at 180 °C for 11 min. of fry-drying time. The relationships between the frying time, temperature and sample's diameter are discussed in details in this subsection.

Table 5.3 DS results of raw sludge and fry-dried sludge with WEO.

Time (X_1), min	**Temperature (X_2), °C**	**Diameter (X_3), cm**	**DS (%)**
No frying time	25	Dewatered sludge cake	24.73
20	140	2	68.49
2	140	2	38.63
11	180	2	93.60
11	100	2	42.24
11	140	3	41.20
11	140	1	86.84
16	160	2.5	65.32
16	160	1.5	97.26
16	120	2.5	51.18
16	120	1.5	80.10
6	160	2.5	55.39
6	120	2.5	40.63
6	160	1.5	81.98
6	120	1.5	48.60
11	140	2	68.40
11	140	2	61.78
11	140	2	50.49

Figures 5.2 and 5.3 indicated the effects of cylinder diameters on dry solids results at 140 °C for 11 min. of fry-drying time and at 120 °C for 6 min. of fry-drying time, respectively. Frying at the same conditions for the samples having different diameters showed that the smaller diameter samples were dried better then the higher

diameter samples. Peregrina et al. (2006) have reported that fry-drying of sewage sludge is sensitive to the thickness of the sample; however, the bound moisture is not sensitive to the geometric conditions. According to their results, fry-dry the sludge using the technologically smallest sample diameter should be applied. In this study, the similar results were also achieved.

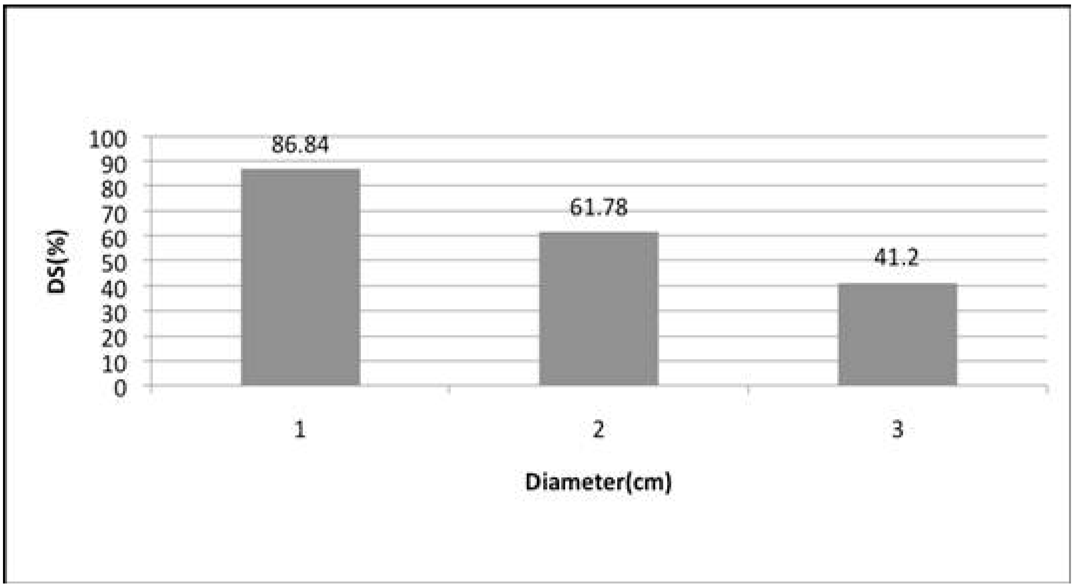

Figure 5.2 Effects of sample's diameter on DS results at 140 °C for 11 minutes fry-drying.

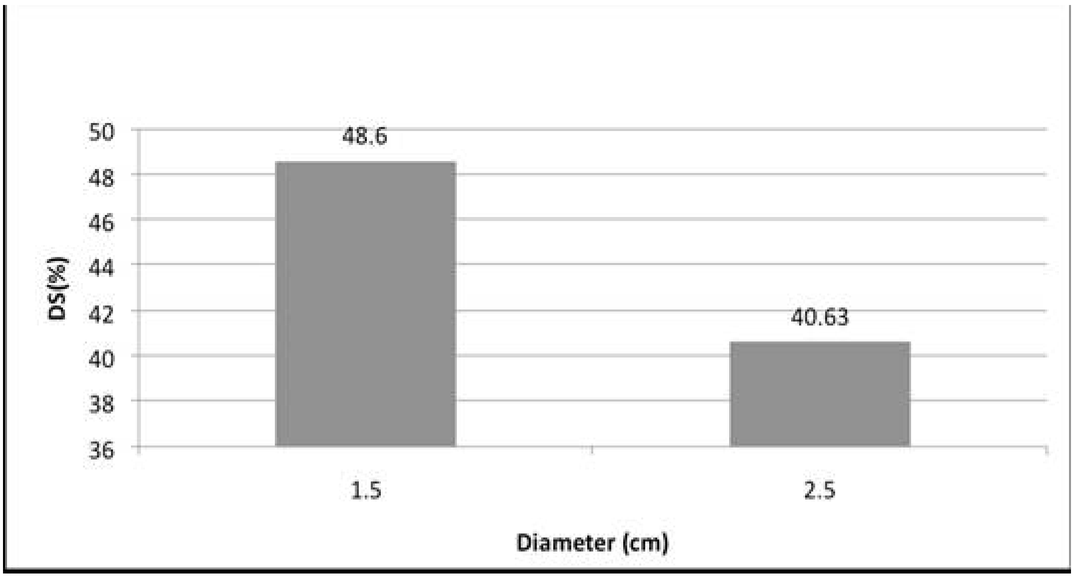

Figure 5.3 Effects of diameter on DS results at 120 °C for 6 minutes fry-drying.

Temperature is another important parameter affecting the DS results. Figure 5.4 shows the DS results for the fry-drying applied samples having 2 cm diameter at different temperatures for 11 min. As seen from the figure, the higher oil temperatures led to higher DS contents of the sludge samples.

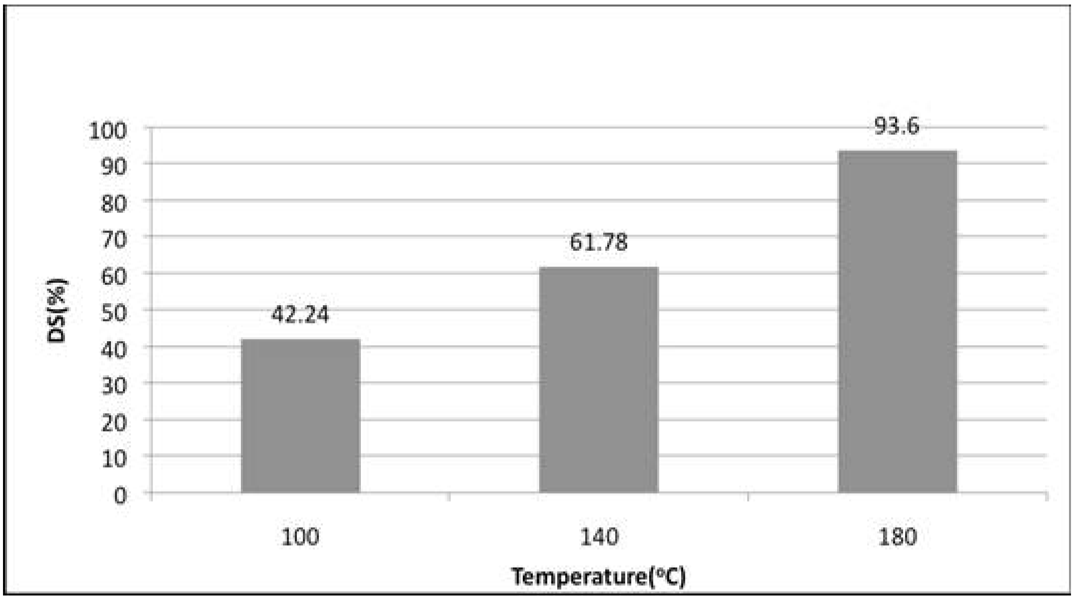

Figure 5.4 DS results fry-dried 2 cm. samples for 11 minutes at different temperatures.

Figure 5.5 presents the DS results of fry-dried 2 cm. samples at 140°C for 2,11, and 20 min. of frying time. DS contents of the sludge samples results increased with the increasing frying time. However, the drastically increases in DS were obtained between 2 and 11 min. of frying, while it was slightly different for the frying applications between 11 and 20 min.

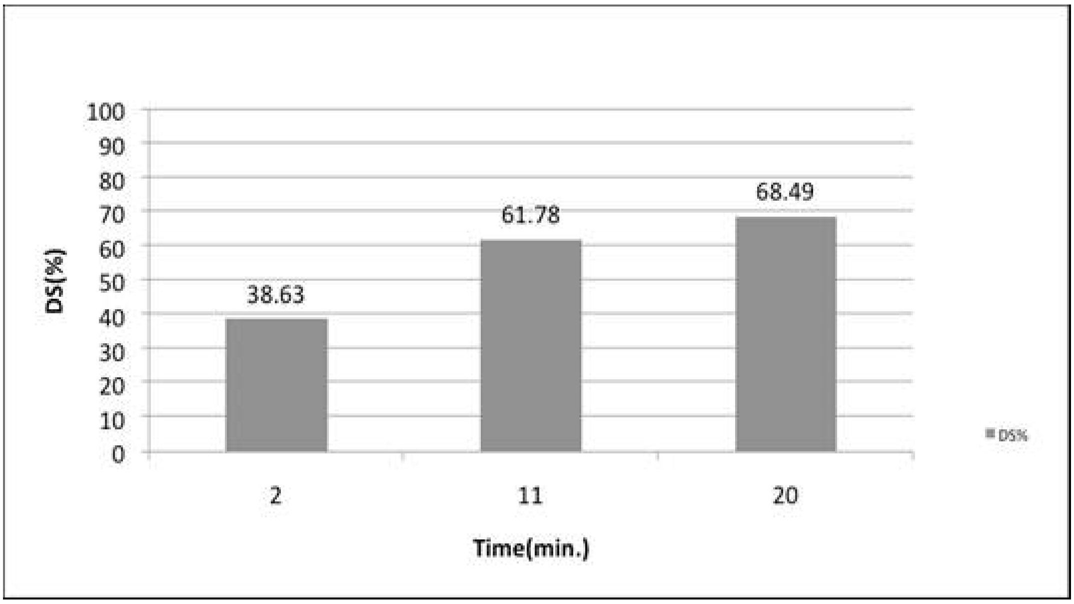

Figure 5.5 Effects of time on DS results on fry-dried 2 cm. samples at 140 °C.

Figure 5.6 shows DS results of 1.5 and 2.5 cm. samples fry-dried at 120 °C and 160 °C for 16 min. Figure 5.7 presents DS results of 1.5 and 2.5 cm. samples fry-dried at 120 °C and 160 °C for 6 and 16 min. It is clear from the figures, DS contents of the samples having smaller diameters were higher than those having bigger diameters. At the same oil temperature conditions, DS increased depending on the increases in the time and temperature.

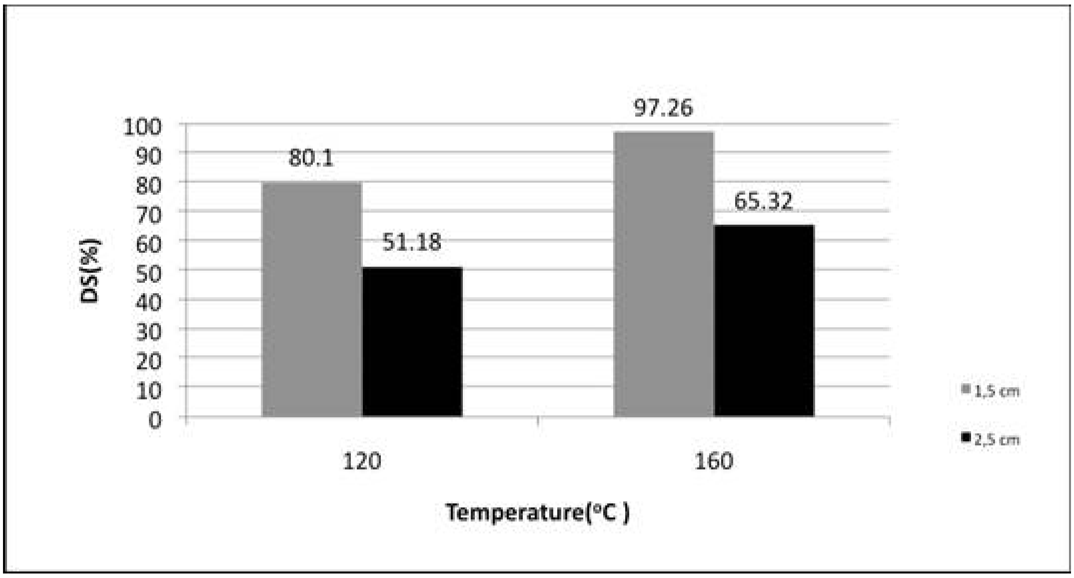

Figure 5.6 Effects of diameter and temperature on DS results fry-dried samples for 16 minutes.

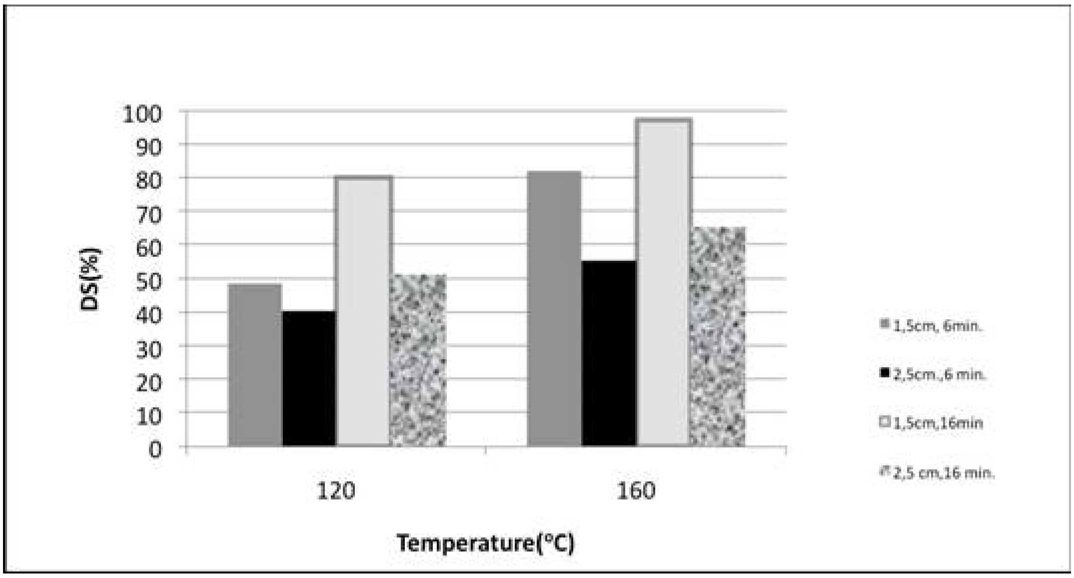

Figure 5.7 Effects of time, diameter and temperature on DS results.

Depending on the experimental data obtained, the DS response function was calculated by Statistica 7 program. Table 5.4 shows the estimated coefficients of the response function. The regression coefficient was achieved as R^2=0.97496844. The predicted and residual values for dry solids content of fry-dried samples were also summarized in Table 5.5.

Table 5.4 DS response function coefficients.

bo	b1	b2	b3	b12
-9.34616	8.65954	-0.17903	9.81548	-0.02105
b13	b23	b11	b22	b33
-1.31466	-0.27043	-0.06416	0.00543	4.79188

Table 5.5 Predicted and residual values for dry solids content of fry-dried samples with WEO.

Temperature (°C)	Time (min)	Diameter (cm)	Predicted	Residuals
20	140	2	71.10909	-2.6205
2	140	2	41.01977	-2.3924
11	180	2	92.71752	0.8806
11	100	2	47.18410	-4.9411
11	140	3	42.71440	-1.5127
11	140	1	89.39253	-2.5477
16	160	2.5	63.00376	2.3165
16	160	1.5	98.32482	-1.0643
16	120	2.5	49.85576	1.3291
16	120	1.5	74.35944	5.7449
6	160	2.5	57.07080	-1.6844
6	120	2.5	35.50275	5.1248
6	160	1.5	79.24525	2.7314
6	120	1.5	46.85982	1.7439
11	140	2	61.26158	-10.7652
11	140	2	61.26158	0.5147
11	140	2	61.26158	7.1424

DS results as a function of temperature at different frying times for different sample diameters as 1, 1.5, 2, 2.5, 3 cm are shown in figures between 5.8 and 5.12. DS contents of the samples having 1 and 1.5 cm diameters were the highest values and also DS increased for all applications with the increasing time and temperature.

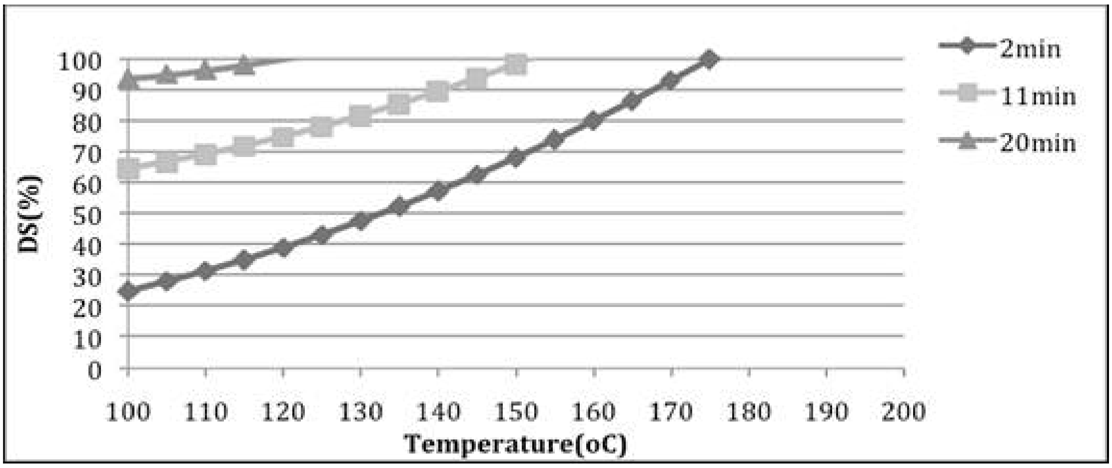

Figure 5.8 DS content curves for 1cm. diameter sludge samples fried for three different process times.

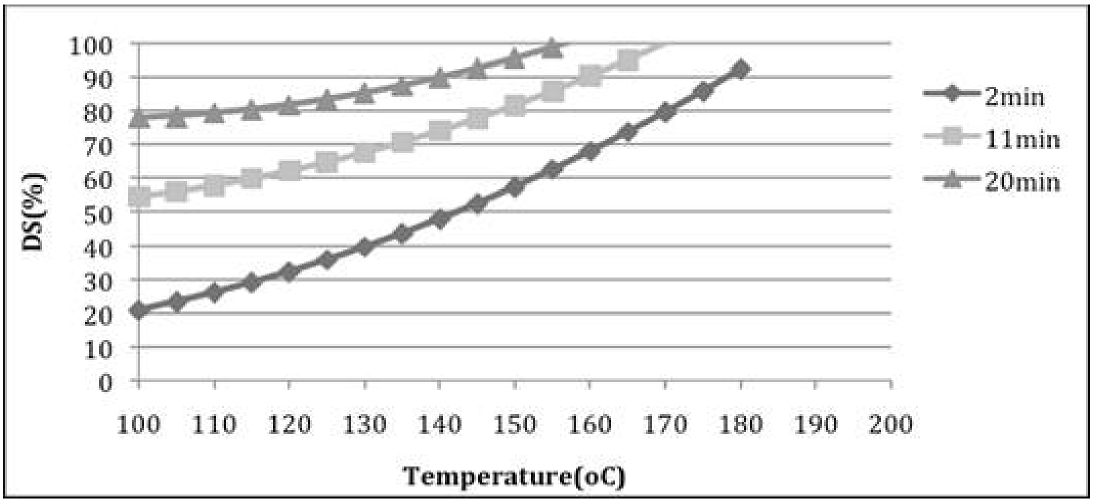

Figure 5.9 DS content curves for 1.5cm diameter sludge samples fried for three different process times.

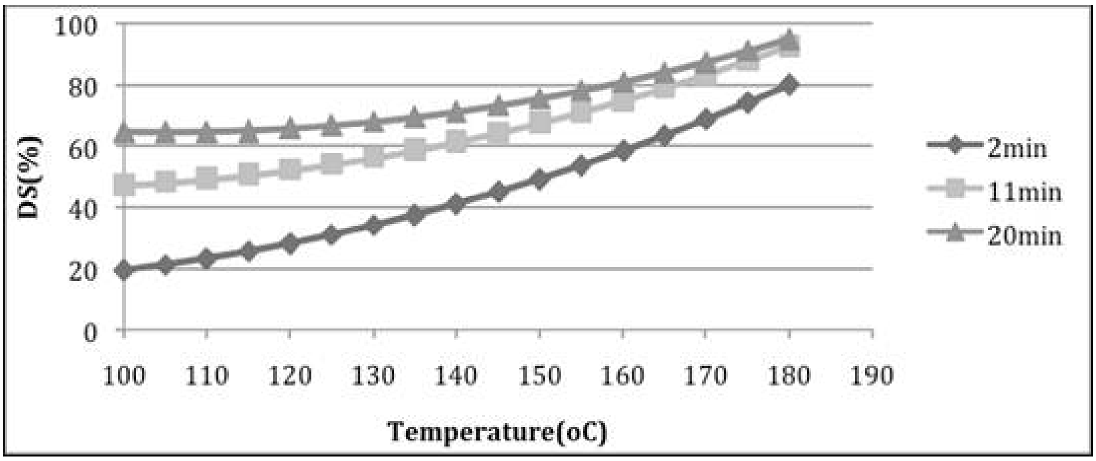

Figure 5.10 DS content curves for 2cm diameter sludge samples fried for three different process times.

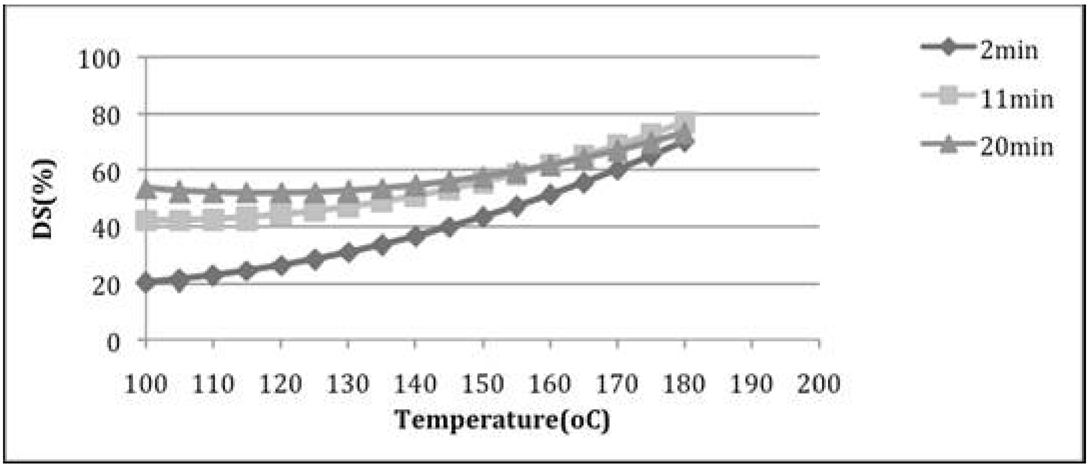

Figure 5.11 DS content curves for 2.5cm diameter sludge samples fried for three different process times.

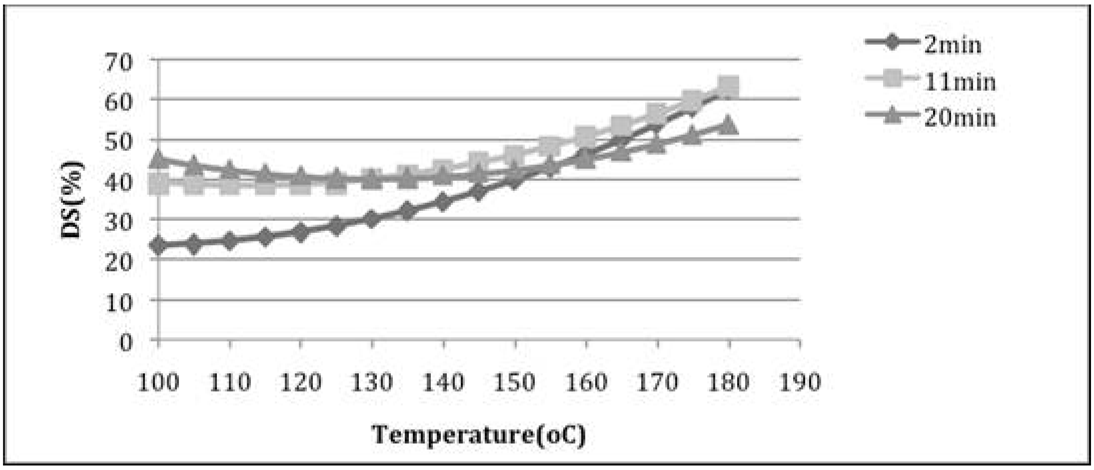

Figure 5.12 DS content curves for 3cm. diameter sludge samples fried for three different process times.

Figures 5.13- 5.17 showed the DS results as a function of frying time at different temperatures and different sample diameters. For the samples having 1 and 1.5 cm diameter, a few minutes of frying time was enough to reach the DS higher than 90% at 180 °C of the oil temperature. Lowest temperature application at 100 °C did not produce higher DS content as well as the temperature range in 140-180 °C. Similar observations were obtained in the literature (e.g., Peregrina et al., 2006; Romdhana et al., 2009).

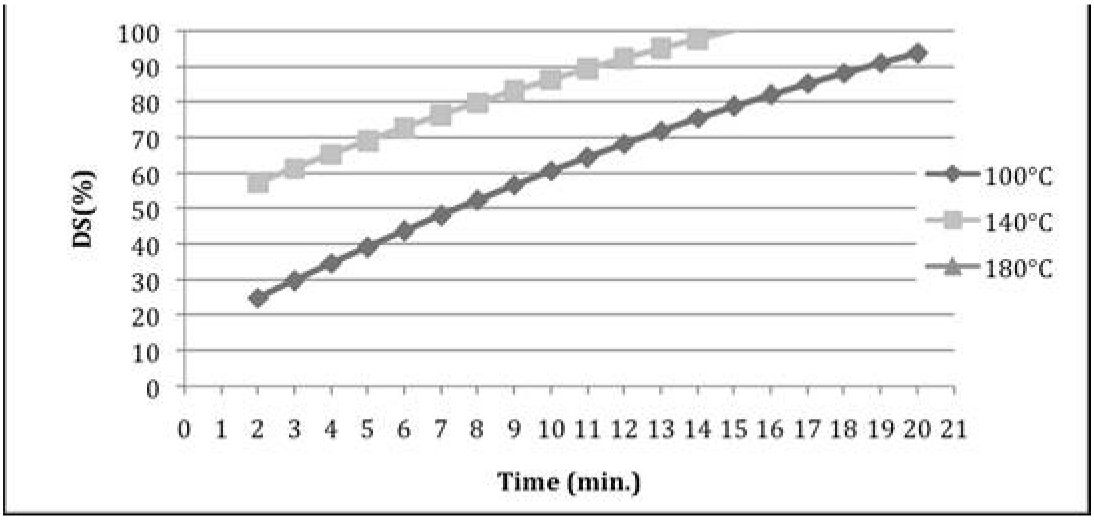

Figure 5.13 DS content curves for 1cm. diameter sludge samples fried at three different temperatures.

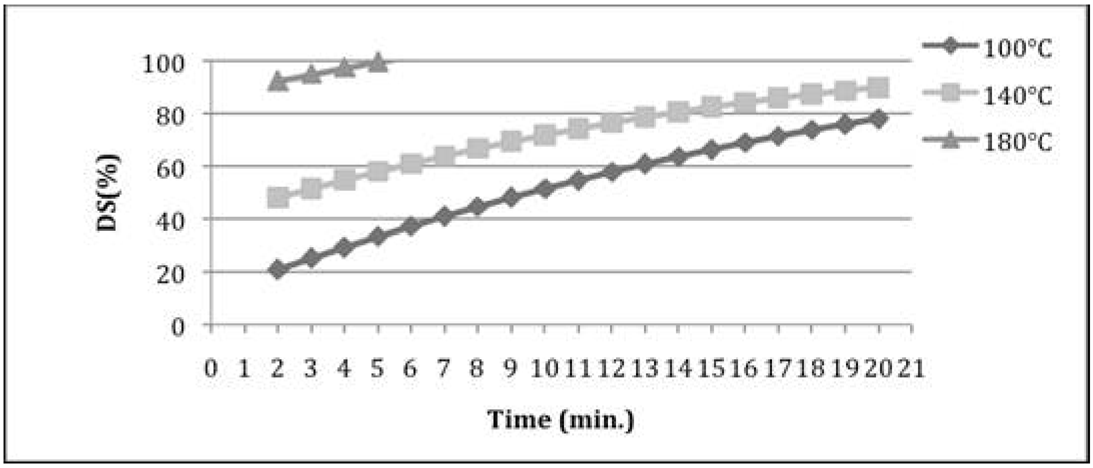

Figure 5.14 DS content curves for 1.5cm diameter sludge samples fried at three different temperatures.

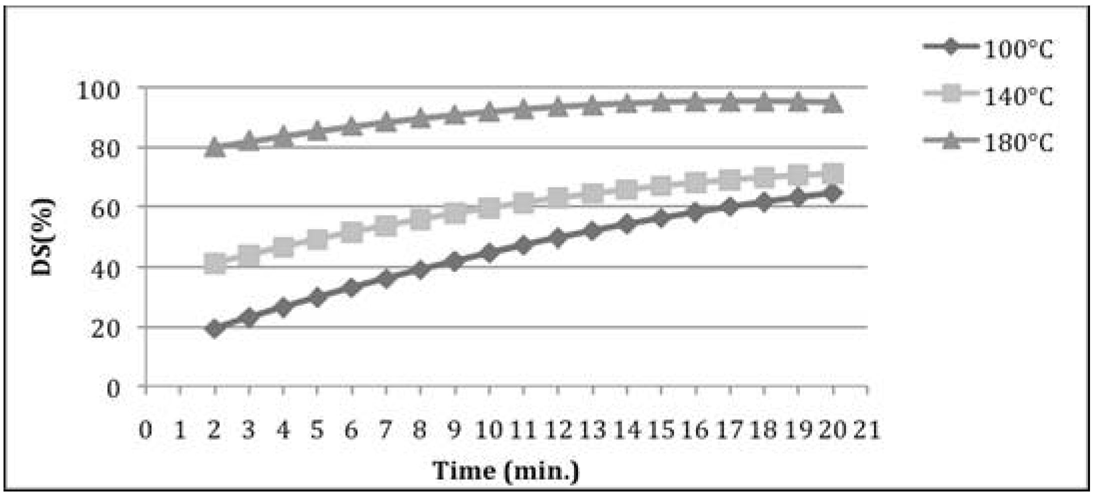

Figure 5.15 DS content curves for 2cm. diameter sludge samples fried at three different temperatures

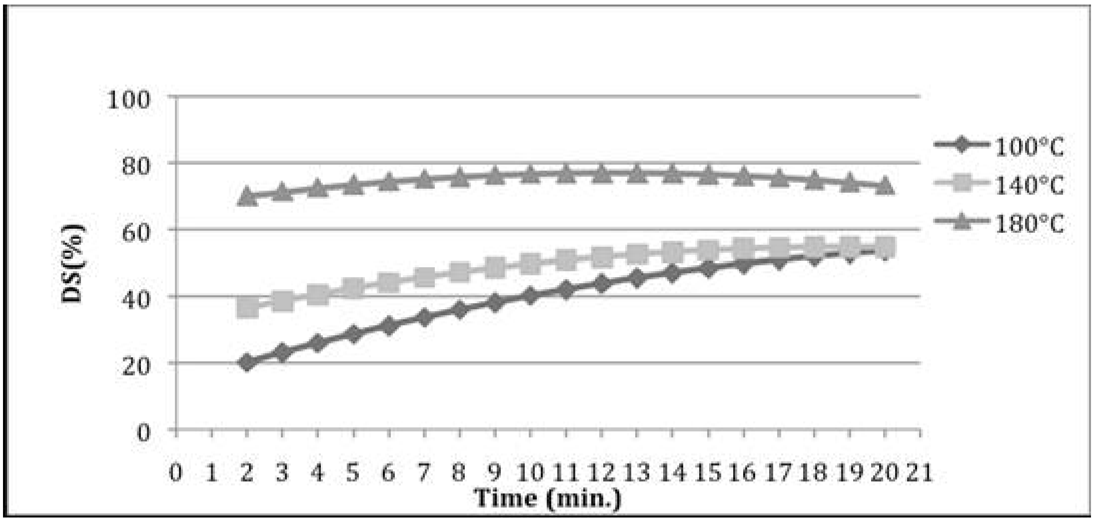

Figure 5.16 DS content curves for 2.5cm diameter sludge samples fried at three different temperatures.

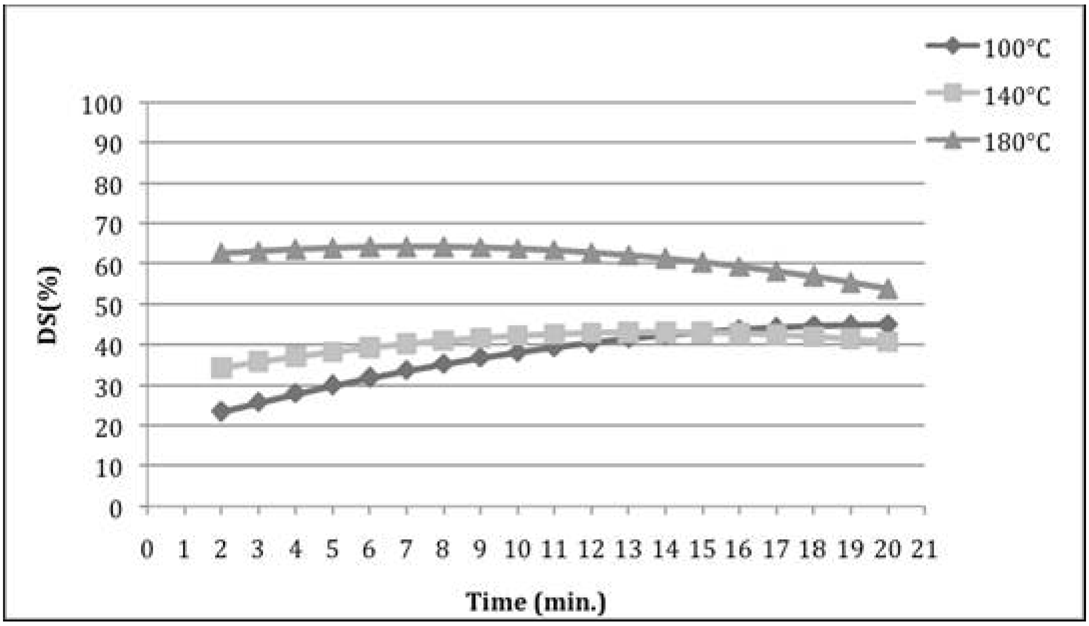

Figure 5.17 DS content curves for 3cm. diameter sludge samples fried at three different temperatures.

5.3.2 Volatile Solids Content (VS) Results of Fry-dried sludge with Waste Engine Oil

VS contents of raw sludge and fry-dried sludge samples were determined at the experimental data points calculated by Box-Wilson statistical design as shown in Table 5.2. VS experimental results are given in Table 5.6.

Table 5.6 VS results of sludge cake and fry-dried sludges with WEO.

Time (X_1), min	Temperature (X_2), °C	Diameter (X_3), cm	VS (%)
No frying time	25	Dewatered sludge cake	53.49
20	140	2	59.82
2	140	2	59.55
11	180	2	64.33
11	100	2	68.91
11	140	3	62.10
11	140	1	70.82
16	160	2.5	63.45
16	160	1.5	73.80
16	120	2.5	59.72
16	120	1.5	69.65
6	160	2.5	59.58
6	120	2.5	60.96
6	160	1.5	67.72
6	120	1.5	63.73
11	140	2	64.99
11	140	2	67.21
11	140	2	65.74

The effects of cylinder diameters on volatile solid results are given in Figure 5.18 and 5.19. Smaller diameter samples have higher VS contents than the bigger diameter samples.

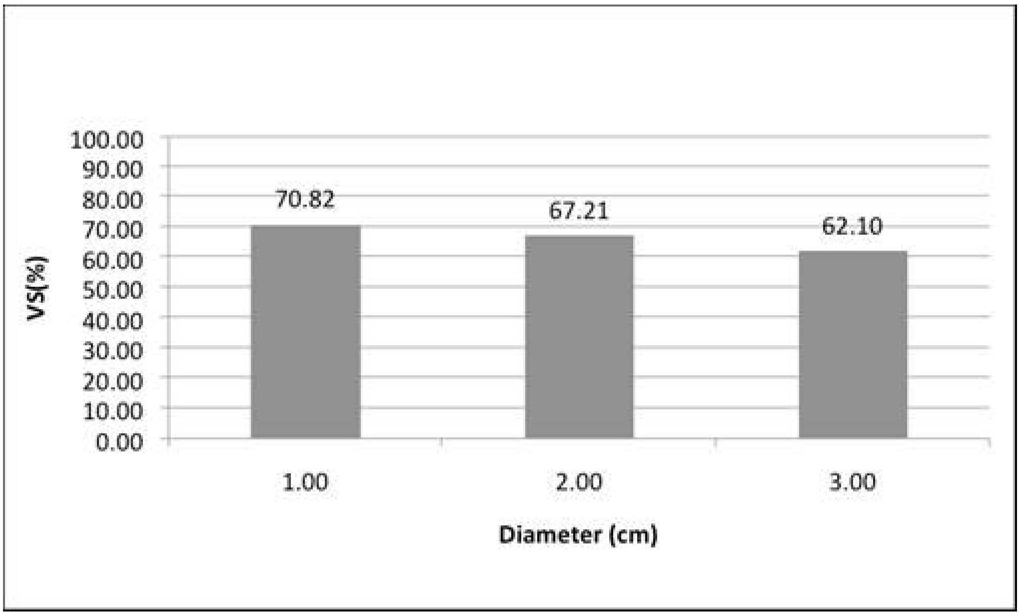

Figure 5.18 Effects of diameter on VS results at 140 °C for 11 minutes fry-drying.

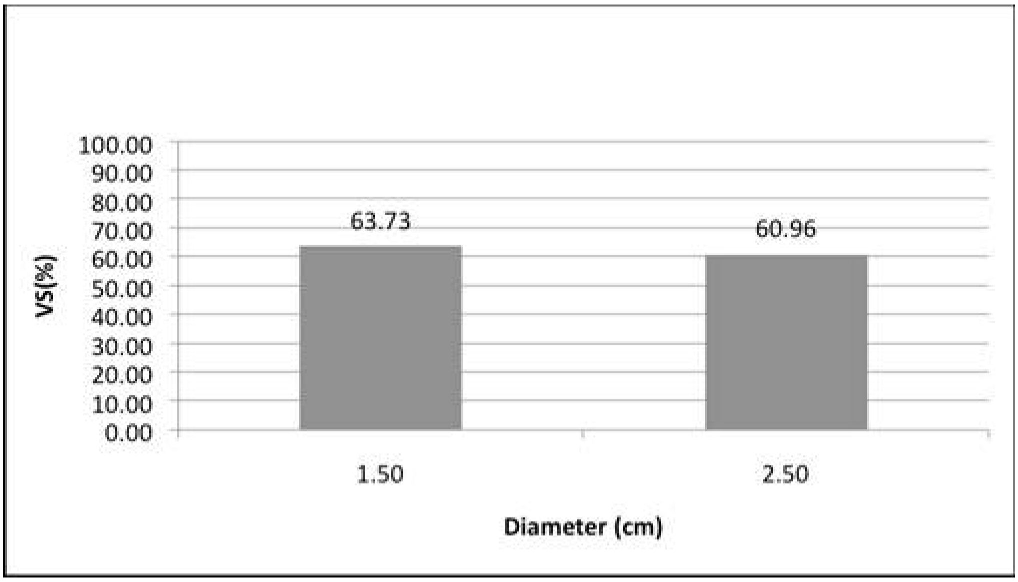

Figure 5.19 Effects of diameter on VS results at 120 °C for 6 minutes fry-drying.

Figure 5.20 shows VS results for the fry-drying applied samples having 2 cm diameter at different temperatures for 11 min. The higher oil temperatures led to lower VS contents. It might be due to volatile fraction of the material is vaporized at the high temperatures.

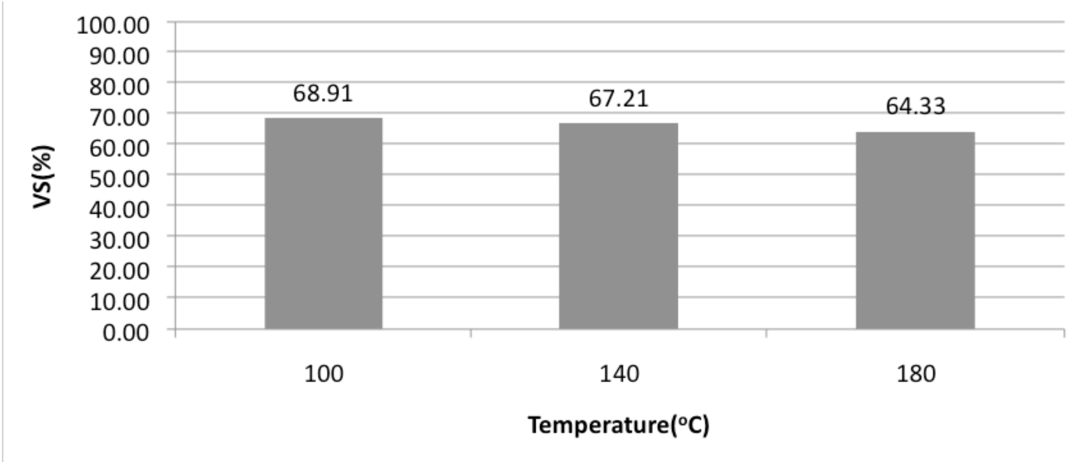

Figure 5.20 VS results fry-dried 2 cm. samples for 11 minutes at different temperatures.

Figure 5.21 presents the VS results of fry-dried 2 cm. samples at 140°C for 2, 11, and 20 min. As seen from the figure, VS results increase slightly for 11 min. of the frying time. Figure 5.22 shows the VS results of 1.5 and 2.5cm samples fry-dried at 120°C and 160°C for 16 min. VS results are slightly increased by the temperature and are higher values for smaller diameters.

Figure 5.23 shows the VS results of diameters 1.5 and 2.5 cm. samples fried for 6 and 16 min. at 120 and 160°C. It can be said that the frying time was not very effective on VS values on the contrary of temperature and sample's diameter.

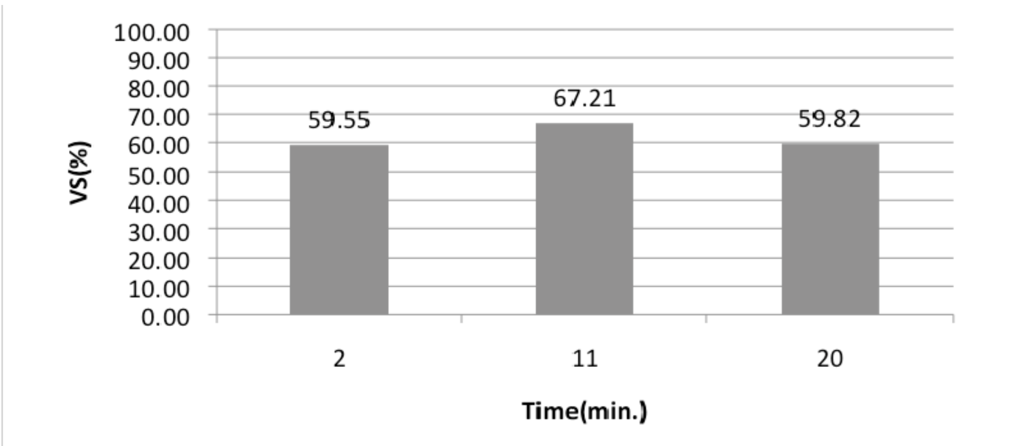

Figure 5.21 Effects of time on VS results on fry-dried 2 cm. samples at 140 °C.

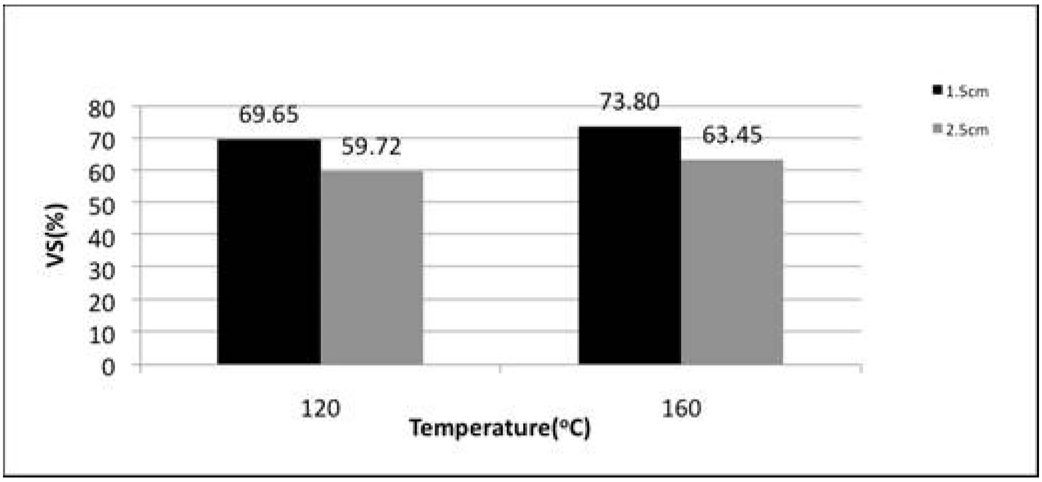

Figure 5.22 Effects of diameter and temperature on VS results fry-dried samples for 16 minutes.

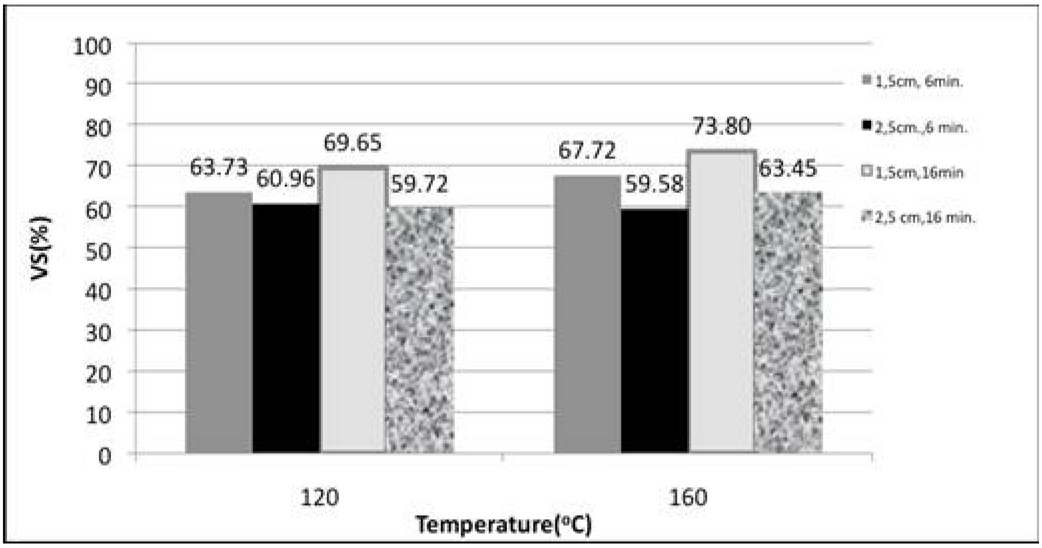

Figure 5.23 Effects of time, diameter, and temperature on VS results.

Table 5.7 shows the estimated coefficients of the response function of VS values, calculated by Statistica 7 program with the experimental data. The predicted VS values were illustrated in Table 5.8. The regression coefficient was achieved as R^2=0.88106811.

Table 5.7 VS response function coefficients.

bo	b1	b2	b3	b12
40.75981	1.46225	0.27304	3.59102	0.00700
b13	b23	b11	b22	b33
-0.50945	-0.03182	-0.06090	-0.00093	0.11277

Table 5.8 Predicted and residual values for volatile solids content of fry-dried samples with WEO.

Temperature (°C)	Time (min)	Diameter (cm)	Predicted	Residuals
20	140	2	63.54493	-2.98988
2	140	2	62.0401	1.60017
11	180	2	67.24966	-2.40518
11	100	2	65.21876	1.27952
11	140	3	61.82123	0.93591
11	140	1	73.85579	-2.06159
16	160	2.5	62.88377	2.44897
16	160	1.5	72.08478	2.58457
16	120	2.5	61.10463	-0.75653
16	120	1.5	69.03265	2.10537
6	160	2.5	63.1948	-0.97971
6	120	2.5	64.21604	-1.4589
6	160	1.5	67.30135	1.8822
6	120	1.5	67.04959	-1.32331
11	140	2	67.72574	-1.97785
11	140	2	67.72574	-0.95686
11	140	2	67.72574	2.0731

VS results as a function of temperature at different frying times for different sample diameters as 1, 1.5, 2, 2.5, 3 cm are shown in figures between 5.24 and 5.28. VS contents of the samples having 1 and 1.5 cm diameters were the highest values and also VS increased for all applications with the increasing time; however, it also decreased for the oil temperatures after 160 °C. 11 min. of the frying time gave the better results for all applications.

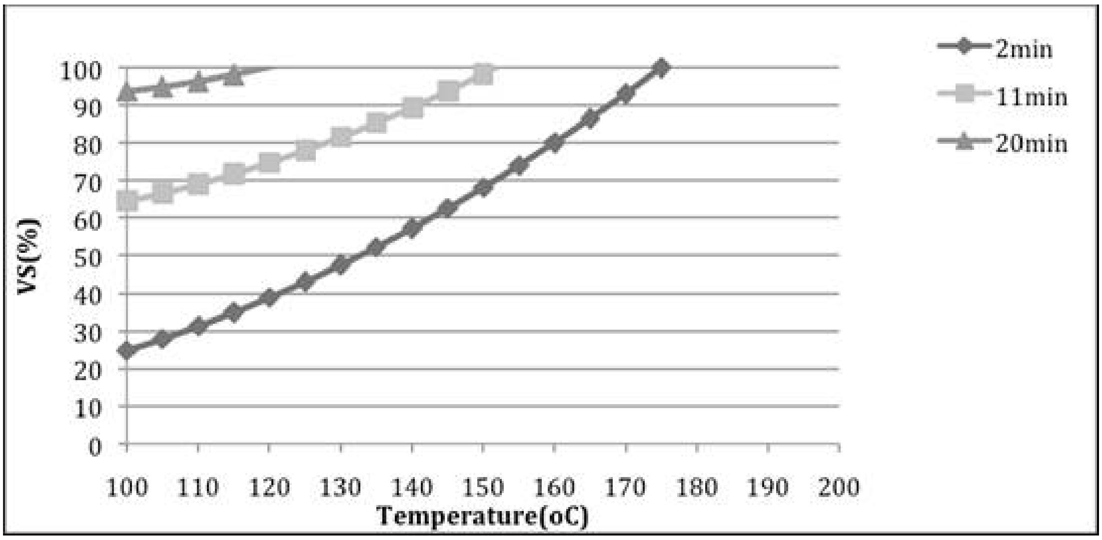

Figure 5.24 VS content curves for 1cm diameter samples fry-dried sludge for three different process times.

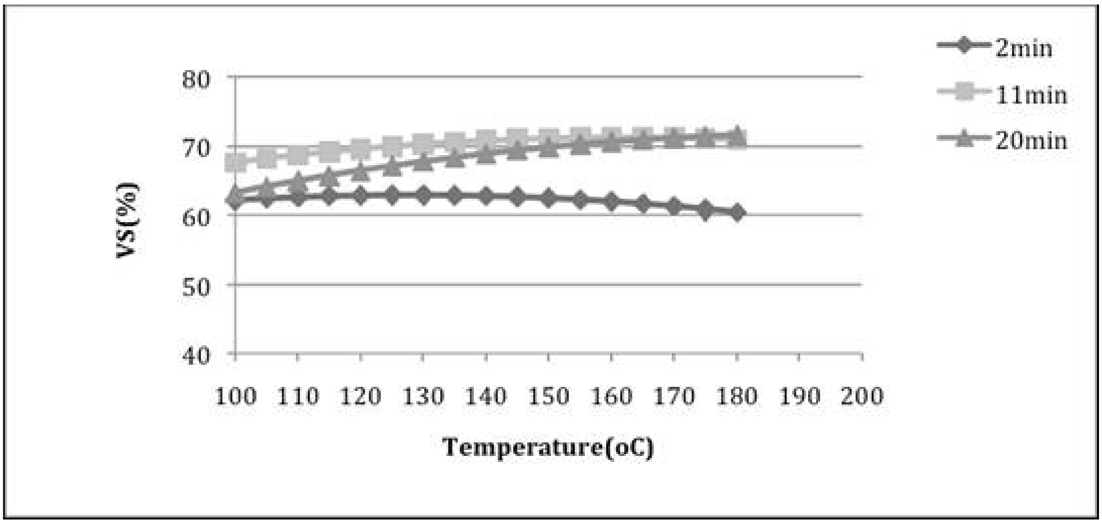

Figure 5.25 VS content curves for 1.5cm diameter samples fried sludge for three different process times.

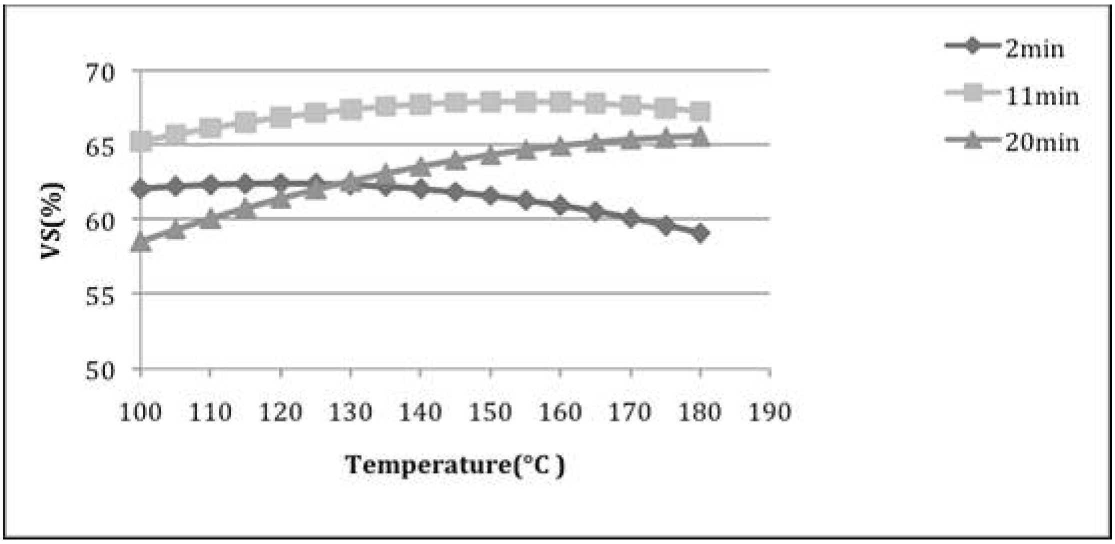

Figure 5.26 VS content curves for 2cm diameter samples fried sludge for three different process times.

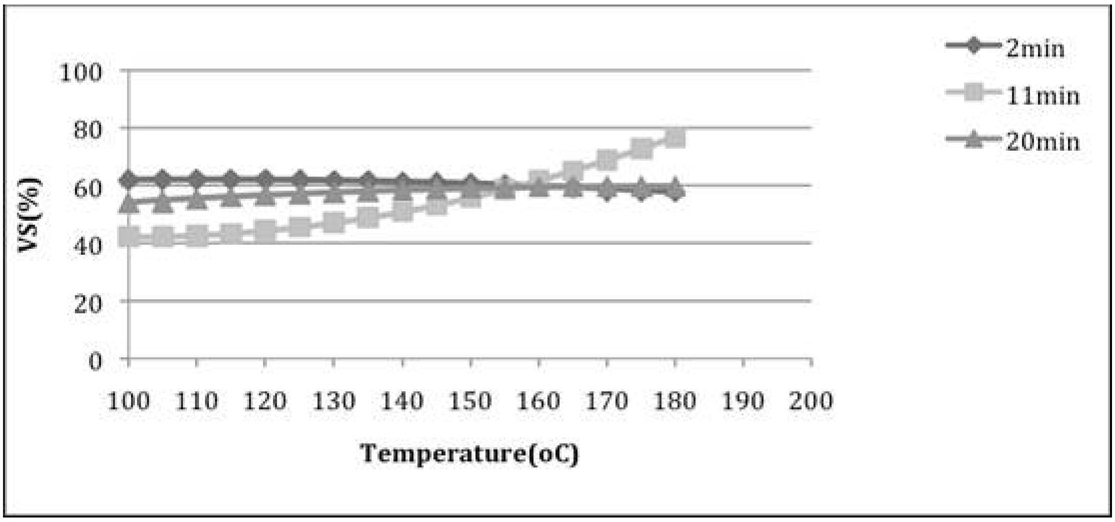

Figure 5.27 VS content curves for 2.5cm diameter samples fried sludge for three different process times.

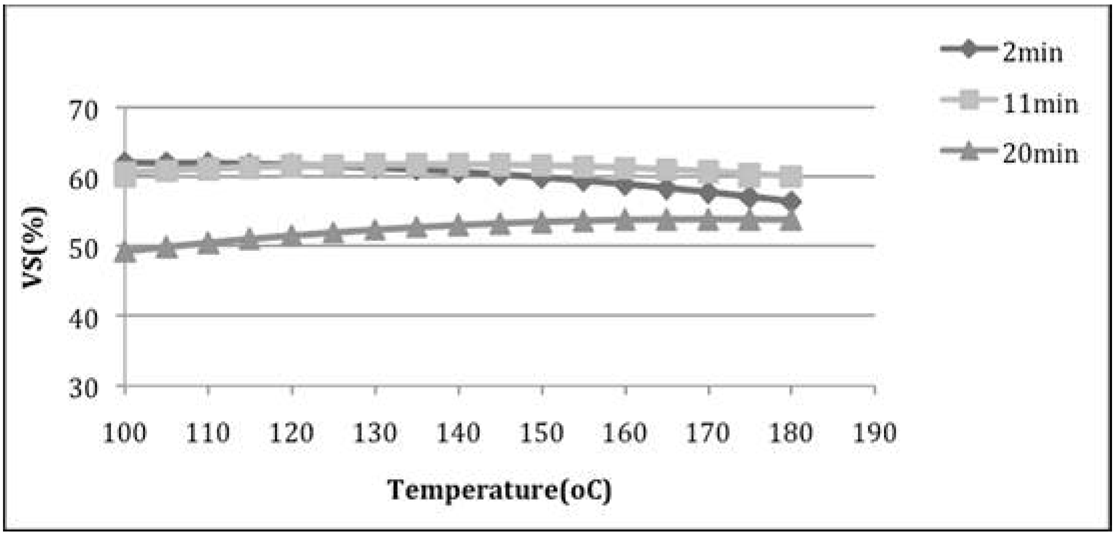

Figure 5.28 VS content curves for 3cm. diameter samples fried sludge for three different process times.

Figures 5.29- 5.33 showed the VS results as a function of frying time at different temperatures and different sample diameters. For the samples having 1 and 1.5 cm diameter, approximately 11 minutes of frying time was enough to reach the VS higher than 80% at 140 °C of the oil temperature. Lowest temperature application at 100 °C did not produce higher VS content as well as the temperature range in 140-160 °C.

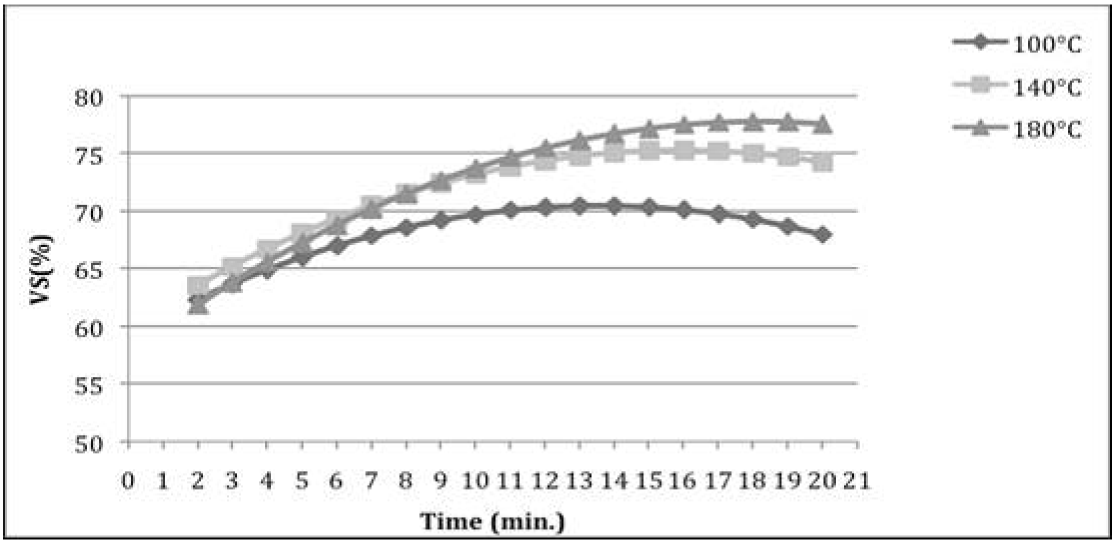

Figure 5.29 VS content curves for 1cm. diameter samples fried sludge at three different temperatures.

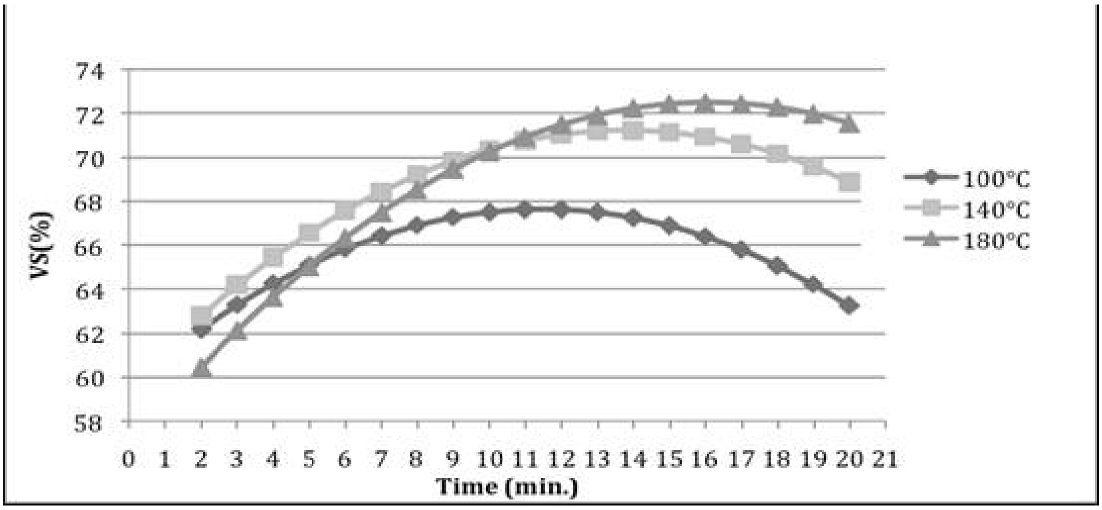

Figure 5.30 VS content curves for 1.5cm diameter samples fried sludge at three different temperatures.

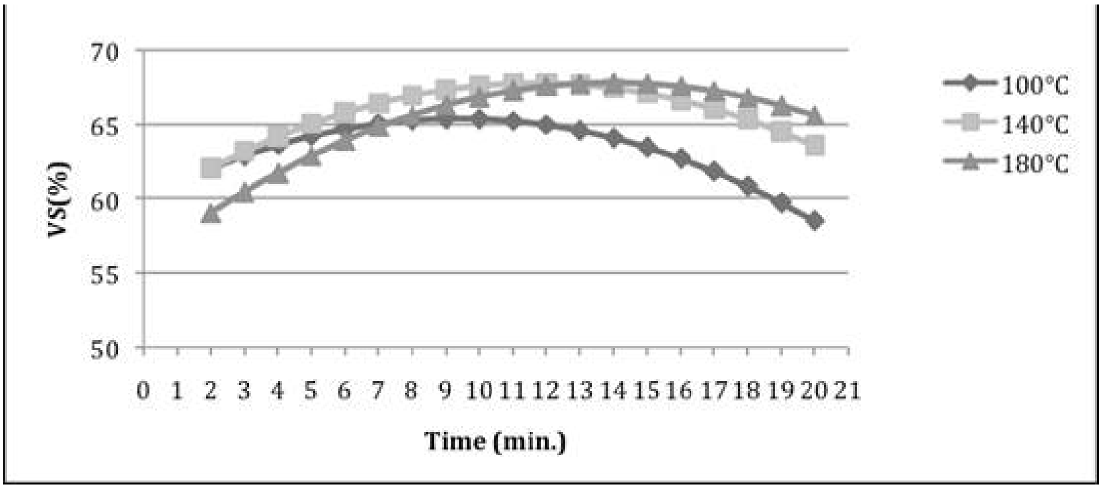

Figure 5.31 VS content curves for 2cm. diameter samples fried sludge at three different temperatures.

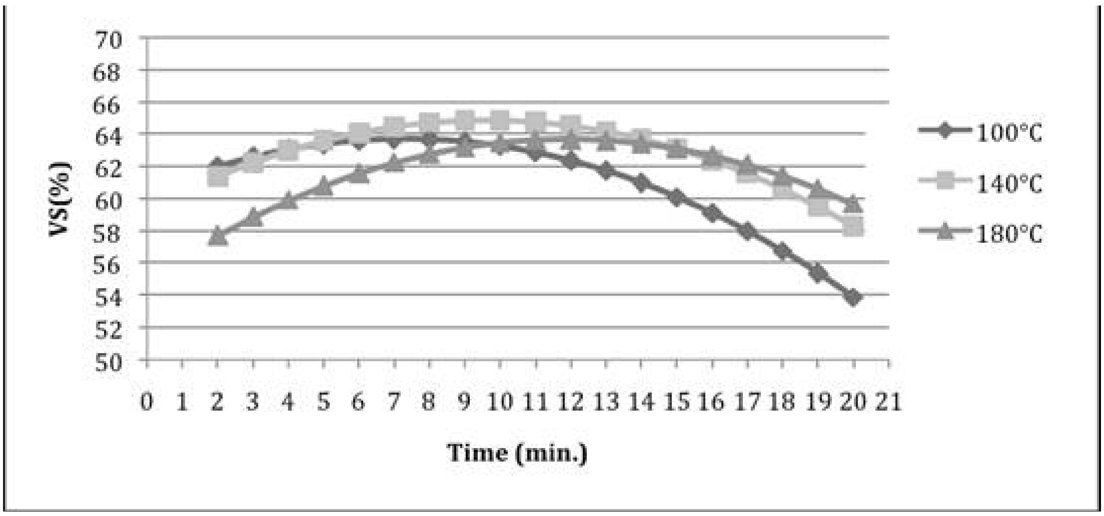

Figure 5.32 VS content curves for 2.5cm diameter samples fried sludge at three different temperatures

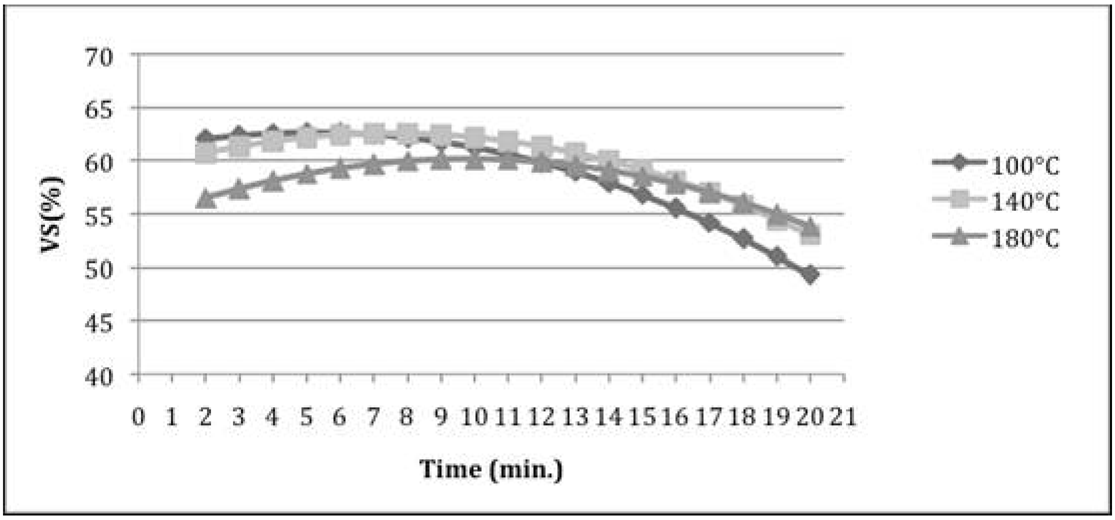

Figure 5.33 VS content curves for 3cm. diameter samples fried sludge at three different temperatures.

5.3.3 Heating Value (Calorific) of The Fried Sludge

The low and high heating values of the sludge were determined based on several original and dry base measurements. The same evaluation method was used as above sections with Statistica 7.0 program for the regression analysis. Response function coefficients were determined by using experimental data for each independent variable.

a) Low Heating (Calorific) Value (LHV) of The Fried Sludge in Original Base

Table 5.9 shows the estimated coefficients of the response function of LHV values, which were calculated by Statistica 7 program with the experimental data. The predicted LHV values were illustrated in Table 5.10. The regression coefficient was achieved as R^2=0. 96681389.

Table 5.9 LHV in original base response function coefficients.

bo	b1	b2	b3	b12
-2852.88	601.52	-13.45	2090.69	-0.44
b13	b23	b11	b22	b33
-136.06	-23.57	-7.60	0.37	236.90

Table 5.10 Predicted and residual values for LHV in original base of fry-dried samples with WEO.

Time (min)	Temperature (°C)	Time (min)	Predicted	Residuals
20	140	2	3286.532	-499.679
2	140	2	1465.838	56.293
11	180	2	5056.83	-88.067
11	100	2	2097.233	-271.076
11	140	3	1470.064	80.351
11	140	1	4987.682	-439.494
16	160	2.5	2754.186	264.458
16	160	1.5	5664.778	253.368
16	120	2.5	1833.022	84.949
16	120	1.5	3800.627	615.885
6	160	2.5	2510.121	-256.742
6	120	2.5	1414.674	105.775
6	160	1.5	4060.133	274.193
6	120	1.5	2021.699	94.685
11	140	2	2991.975	-768.456
11	140	2	2991.975	319.787
11	140	2	2991.975	173.77

LHV in original base results are shown as a function of temperature at different frying times and different sample diameter in Figures between 5.34 and 5.38. LHV in original base decreased with the increasing sample's diameter. These findings are also consisted with the VS results.

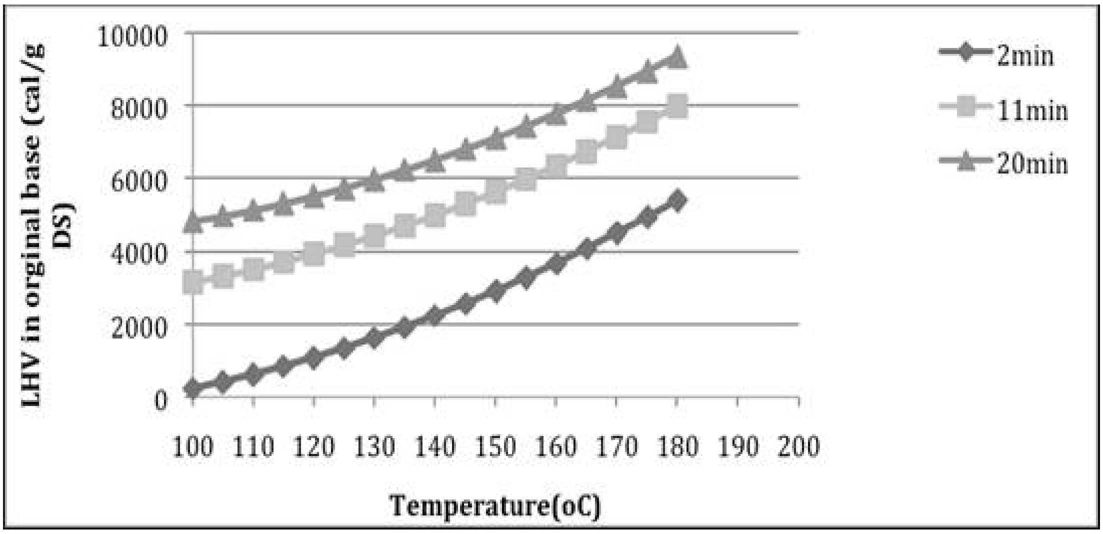

Figure 5.34 LHV in original base curves for 1cm diameter samples fry-dried sludge for three different process times.

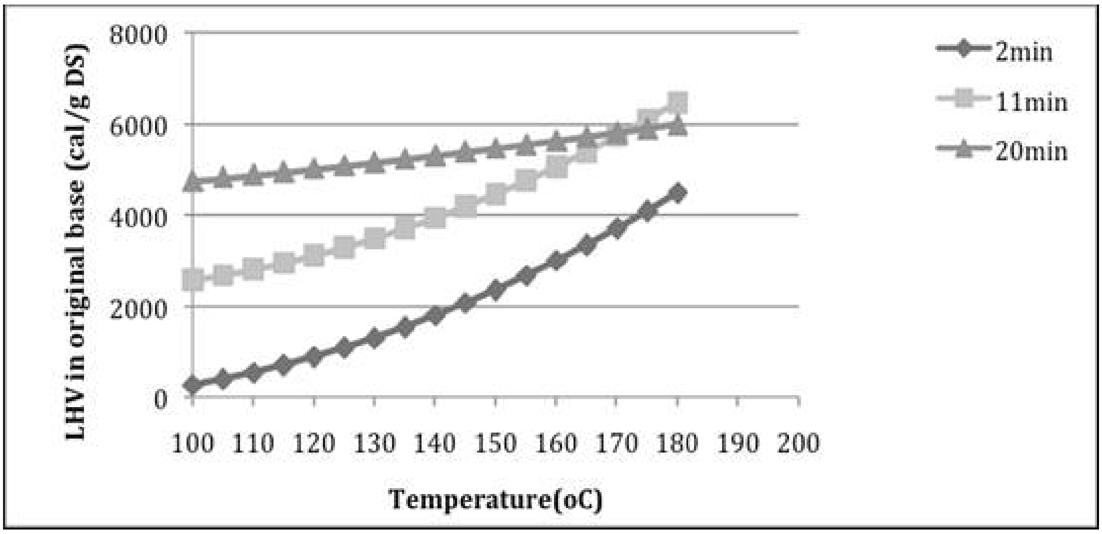

Figure 5.35 LHV in original base curves for 1.5cm diameter samples fry-dried sludge for three different process times.

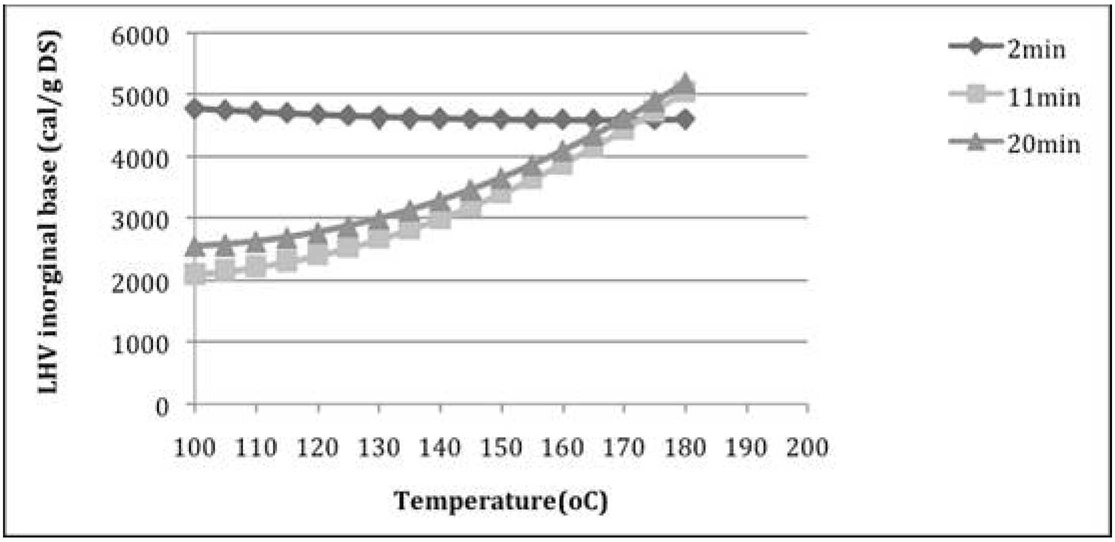

Figure 5.36 LHV in original base curves for 2cm. diameter samples fry-dried sludge for three different process times.

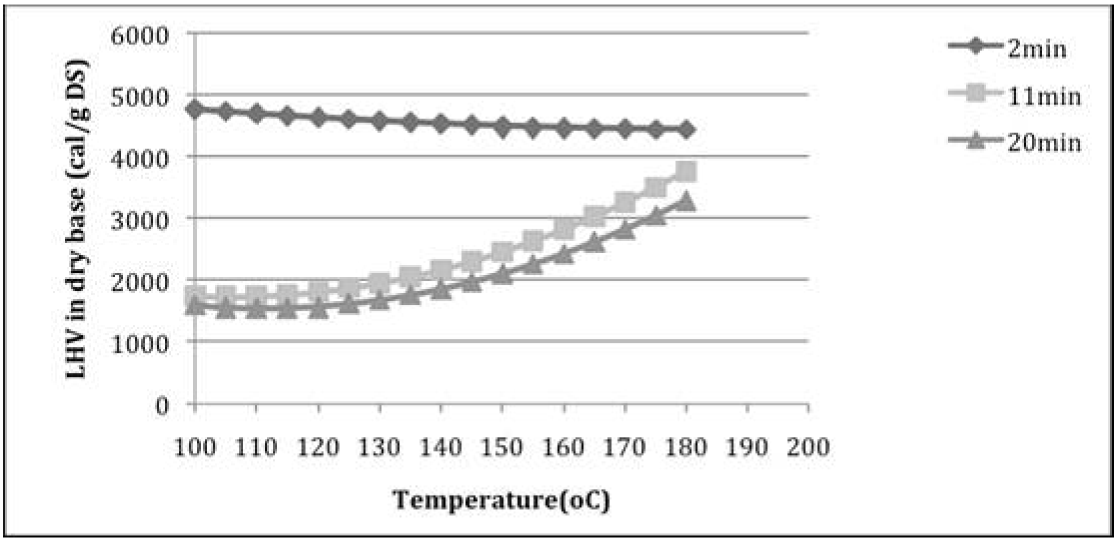

Figure 5.37 LHV in original base curves for 2.5cm diameter samples fry-dried sludge for three different process times.

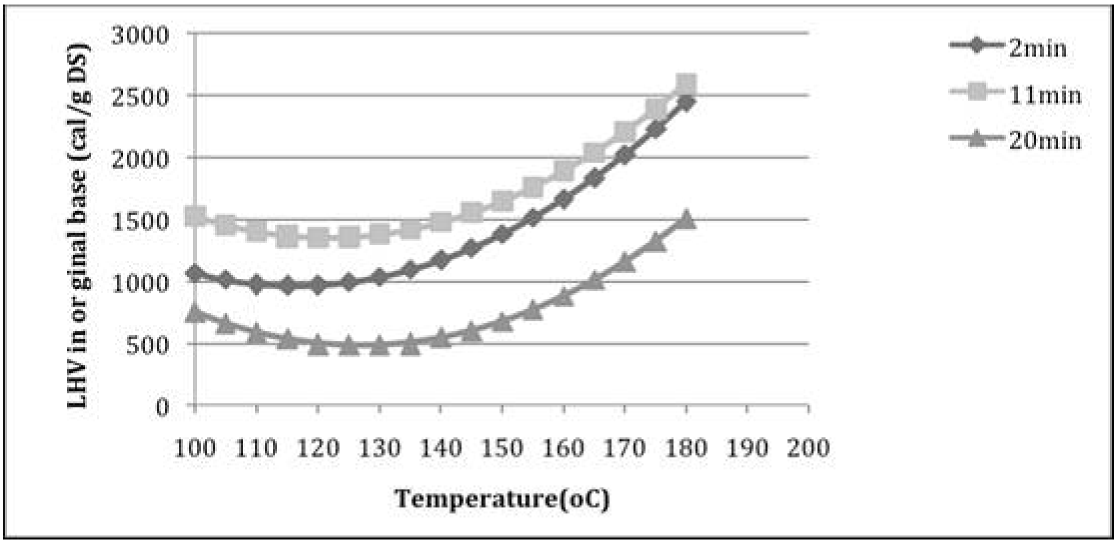

Figure 5.38 LHV in original base curves for 3cm. diameter samples fry-dried sludge for three different process times.

Figures 5.39 and 5.43 also show LHV in original base results as a function of time at different temperatures and different sample diameters.

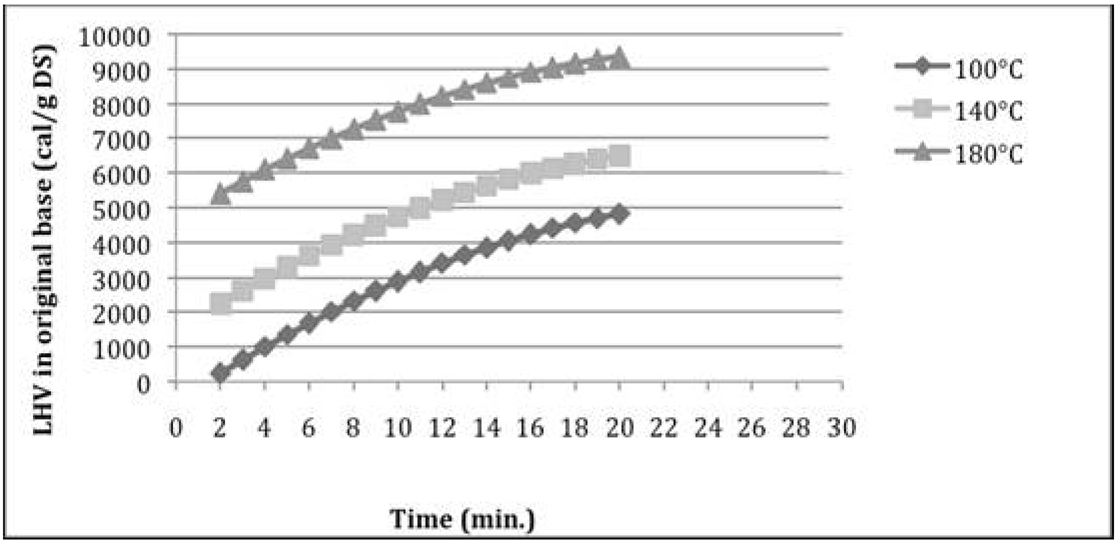

Figure 5.39 LHV in original base curves for 1cm. diameter sludge samples fried at three different temperatures.

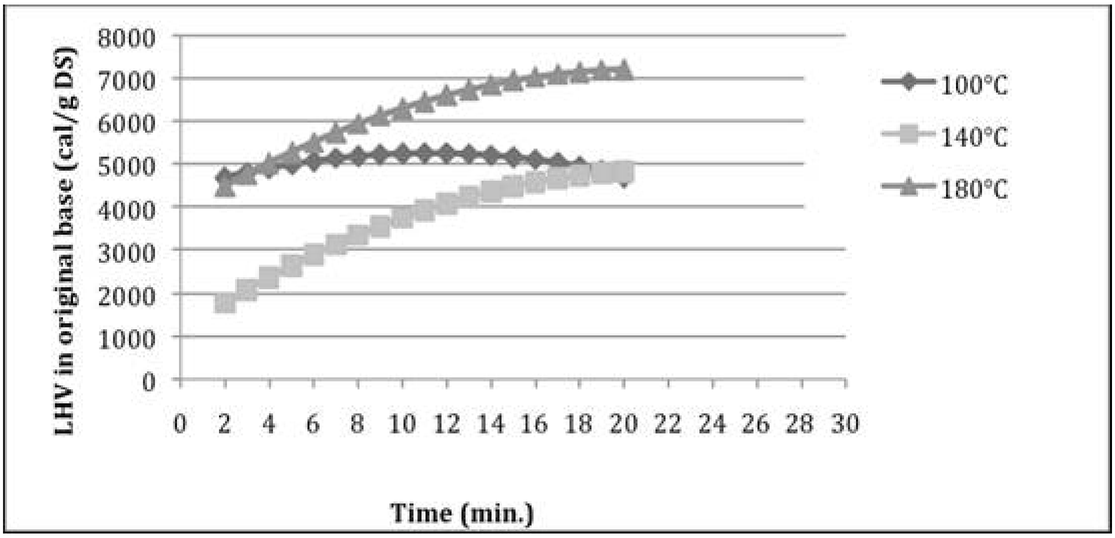

Figure 5.40 LHV in original base curves for 1.5cm diameter sludge samples fried at three different temperatures.

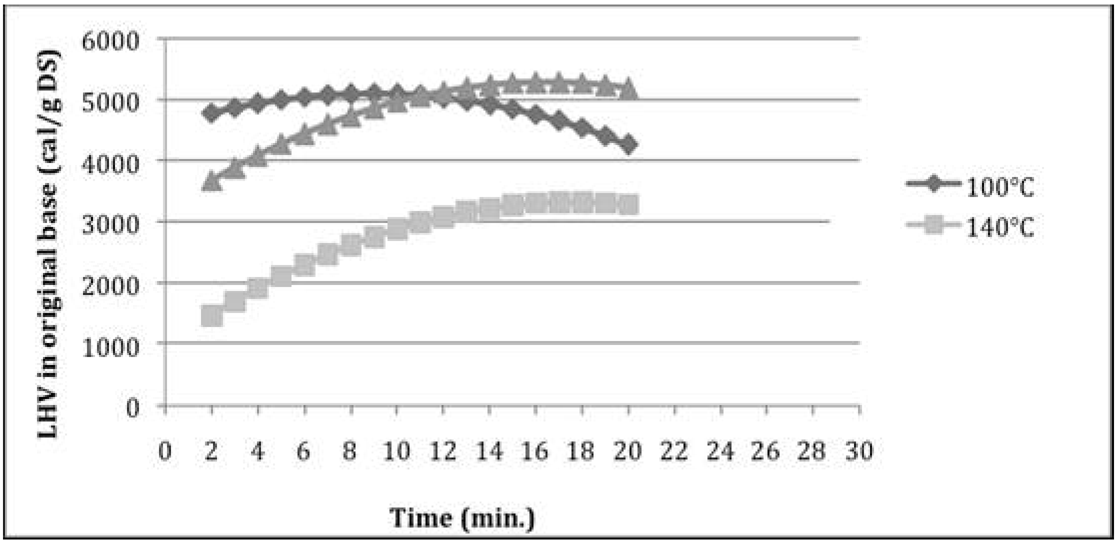

Figure 5.41 LHV in original base curves for 2cm diameter sludge samples fried at three different temperatures.

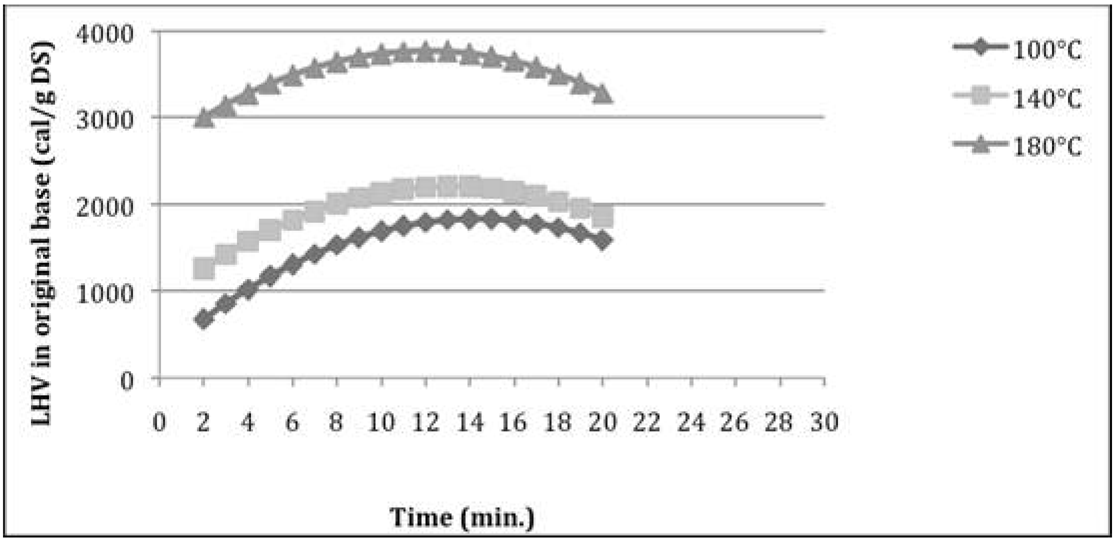

Figure 5.42 LHV in original base curves for 2.5cm diameter samples fried sludge at three different temperatures.

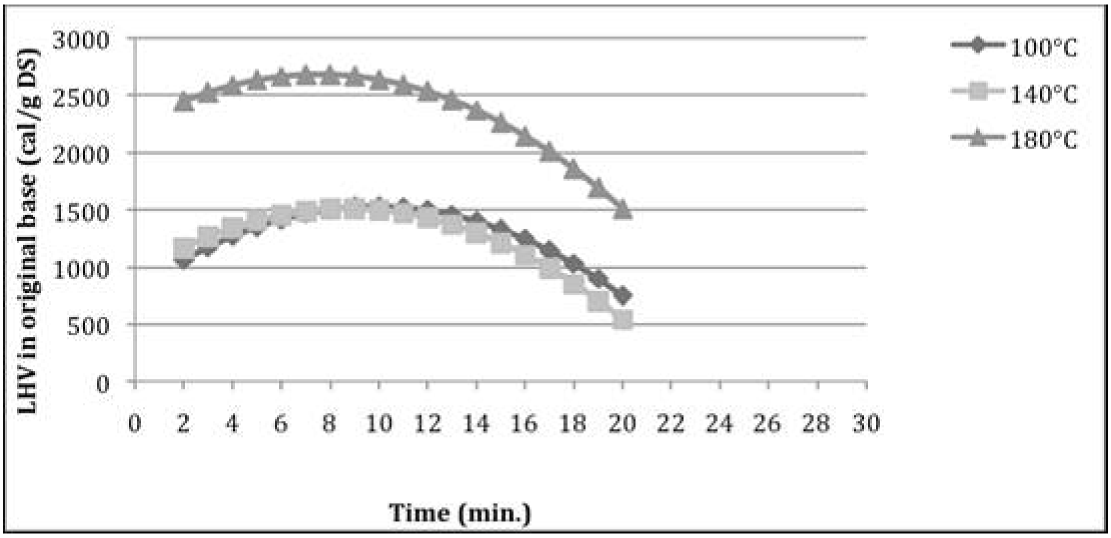

Figure 5.43 LHV in original base curves for 3cm diameter samples fried sludge at three different temperatures.

b) Low Heating (Calorific) Value (LHV) of The Fried Sludge in Dry Base

Table 5.11 shows the estimated coefficients of the response function of LHV values in dry base, which were calculated by Statistica 7 program with the experimental data. The predicted LHV values illustrated in Table 5.12. The regression coefficient was achieved as R^2=0.84853824.

Table 5.11 LHV in dry base response function coefficients.

bo	b1	b2	b3	b12
3698.136	159.510	-8.013	1421.787	0.871
b13	b23	b11	b22	b33
-63.399	-3.958	-6.743	0.043	-203.816

Table 5.12 Predicted and residual values for LHV in dry base of fry-dried samples with WEO.

Time(min)	Temperature(°C)	Diameter(cm)	Predicted	Residuals
20	140	2	4738.078	-392.946
2	140	2	4624.535	269.323
11	180	2	5525.965	-176.316
11	100	2	5067.152	76.182
11	140	3	4378.757	240.486
11	140	1	5668.652	-340.62
16	160	2.5	4738.042	201.805
16	160	1.5	5779.141	322.599
16	120	2.5	4413.575	-94.203
16	120	1.5	5296.365	366.109
6	160	2.5	4817.745	-265.975
6	120	2.5	4841.708	-222.465
6	160	1.5	5224.849	194.337
6	120	1.5	5090.504	-101.671
11	140	2	5227.52	-235.996
11	140	2	5227.52	-108.906
11	140	2	5227.52	268.256

LHV in dry base results are shown as a function of temperature at different frying times and different sample diameters in Figures 5.44-5.48. Similar observations were obtained as in LHV in original base.

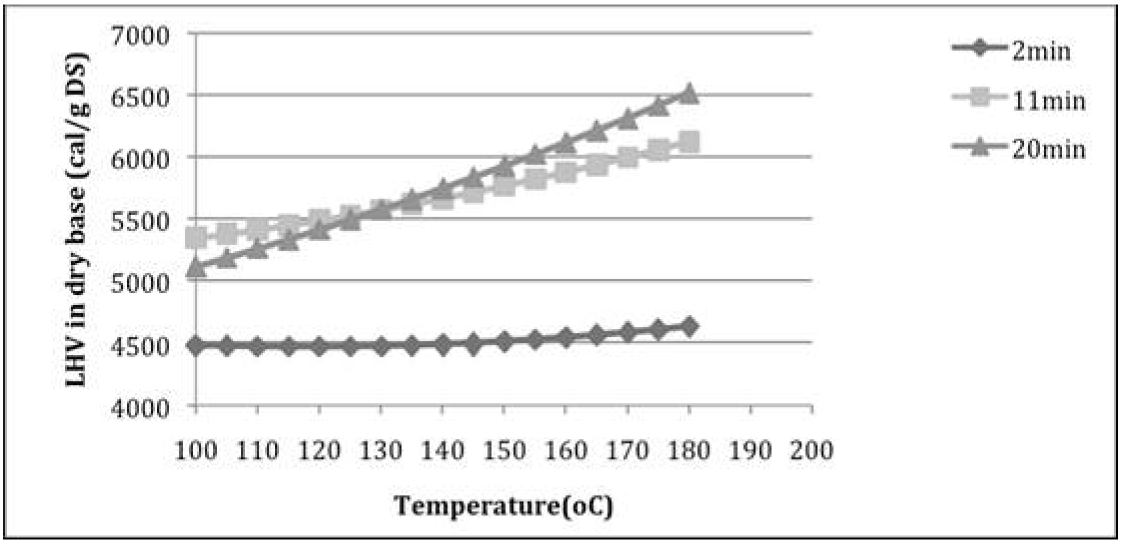

Figure 5.44 LHV in dry base curves for 1cm. diameter samples fry-dried sludge for three different process times.

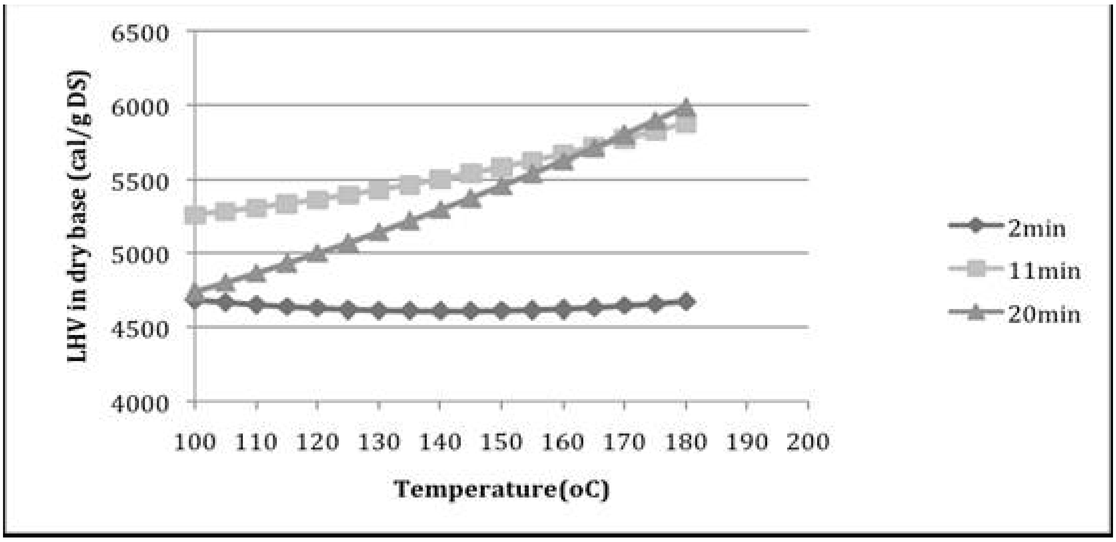

Figure 5.45 LHV in dry base curves for 1.5cm diameter samples fry-dried sludge for three different process times.

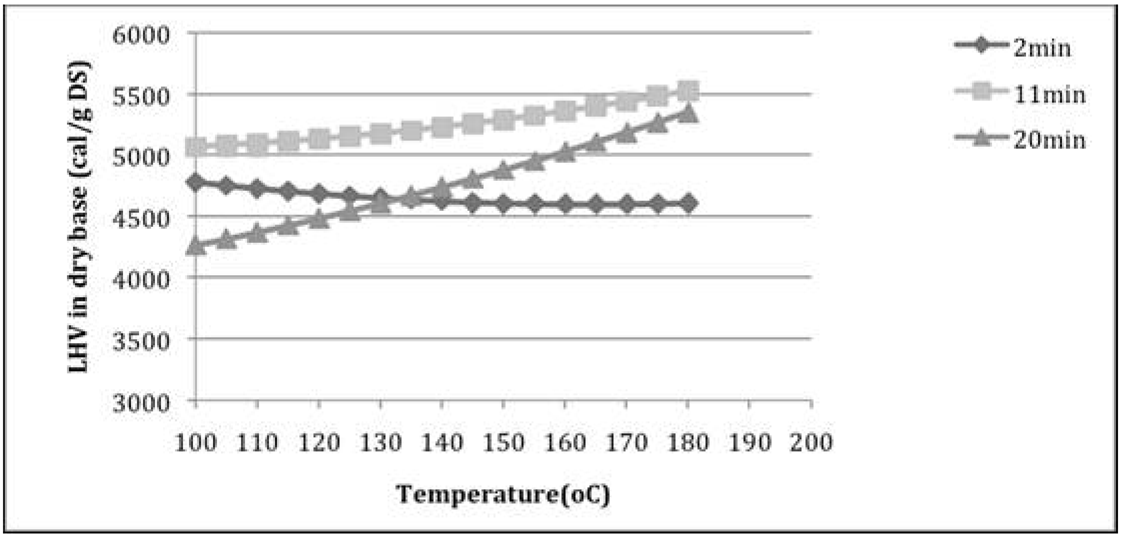

Figure 5.46 LHV in dry base curves for 2cm diameter samples fry-dried sludge for three different process times.

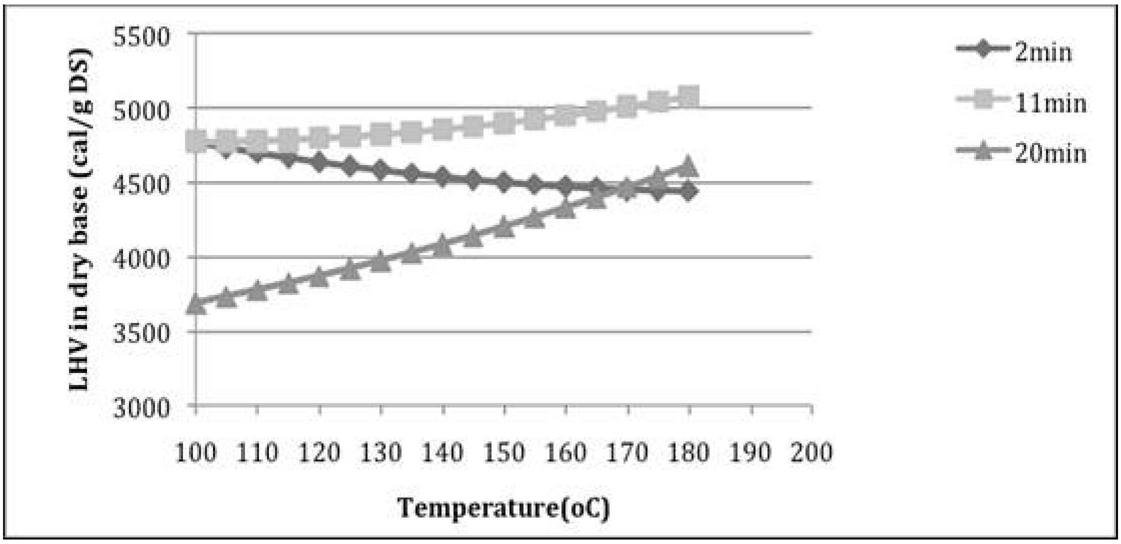

Figure 5.47 LHV in dry base curves for 2.5cm diameter samples fry-dried sludge for three different process times.

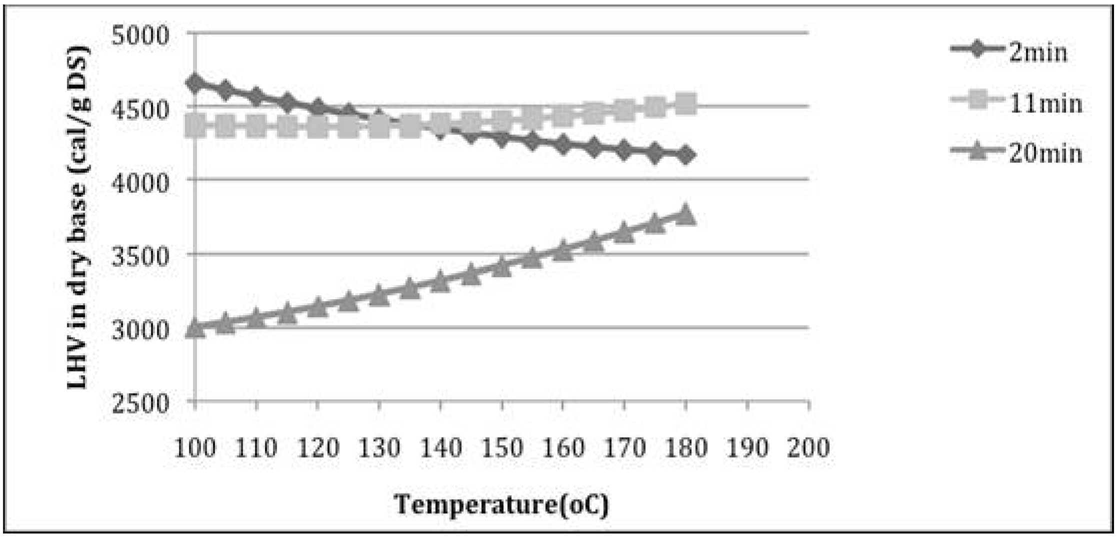

Figure 5.48 LHV in dry base curves for 3cm diameter samples fry-dried sludge for three different process times.

Figures 5.49-5.53 show LHV in dry base results as a function of time at different temperatures and different sample diameters.

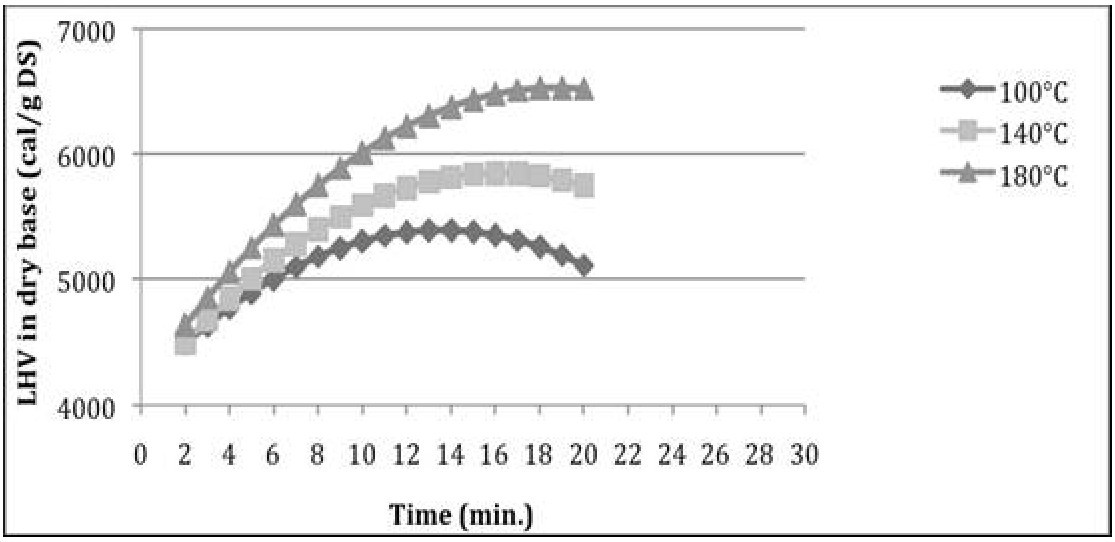

Figure 5.49 LHV in dry base curves for 1cm diameter samples fried sludge at three different temperatures.

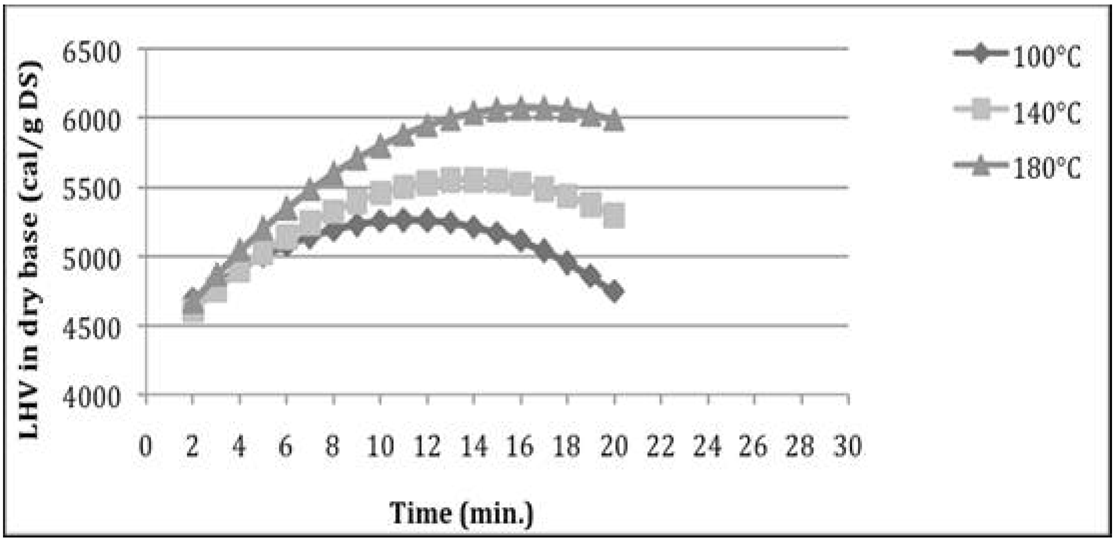

Figure 5.50 LHV in dry base curves for 1.5cm diameter samples fried sludge at three different temperatures.

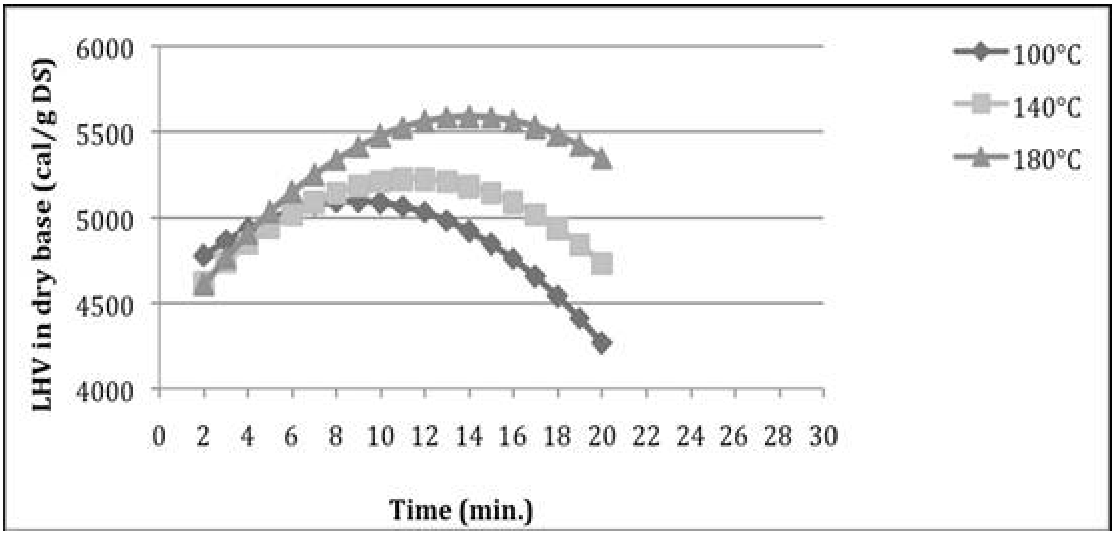

Figure 5.51 LHV in dry base curves for 2cm diameter samples fried sludge at three different temperatures.

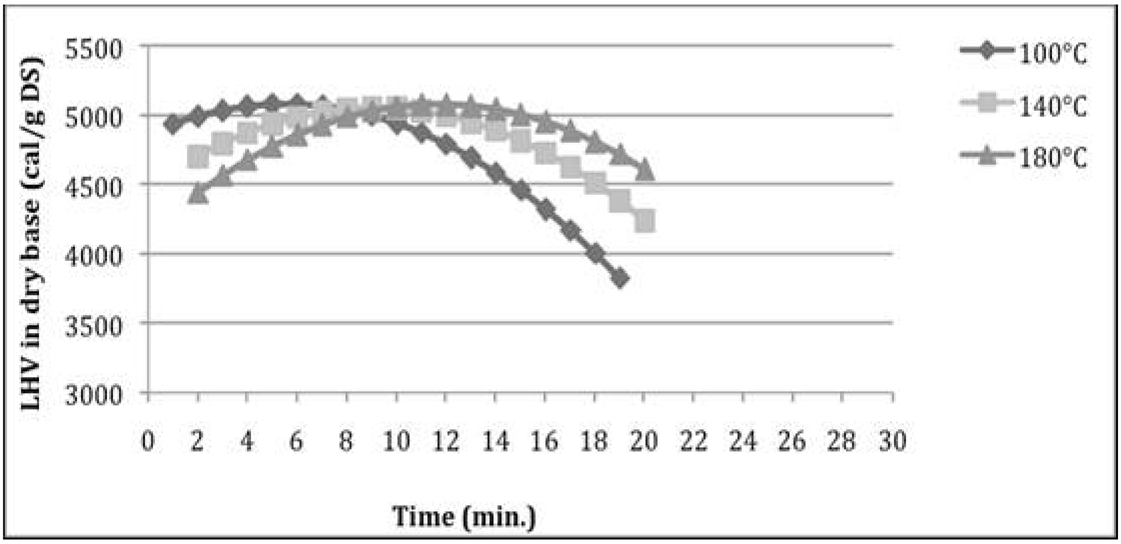

Figure 5.52 LHV in dry base curves for 2.5cm diameter samples fried sludge at three different temperatures.

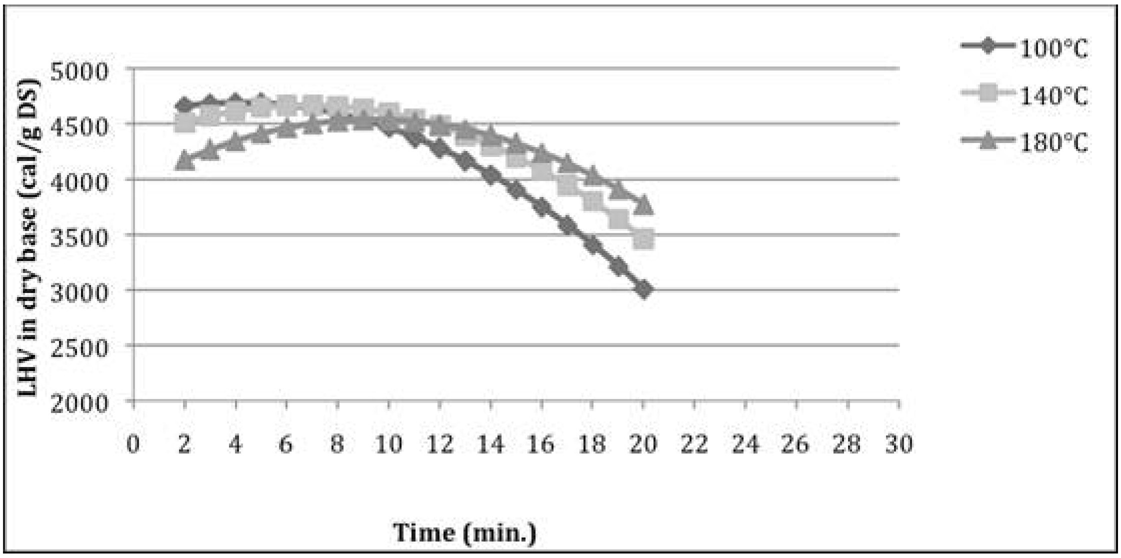

Figure 5.53 LHV in dry base curves for 3cm diameter samples fried sludge at three different temperatures.

*c) High Heating (Calorific) Value (*HHV*) of The Fried Sludge in Dry Base*

Table 5.13 shows the estimated coefficients of the response function of HHV values, which were calculated by Statistica 7 program with the experimental data. The predicted LHV values were illustrated in Table 5.14. The regression coefficient was achieved as R^2=0.84907815.

Table 5.13 HHV in dry base response function coefficients

bo	b1	b2	b3	b12
3800.657	163.317	-7.222	1433.098	0.890
b13	b23	b11	b22	b33
-64.756	-4.045	-6.903	0.040	-203.778

Table 5.14 Predicted and residual values for HHV in dry base of fry-dried samples with WEO

Time (min)	Temperature (°C)	Diameter (cm)	Predicted	Residuals
20	140	2	4907.155	-401.003
2	140	2	4789.575	273.425
11	180	2	5704.047	-183.047
11	100	2	5240.292	79.708
11	140	3	4543.033	243.027
11	140	1	5864.365	-346.365
16	160	2.5	4905.054	208.391
16	160	1.5	5970.404	329.817
16	120	2.5	4576.104	-96.257
16	120	1.5	5479.644	371.71
6	160	2.5	4985.532	-268.372
6	120	2.5	5012.538	-226.479
6	160	1.5	5403.325	199.595
6	120	1.5	5268.521	-105.054
11	140	2	5407.478	-241.264
11	140	2	5407.478	-111.486
11	140	2	5407.478	273.652

HHV in dry base results are shown as a function of temperature at different frying durations and different sample diameters in Figures between 5.54 and 5.58.

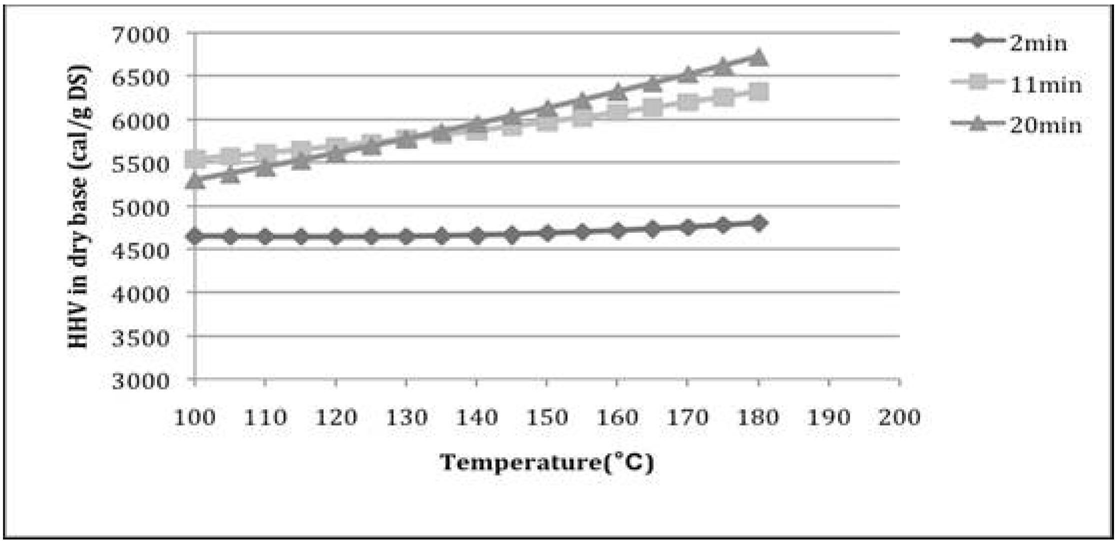

Figure 5.54 HHV in dry base curves for 1cm diameter samples fry-dried sludge for three different process times.

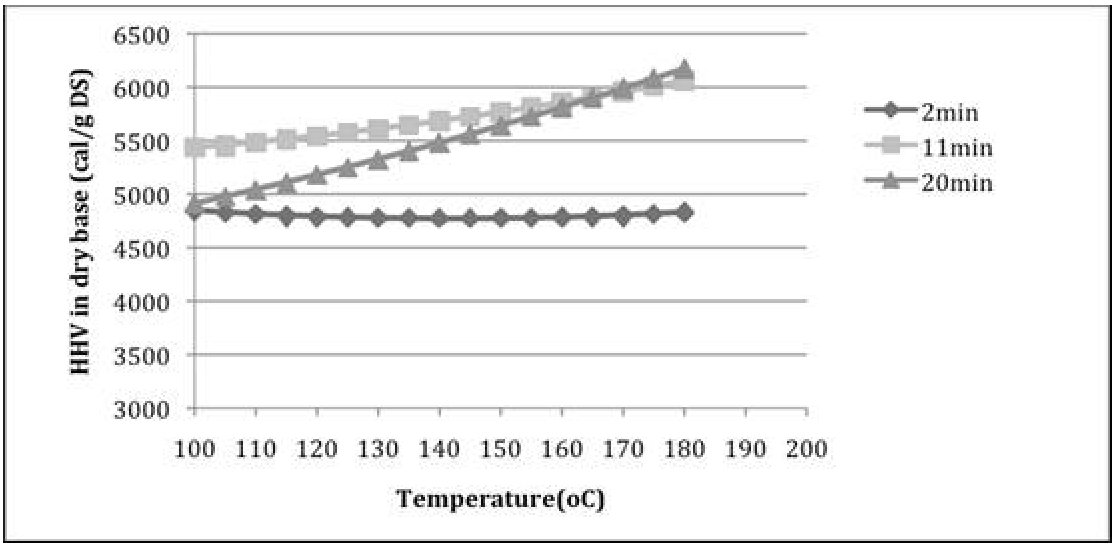

Figure 5.55 HHV in dry base curves for 1.5cm diameter samples fry-dried sludge for three different process times.

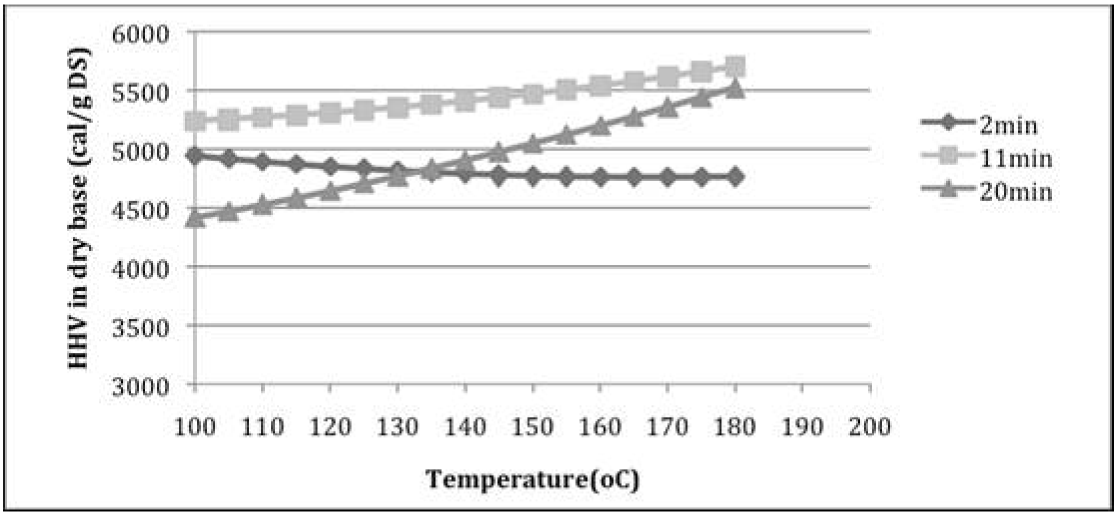

Figure 5.56 HHV in dry base curves for 2cm diameter samples fry-dried sludge for three different process times.

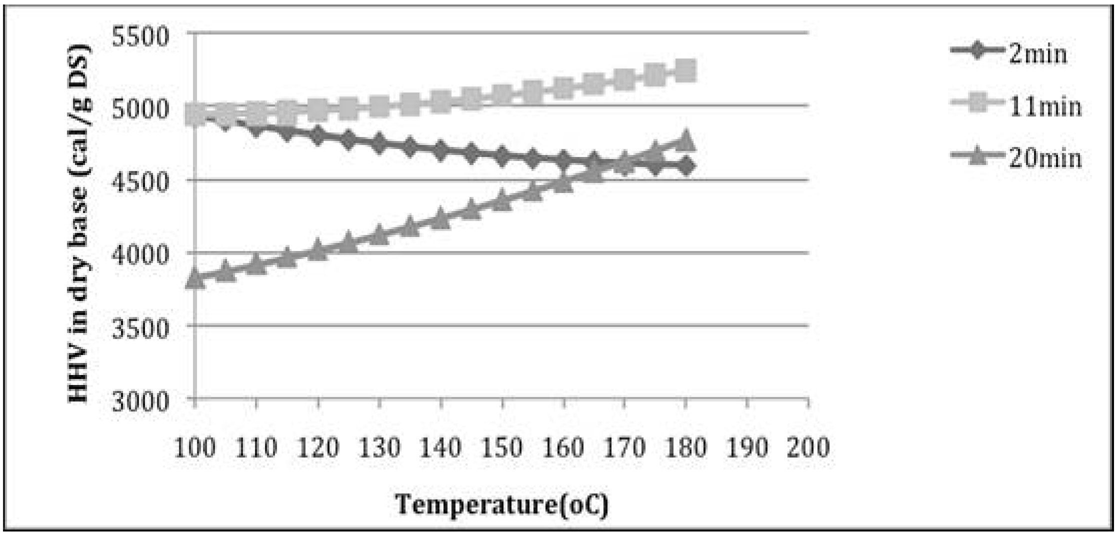

Figure 5.57 HHV in dry base curves for 2.5cm diameter samples fry-dried sludge for three different process times.

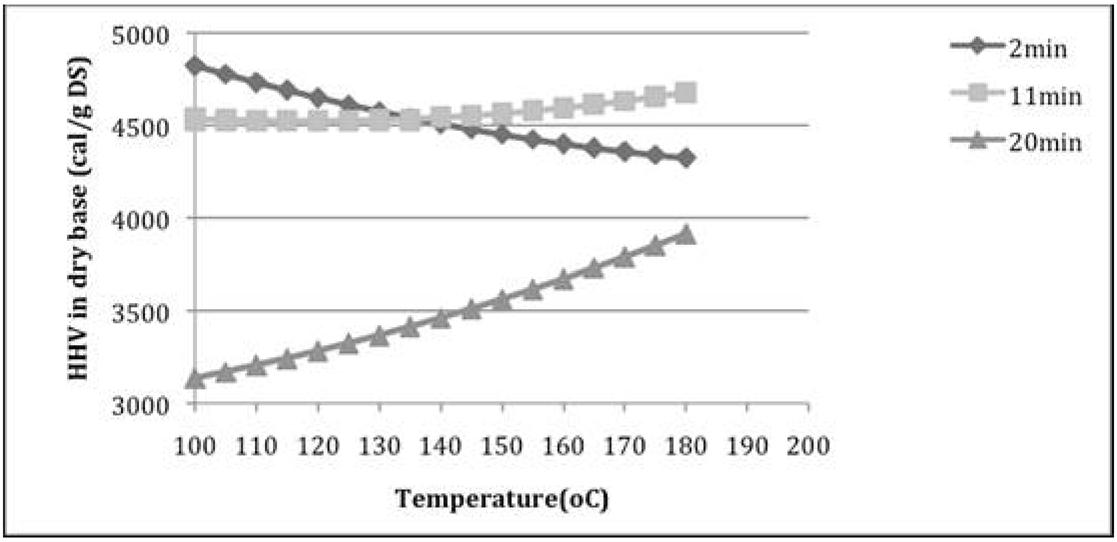

Figure 5.58 HHV in dry base curves for 3cm diameter samples fry-dried sludge for three different process times.

Figures 5.59- 5.63 show HHV in dry base results as a function of time at different temperatures and different sample diameters.

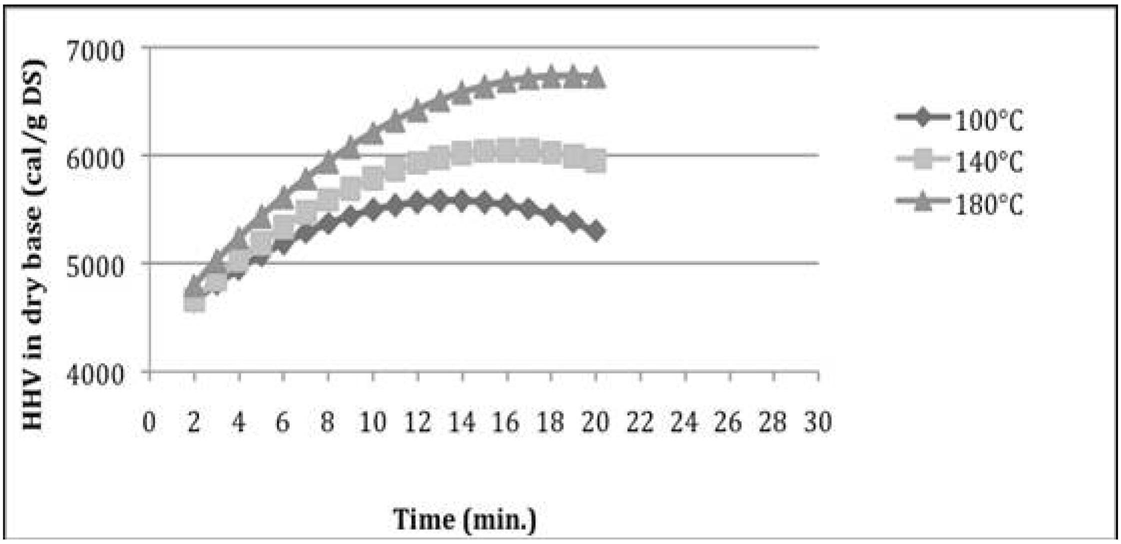

Figure 5.59 HHV in dry base curves for 1cm diameter samples fried sludge at three different temperatures.

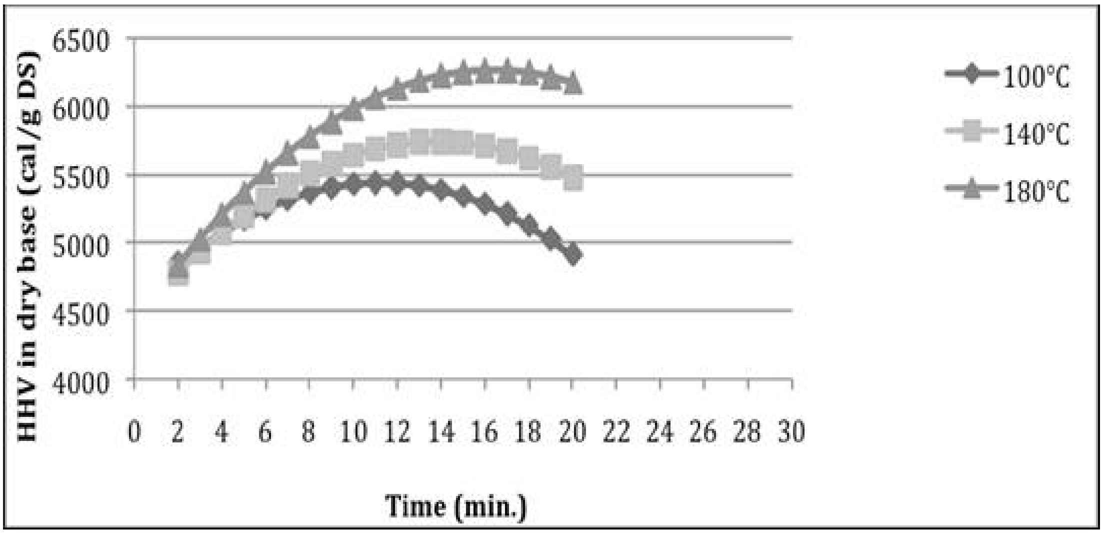

Figure 5.60 HHV in dry base curves for 1.5cm diameter samples fried sludge at three different temperatures.

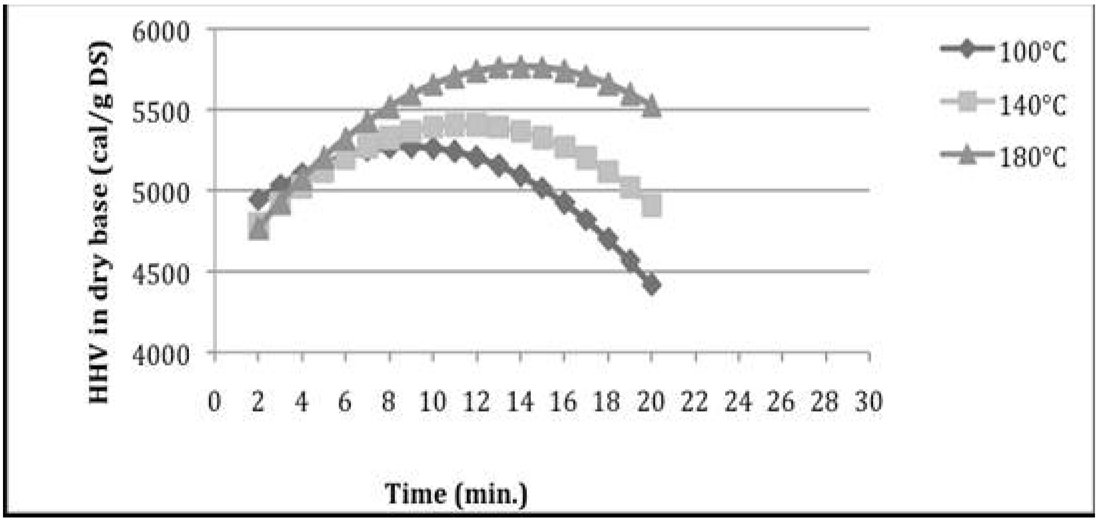

Figure 5.61 HHV in dry base curves for 2cm diameter samples fried sludge at three different temperatures.

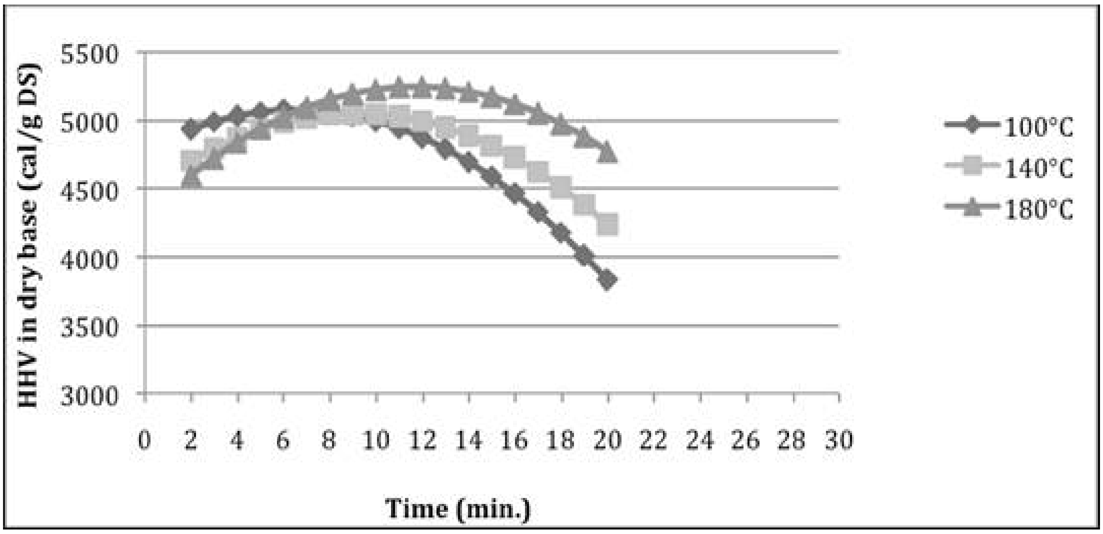

Figure 5.62 HHV in dry base curves for 2.5cm diameter samples fried sludge at three different temperatures.

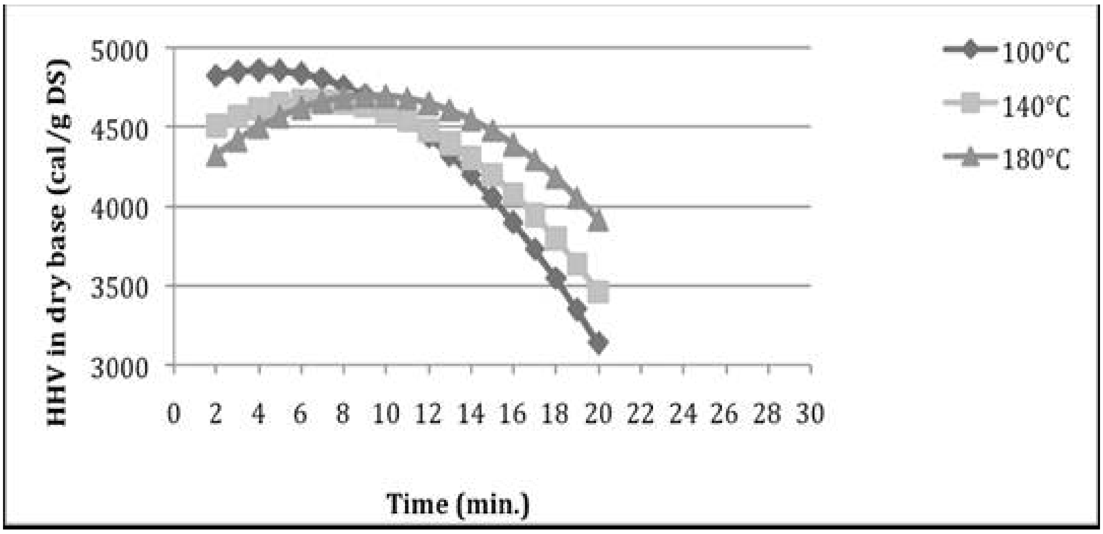

Figure 5.63 HHV in dry base curves for 3cm. diameter samples fried sludge at three different temperatures.

d) High Heating (Calorific) Value (HHV) of The Fried Sludge in Original Base

Table 5.14 shows the estimated coefficients of the response function of HHV values in original base, which were calculated by Statistica 7 program with the experimental data. The predicted HHV values were given in Table 5.15. The regression coefficient was found as R^2=0. 96701905.

High heating values in original base are shown as a function of temperature at different frying times and different sample diameters in Figures 5.64 and 5.68.

Table 5.14 HHV in original base response function coefficients.

bo	b1	b2	b3	b12
-2421.52	630.26	-14.77	2002.21	-0.33
b13	b23	b11	b22	b33
-132.00	-22.65	-9.75	0.35	236.51

Table 5.15 Predicted and residual values for HHV in original base of fry-dried samples with WEO.

Time(min)	Temperature(°C)	Diameter(cm)	Predicted	Residuals
20	140	2	3501.607	-420.132
2	140	2	1610.862	-88.731
11	180	2	5297.092	-130.497
11	100	2	2520.346	-281.682
11	140	3	1908.256	54.861
11	140	1	5257.163	-467.04
16	160	2.5	3094.499	240.415
16	160	1.5	5881.914	245.302
16	120	2.5	2225.735	59.944
16	120	1.5	4107.245	576.958
6	160	2.5	2770.751	-164.779
6	120	2.5	1768.674	166.877
6	160	1.5	4238.147	352.235
6	120	1.5	2330.166	171.764
11	140	2	3346.204	-744.877
11	140	2	3346.204	271.728
11	140	2	3346.204	157.654

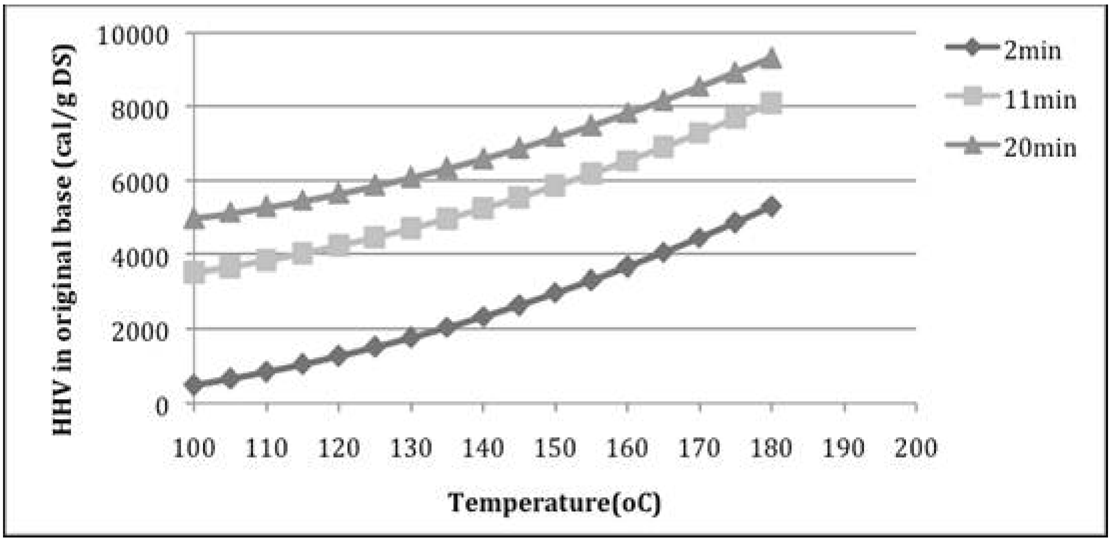

Figure 5.64 HHV in dry base curves for 1cm. diameter samples fry-dried sludge for three different process times.

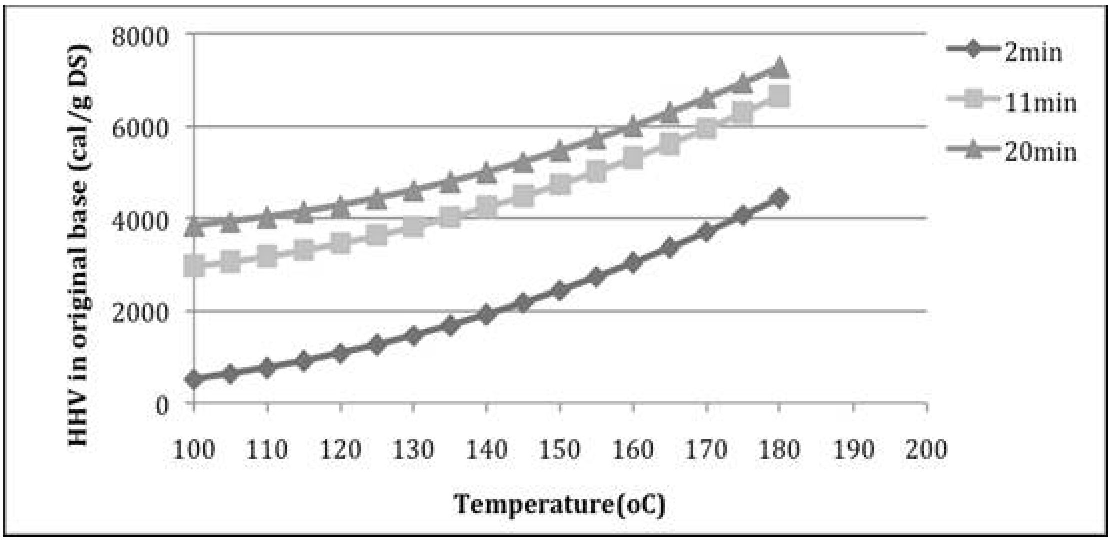

Figure 5.65 HHV in dry base curves for 1.5cm diameter samples fry-dried sludge for three different process times.

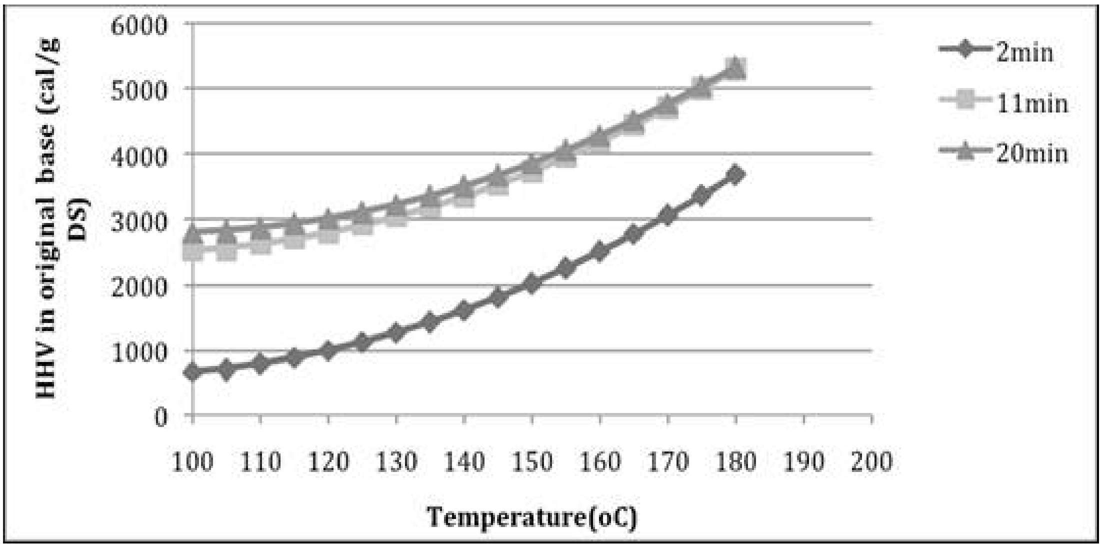

Figure 5.66 HHV in dry base curves for 2cm. diameter samples fry-dried sludge for three different process times.

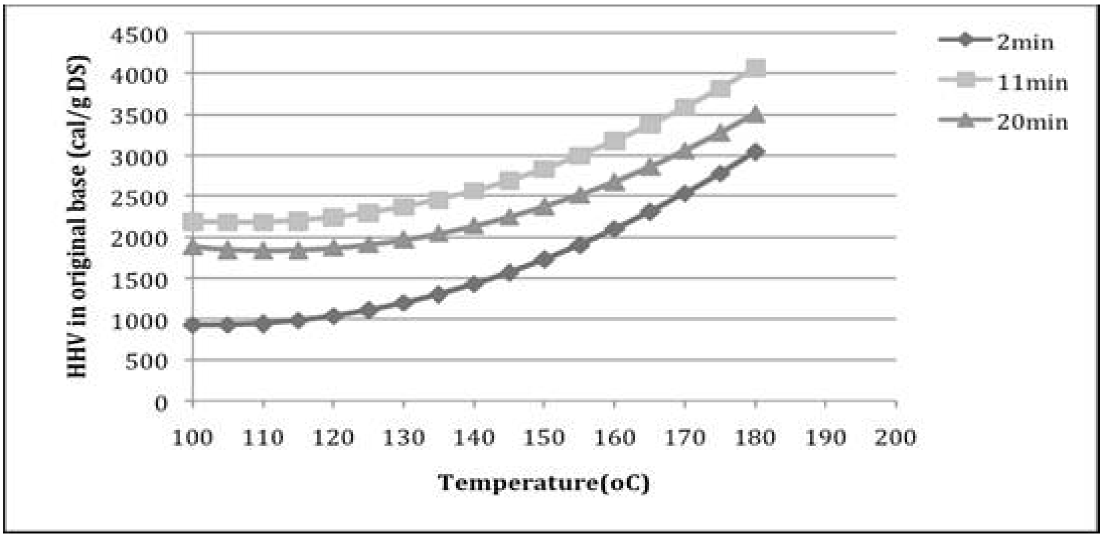

Figure 5.67 HHV in dry base curves for 2.5cm diameter samples fry-dried sludge for three different process times.

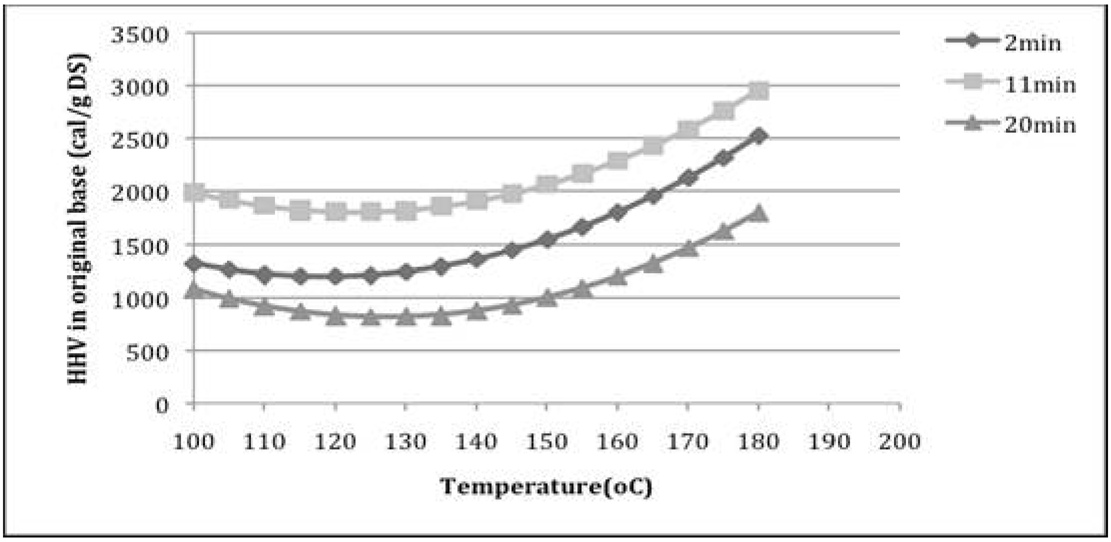

Figure 5.68 HHV in dry base curves for 3cm. diameter samples fry-dried sludge for three different process times.

Figures 5.69- 5.73 show the high heating values in original base as a function of time at different temperatures and different sample diameters. Similar observations were achieved as in LHV original and dry base calculations.

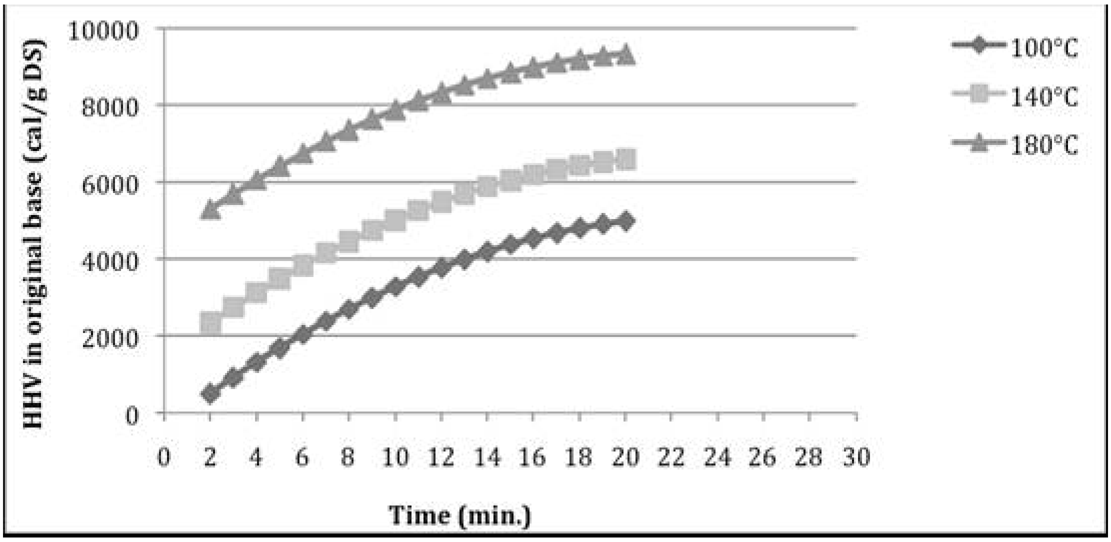

Figure 5.69 HHV in dry base curves for 1cm. diameter samples fried sludge at three different temperatures.

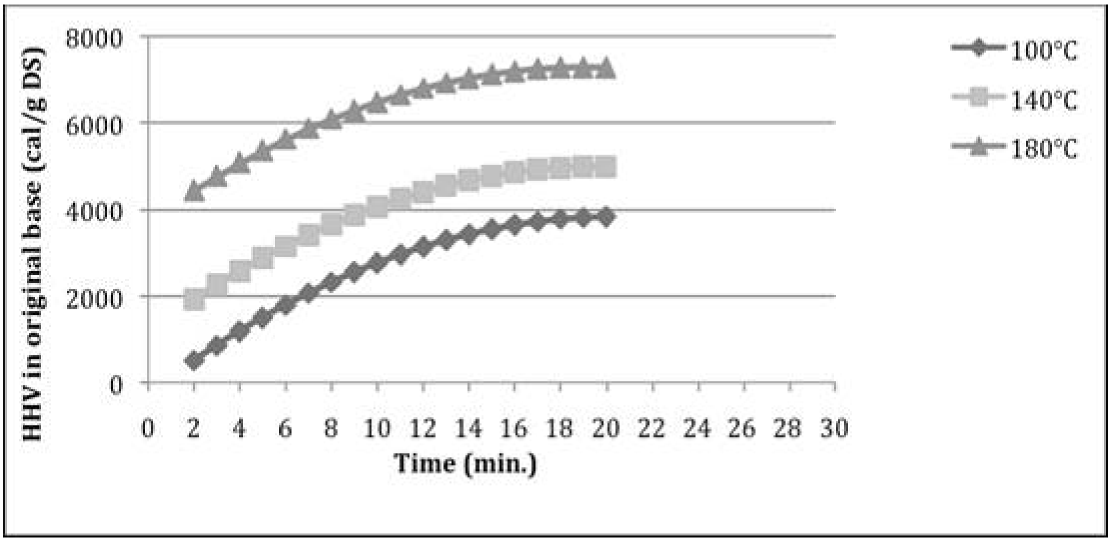

Figure 5.70 HHV in dry base curves for 1.5cm diameter samples fried sludge at three different temperatures.

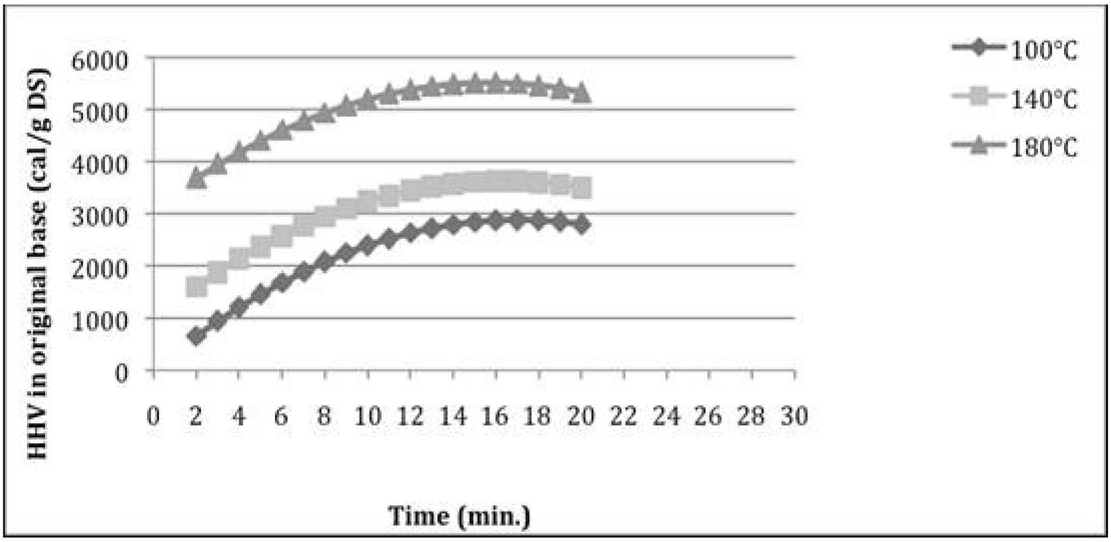

Figure 5.71 HHV in dry base curves for 2cm diameter samples fried sludge at three different temperatures.

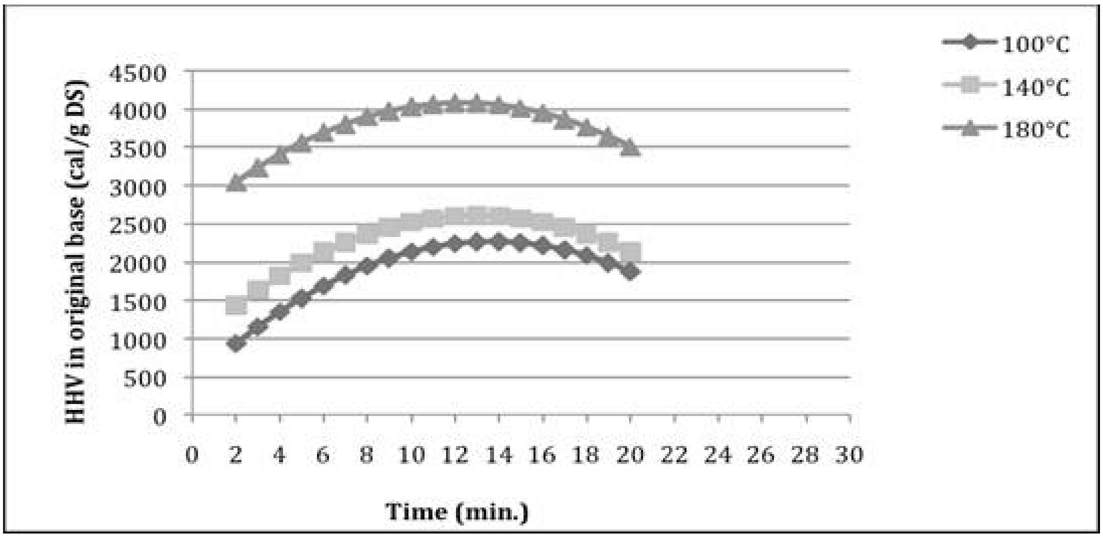

Figure 5.72 HHV in dry base curves for 2.5cm diameter samples fried sludge at three different temperatures.

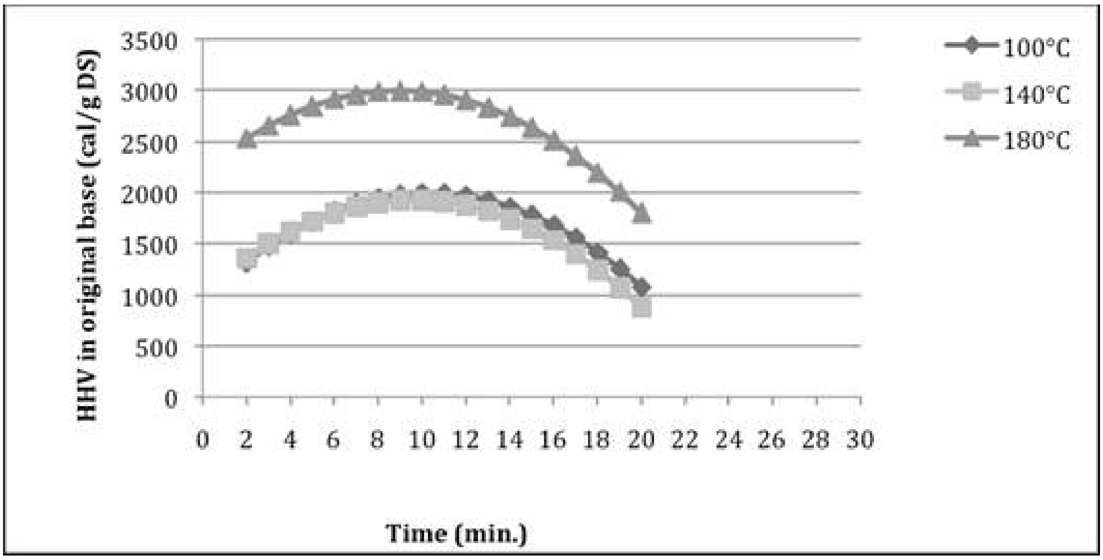

Figure 5.73 HHV in dry base curves for 3cm. diameter samples fried sludge at three different temperatures.

5.3.4 Oil Uptake Performance of Fry-dried sludge with Waste Engine Oil

During the frying process sludge uptakes oil while loses moisture. Relationships between oil uptake and cylinder diameters are shown in Figure 5.74 and 5.75. Frying different diameters at the same conditions showed that the bigger diameter samples have higher oil content than smaller diameter samples.

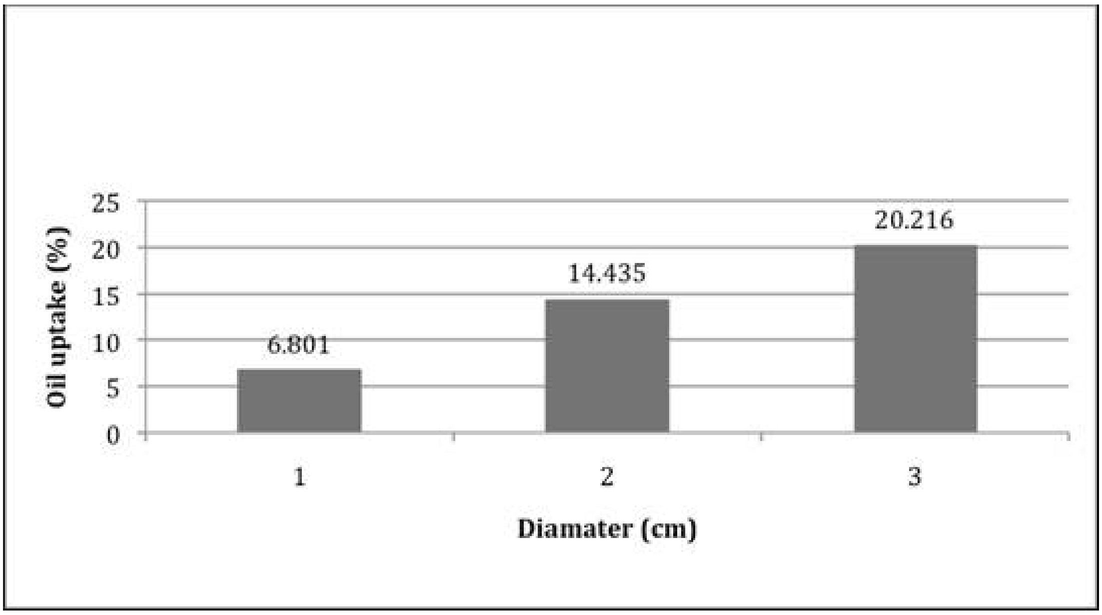

Figure 5.74 Effects of diameter on oil uptake results at 140 °C for 11 minutes fry-drying.

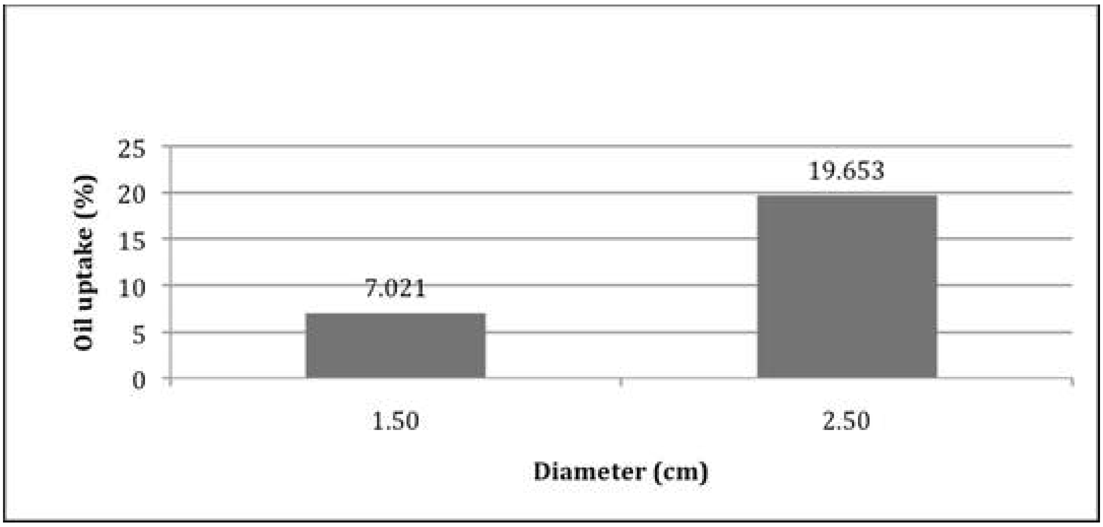

Figure 5.75 Effects of diameter on oil uptake results at 120 °C for 6 minutes fry-drying.

Figure 5.76 shows the oil uptakes of the fried 2cm diameter samples for 11 min. at different temperatures. The higher oil temperatures led to higher oil uptakes.

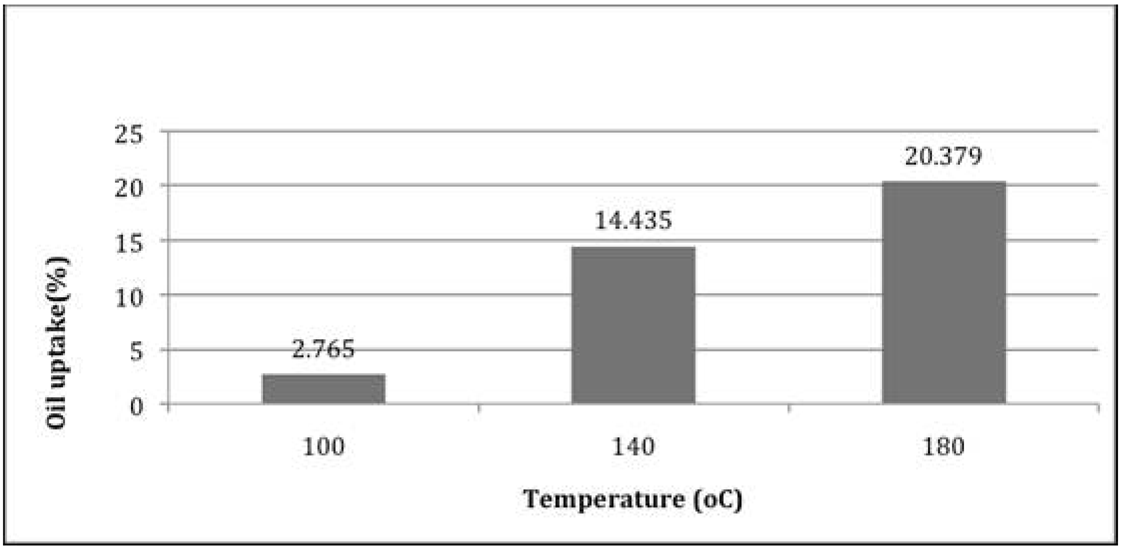

Figure 5.76 Oil uptake results fry-dried 2 cm. samples for 11 minutes at different temperatures.

Figure 5.77 presents the oil uptake results of fry-dried 2 cm. samples at 140°C for 2, 11, and 20 min. As seen from the figure, oil uptakes increased for 11 min. application; but it decreased for higher drying times.

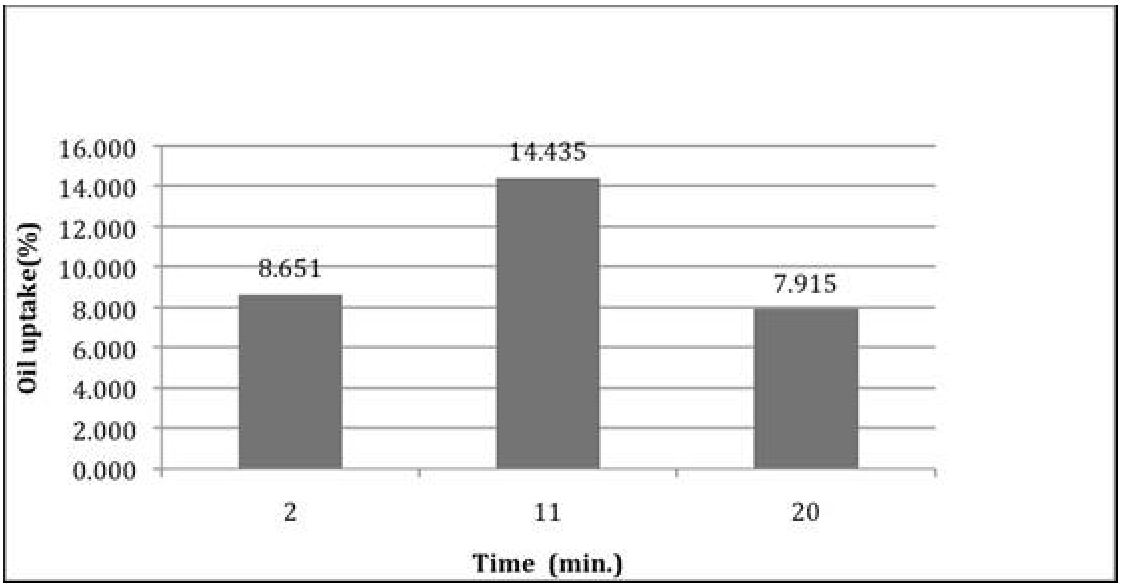

Figure 5.77 Effects of time on oil uptake results on fry-dried 2 cm. samples at 140 °C.

Figure 5.78 shows oil uptakes of 1.5 and 2.5 cm. samples fry-dried at 120°C and 160°C for 16 min. Higher diameter samples up taken oil much more than smaller diameter samples.

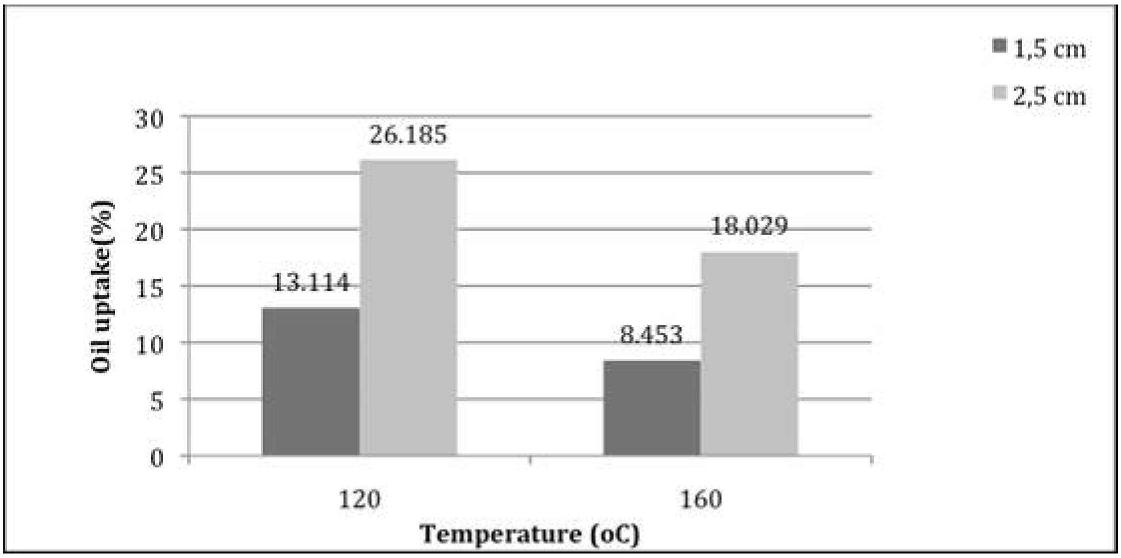

Figure 5.78 Effects of diameter and temperature on oil uptake results fry-dried samples for 16 minutes.

Figure 5.79 shows the oil uptakes for the 1.5 and 2.5 cm. diameter samples fried for 6 and 16 min. at 120 and 160°C.

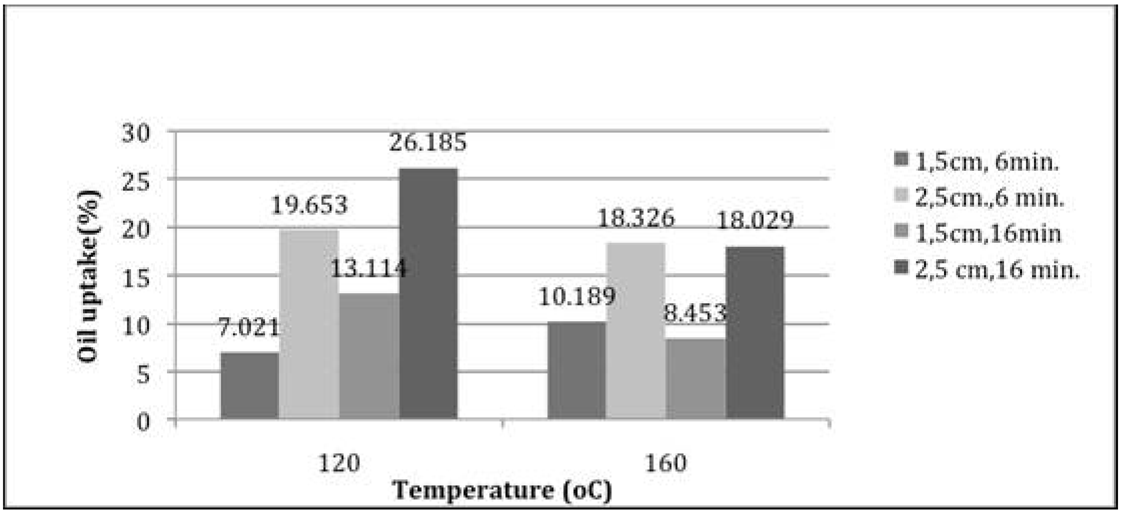

Figure 5.79 Effects of time, diameter, and temperature on oil uptake results.

Table 5.15 shows the estimated coefficients of the response function of oil uptake calculated by Statistica 7 program with the experimental data. The predicted oil contents were given in Table 5.16. The regression coefficient was obtained as R^2=0.8011496.

Table 5.15 Oil uptake response function coefficients.

bo	b1	b2	b3	b12
-82.0946	3.5275	0.6375	17.6495	-0.0183
b13	b23	b11	b22	b33
0.0940	-0.0999	-0.0465	-0.0006	1.0198

Table 5.16 Predicted and residual values for oil uptake of fry-dried samples with WEO.

Time(min)	Temperature(°C)	Diameter(cm)	Predicted	Residuals
20	140	2	11.76126	-3.84616
2	140	2	9.45704	-0.80585
11	180	2	16.48779	3.89162
11	100	2	10.42436	-7.65975
11	140	3	24.17344	-3.9575
11	140	1	6.61188	0.18937
16	160	2.5	17.18726	0.84202
16	160	1.5	9.934	-1.48144
16	120	2.5	19.81742	6.36768
16	120	1.5	8.56949	4.54427
6	160	2.5	19.10186	-0.77614
6	120	2.5	14.40294	5.24957
6	160	1.5	12.78823	-2.59955
6	120	1.5	4.09465	2.92611
11	140	2	14.3729	-4.0768
11	140	2	14.3729	0.06238
11	140	2	14.3729	1.13018

Oil uptake curves are shown as a function of temperature at different frying times and different sample diameters in between the Figures 5.80 and 5.84.

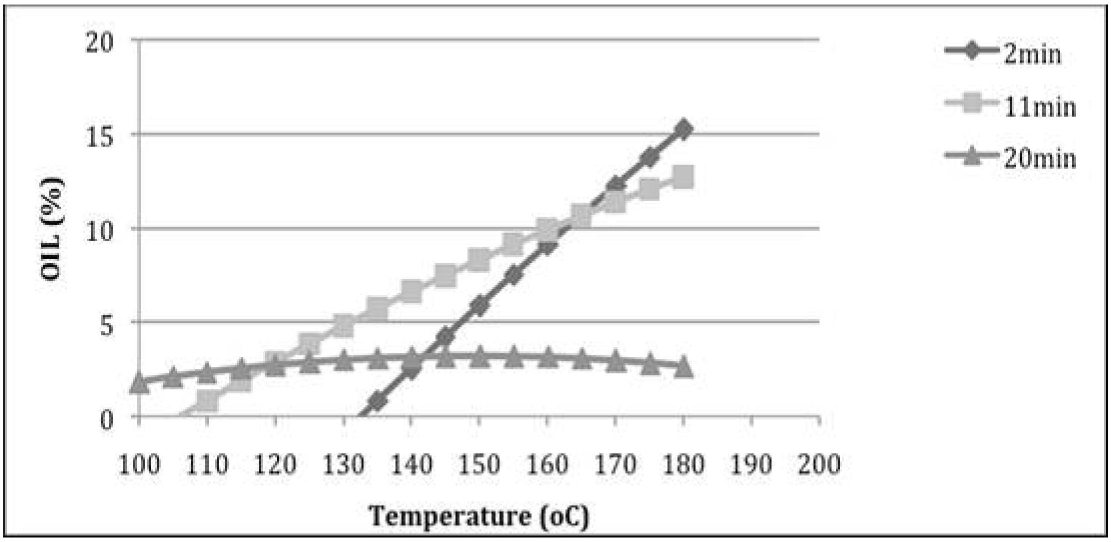

Figure 5.80 Oil uptake curves for 1cm diameter samples fry-dried sludge for three different process times.

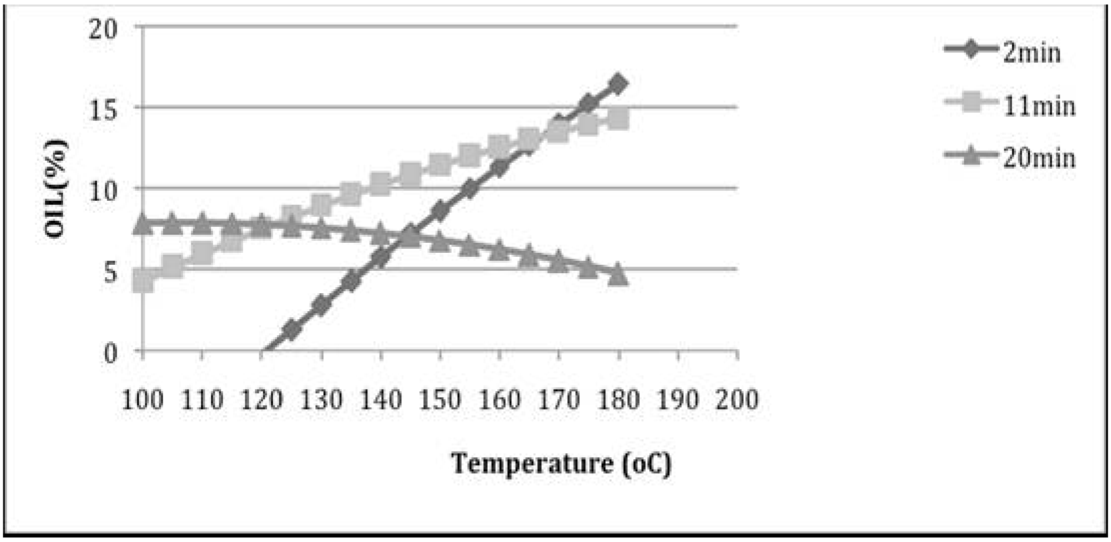

Figure 5.81 Oil uptake curves for 1.5cm diameter samples fry-dried sludge for three different process times.

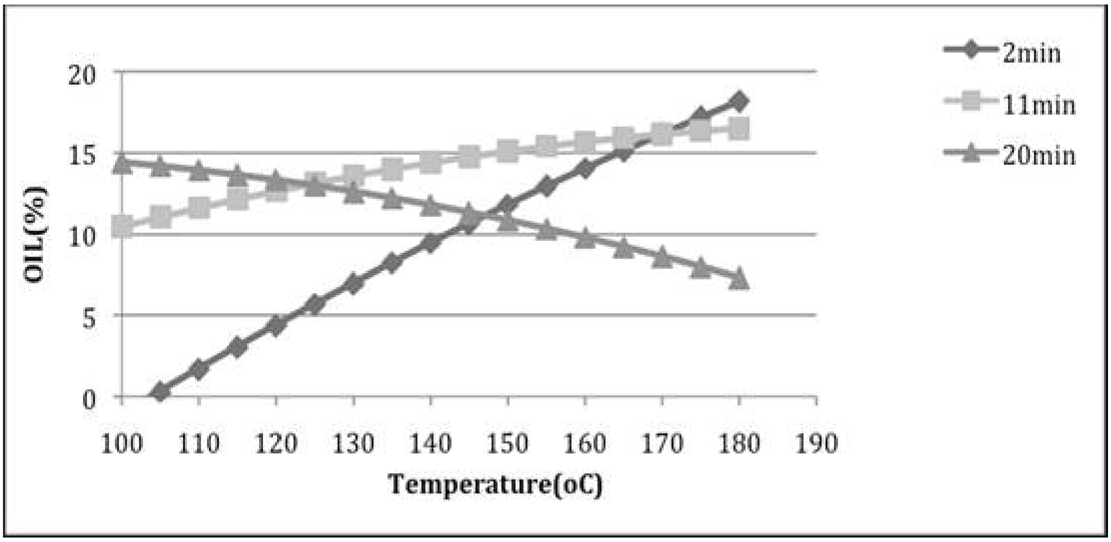

Figure 5.82 Oil uptake curves for 2cm diameter samples fry-dried sludge for three different process times.

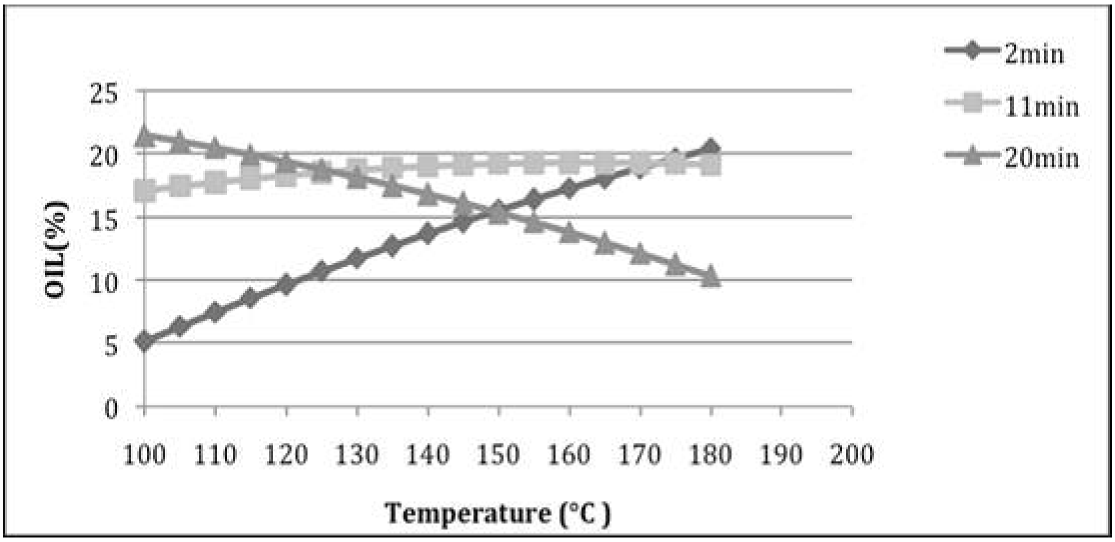

Figure 5.83 Oil uptake curves for 2.5cm diameter samples fry-dried sludge for three different process times.

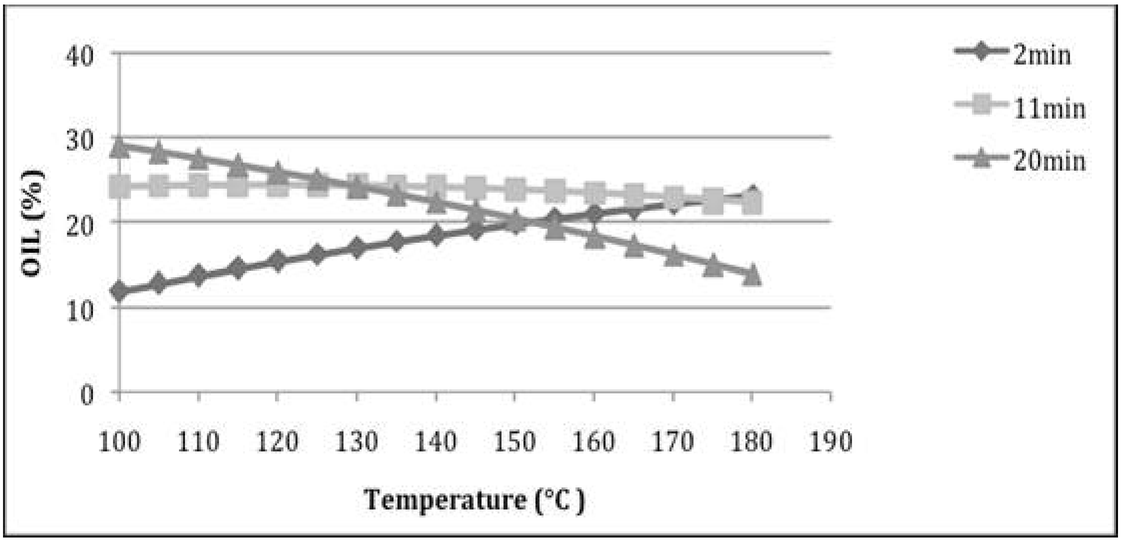

Figure 5.84 Oil uptake curves for 3cm diameter samples fry-dried sludge for three different process times.

Figures 5.85-5.89 show oil uptake curves as a function of time at different temperatures and different sample diameters.

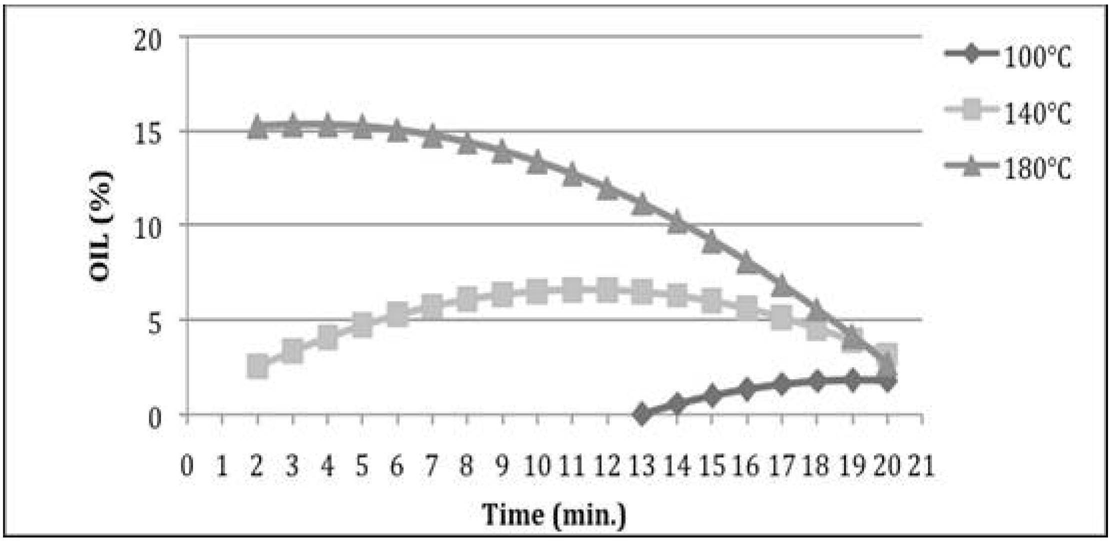

Figure 5.85 Oil uptake curves for 1cm. diameter samples fried sludge at three different temperatures.

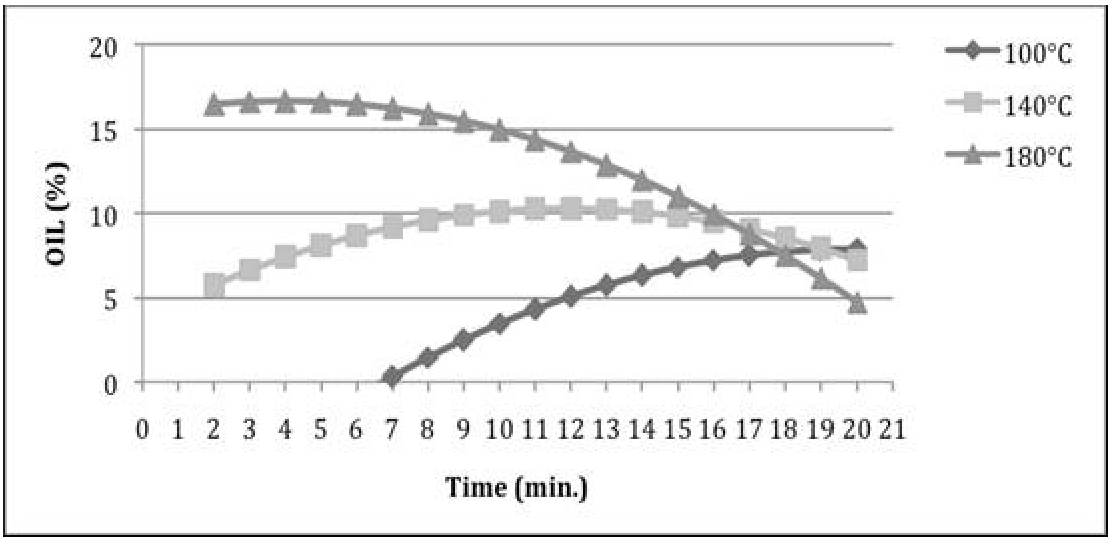

Figure 5.86 Oil uptake curves for 1.5cm diameter samples fried sludge at three different temperatures.

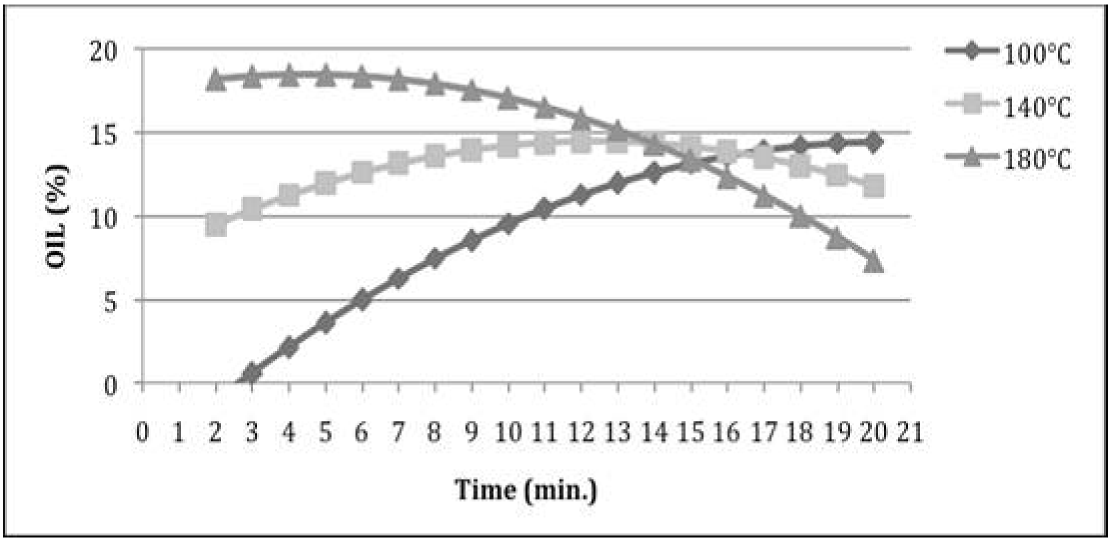

Figure 5.87 Oil uptake curves for 2cm diameter samples fried sludge at three different temperatures.

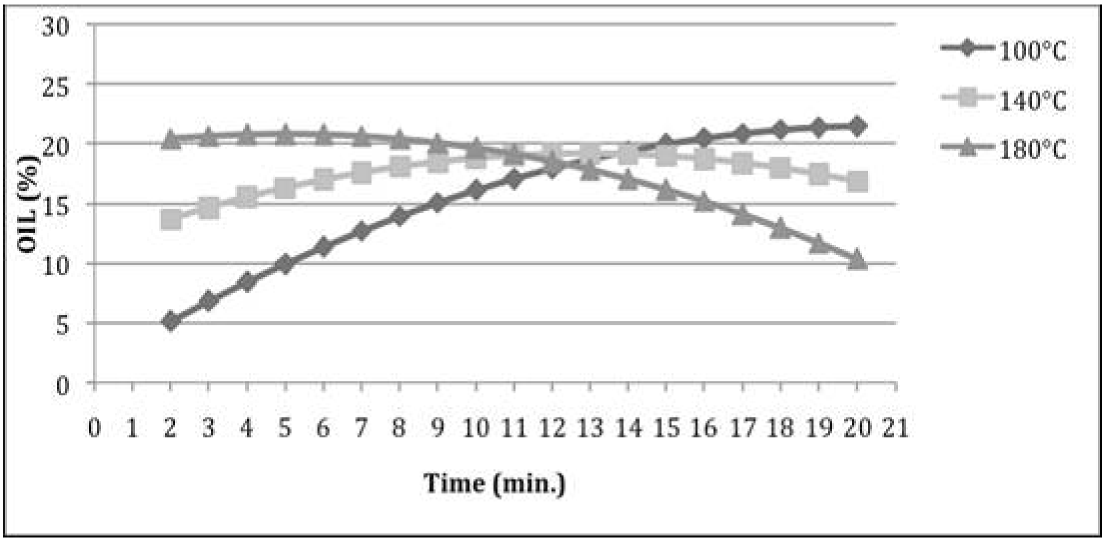

Figure 5.88 Oil uptake curves for 2.5cm diameter samples fried sludge at three different temperatures.

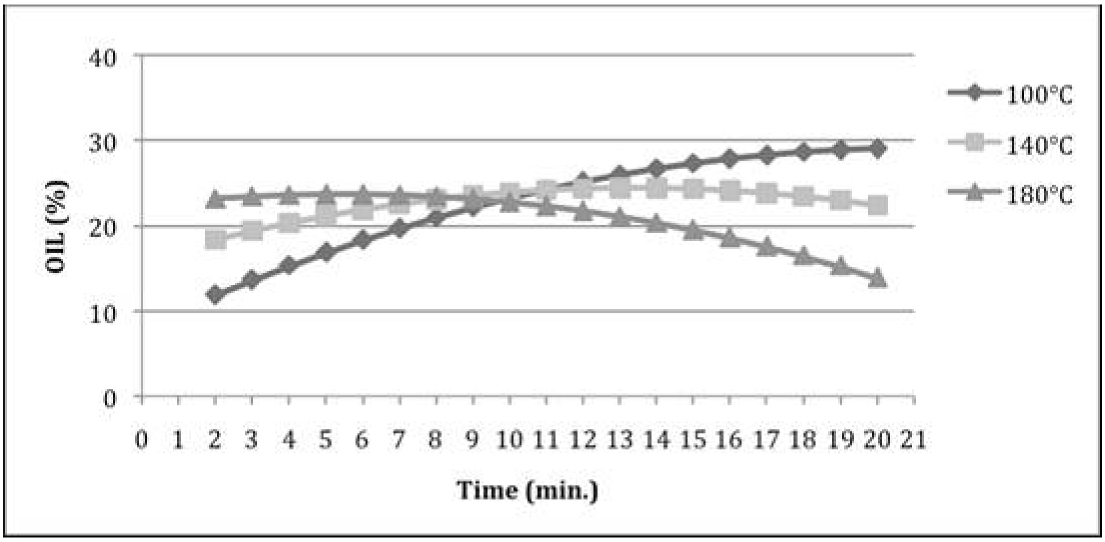

Figure 5.89 Oil uptake curves for 3cm diameter samples fried sludge at three different temperatures.

During the fry-drying applications, the sludge samples having different thickness gained an additional heating value. Increased DS contents of the samples were obtained and similarly VS contents of the samples increased in the temperature range of 120- 160 °C. Some pictures from the experimental studies showing the dewatered sludge cake and fry-dried sludge samples are given in Figure 5.90. This application was also done using waste cooking oil. In the subsequent sections, the results for the WCO application will be given.

Figure 5.90 Some pictures from the experimental studies showing the dewatered sludge cake and fry-dried sludge samples with WEO.

5.4 Results Of The Fry-Drying With Waste Cooking Oil

Three operating parameters: frying time (X_1), frying temperature (X_2) and sludge samples diameter (X_3) were chosen as independent variables as in the first experimental study done by using waste engine oil. Experimental data points used in Box-Wilson were; frying time (X_1) between 2-20 minutes, frying temperature (X_2) between 100 -180 °C and sludge samples diameter (X_3) 1-3 cm. (as given in Table 5.2). The performance of the fry-drying process was described by the following response function:

$$Y=b_o + b_1X_1 + b_2X_2 + b_3X_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2$$

The relationships between the frying time, temperature and sample's diameter for the response functions – DS, VS, LHV, HHV, and oil uptake are discussed in details in this subsection.

5.4.1 Dry Solids Content Results of the Fry-drying Process with Waste Cooking Oil

DS contents of dewatered sludge and fry-dried sludge determined at the data points calculated by Box-Wilson statistical design are given in Table 5.16. The obtained DS results are given in Table 5.17. DS values increased with the increasing frying time and temperature and the decreasing cylinder diameter of the samples. WCO application produced dried sludge products having higher DS content than those in WEO results. Even, more than 95% DS results were obtained for some applications as shown in Table 5.16.

Table 5.16 DS results of raw sludge and fry-dried sludge with WCO.

Time (X_1), min	**Temperature (X_2), °C**	**Diameter (X_3), cm**	**DS (%)**
No frying time	25	Dewatered sludge cake	22.99
20	140	2	98.41
2	140	2	37.99
11	180	2	95.22
11	100	2	35.87
11	140	3	40.00
11	140	1	99.53
16	160	2.5	93.82
16	160	1.5	99.43
16	120	2.5	49.04
16	120	1.5	85.67
6	160	2.5	48.57
6	120	2.5	34.98
6	160	1.5	99.40
6	120	1.5	51.02
11	140	2	81.69
11	140	2	73.00
11	140	2	82.06

Figures 5.91 and 5.92 showed the effects of cylinder diameters on dry solid results. Frying at the same conditions for the samples having different diameters showed that the smaller diameter samples were dried better then the higher diameter samples.

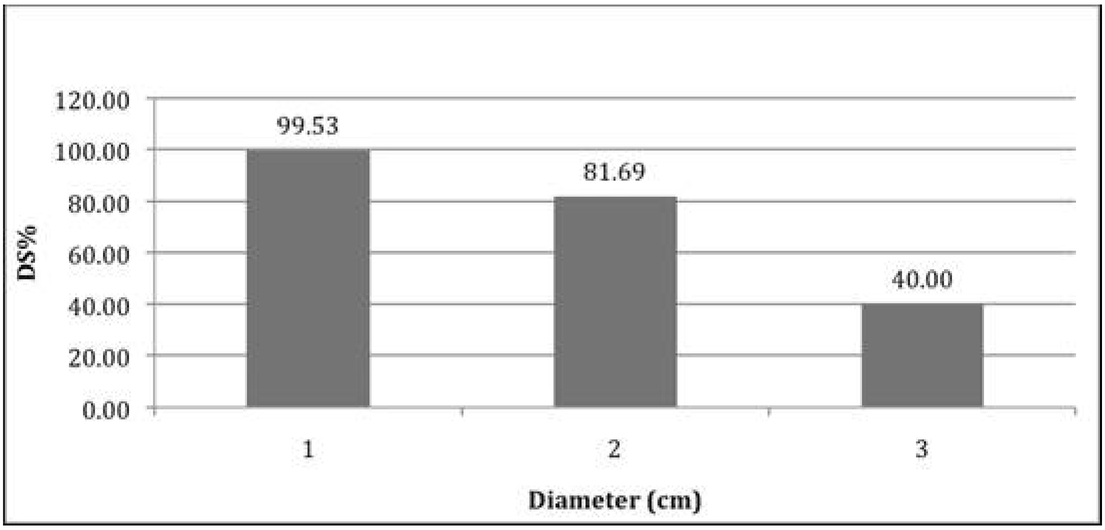

Figure 5.91 effects of diameter on DS results at 140 °C for 11 minutes fry-drying.

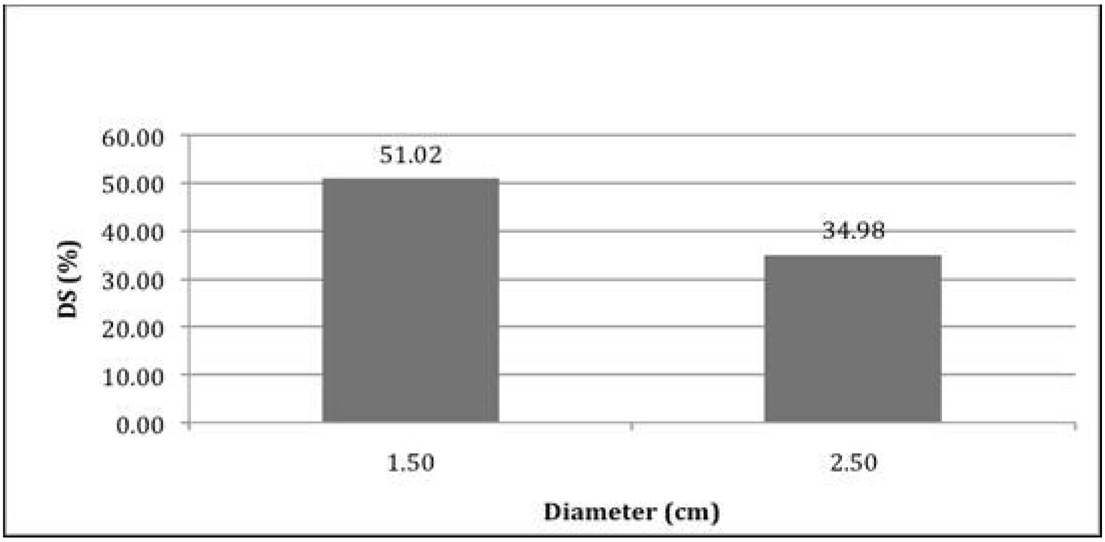

Figure 5.92 Effects of diameter on DS results at 120 °C for 6 minutes fry-drying.

Temperature is another important parameter affecting the DS results. Figure 5.93 shows the DS results for the fry-drying applied samples having 2 cm diameter at different temperatures for 11 min. The higher oil temperatures led to higher DS contents of the sludge samples.

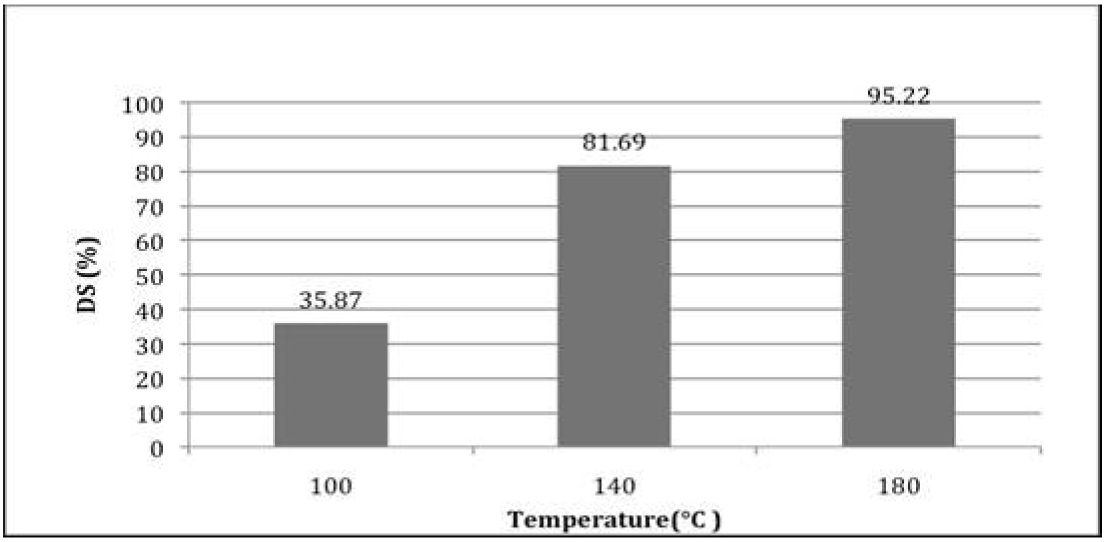

Figure 5.93 DS results fry-dried 2 cm samples for 11 minutes at different temperatures.

Figure 5.94 gives the DS results of fry-dried 2 cm. samples at 140°C for 2,11, and 20 min. of frying time. DS contents of the sludge samples results increased by longer drying times.

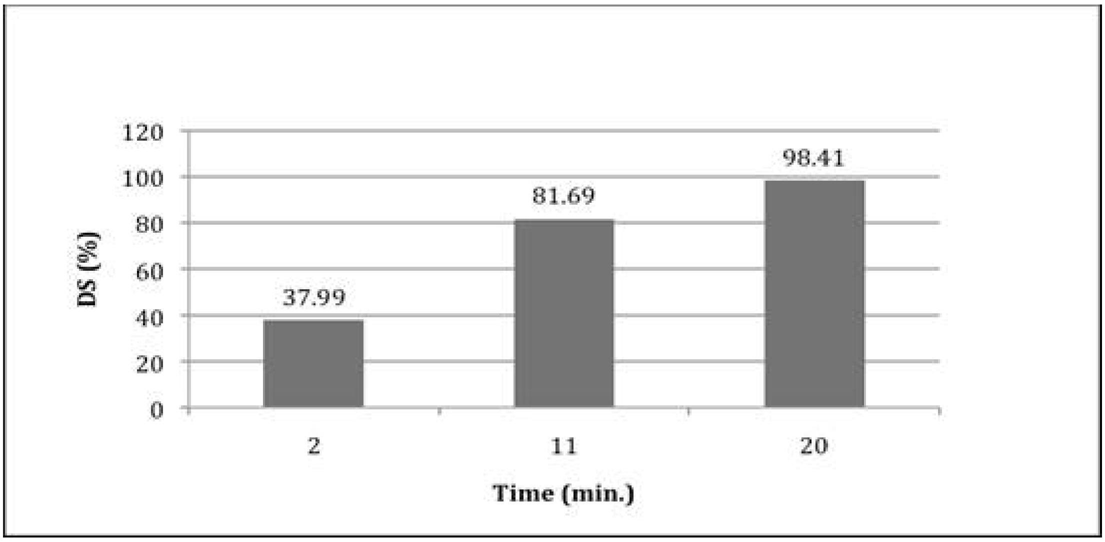

Figure 5.94 Effects of fry-drying time on DS results for fry-dried 2 cm samples at 140 °C.

Figure 5.95 shows DS results of 1.5 and 2.5 cm. samples fry-dried at 120 °C and 160 °C for 16 min. Figure 5.96 presents DS results of 1.5 and 2.5 cm. samples fry-dried at 120 °C and 160 °C for 6 and 16 min. It is clear from the figures, DS contents of the samples having smaller diameters were higher than those having bigger diameters. At the same oil temperature conditions, DS increased depending on the increases in the time and temperature.

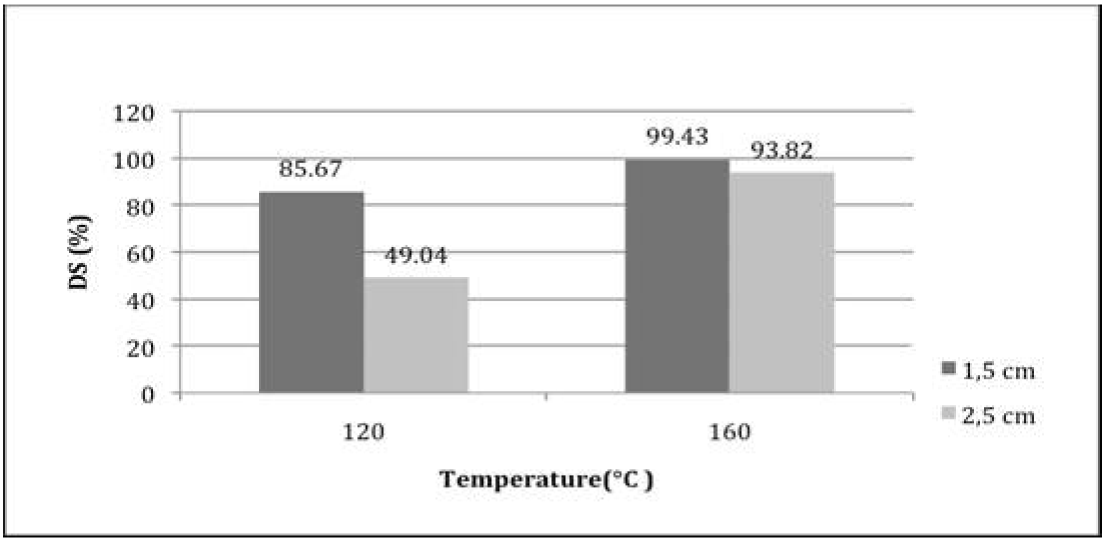

Figure 5.95 Effects of diameter and temperature on DS results fry-dried samples for 16 minutes.

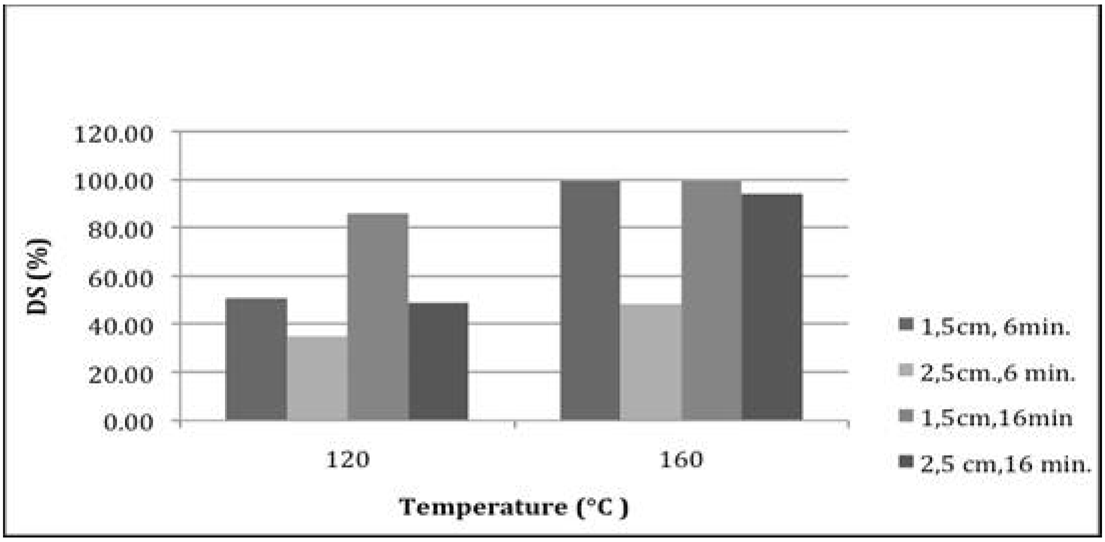

Figure 5.96 Effects of time, diameter, and temperature on DS results.

Depending on the experimental data, the DS response function was calculated by using Statistica 7 program. Table 5.17 gives the estimated coefficients of the response function. The regression coefficient was achieved as R^2=0. 96719027. The predicted and residual values for dry solids content of fry-dried samples were also presented in Table 5.18.

Table 5.17 DS response function coefficients.

bo	b1	b2	b3	b12
-.207267	3.818	3.217	0.857	-0.004
b13	b23	b11	b22	b33
1.231	-0.047	-0.131	-0.008	-9.085

Table 5.18 Predicted and residual values for dry solids content of fry-dried samples with WCO.

Temperature (°C)	Time (min)	Diameter (cm)	Predicted	Residuals
20	140	2	93.5678	4.8456
2	140	2	43.1627	-5.1709
11	180	2	95.5799	-0.3570
11	100	2	35.7755	0.0935
11	140	3	41.3758	-1.3757
11	140	1	98.4205	1.1121
16	160	2.5	86.9811	6.8373
16	160	1.5	110.2876	-10.8560
16	120	2.5	58.8726	-9.8373
16	120	1.5	80.2975	5.3681
6	160	2.5	53.6745	-5.1047
6	120	2.5	23.8603	11.1196
6	160	1.5	89.2944	10.1009
6	120	1.5	57.5985	-6.5740
11	140	2	78.9827	2.7032
11	140	2	78.9827	-5.9859
11	140	2	78.9827	3.0812

DS results as a function of temperature at different frying times for different sample diameters as 1, 1.5, 2, 2.5, 3 cm are shown in figures between 5.97 and 5.101. DS contents of the samples having 1 and 1.5 cm diameters were the highest values and also DS increased for all applications with the increasing time and temperature.

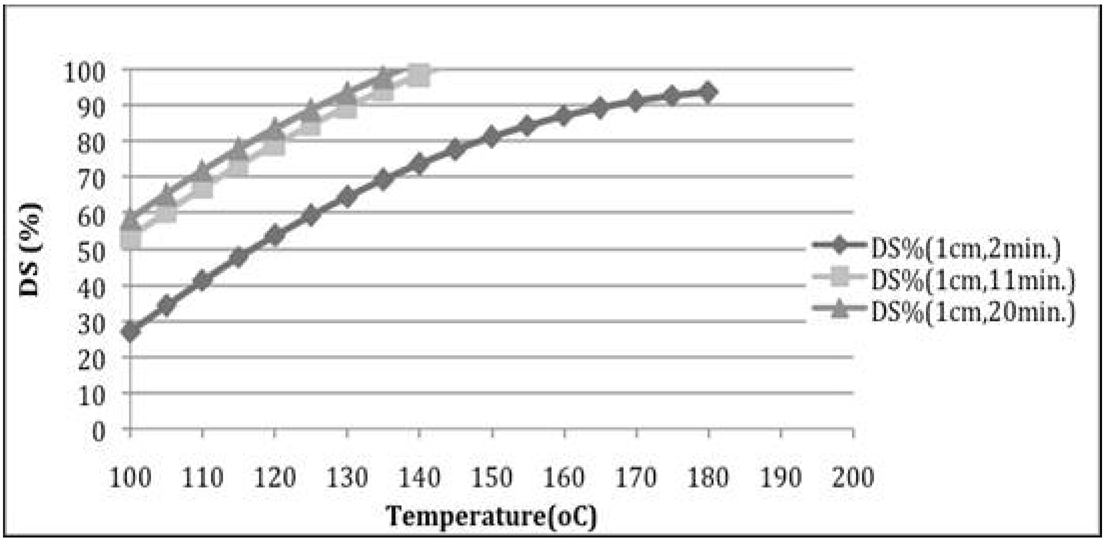

Figure 5.97 DS content curves for 1cm. diameter samples fried sludge for three different process times.

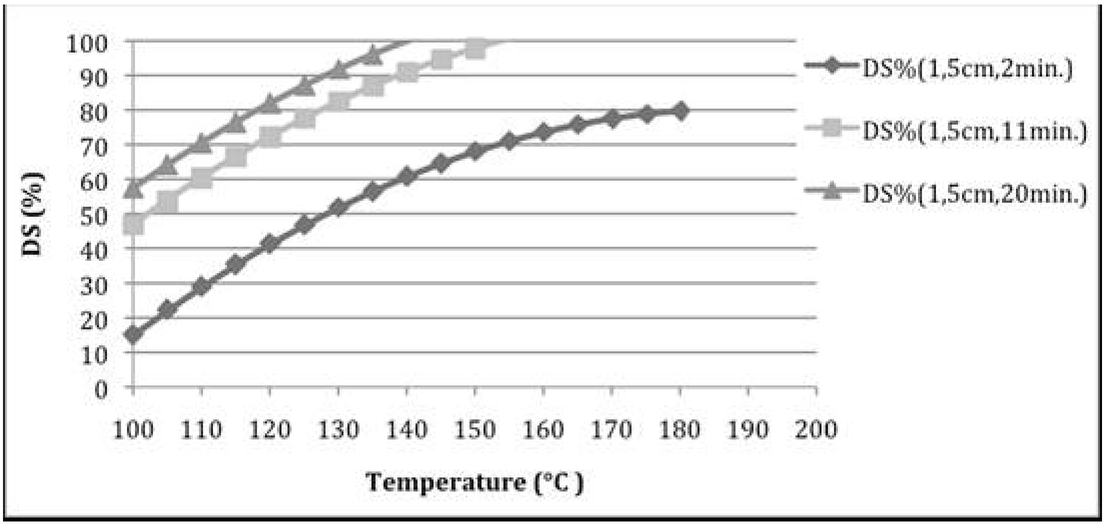

Figure 5.98 DS content curves for 1.5cm diameter samples fried sludge for three different process times.

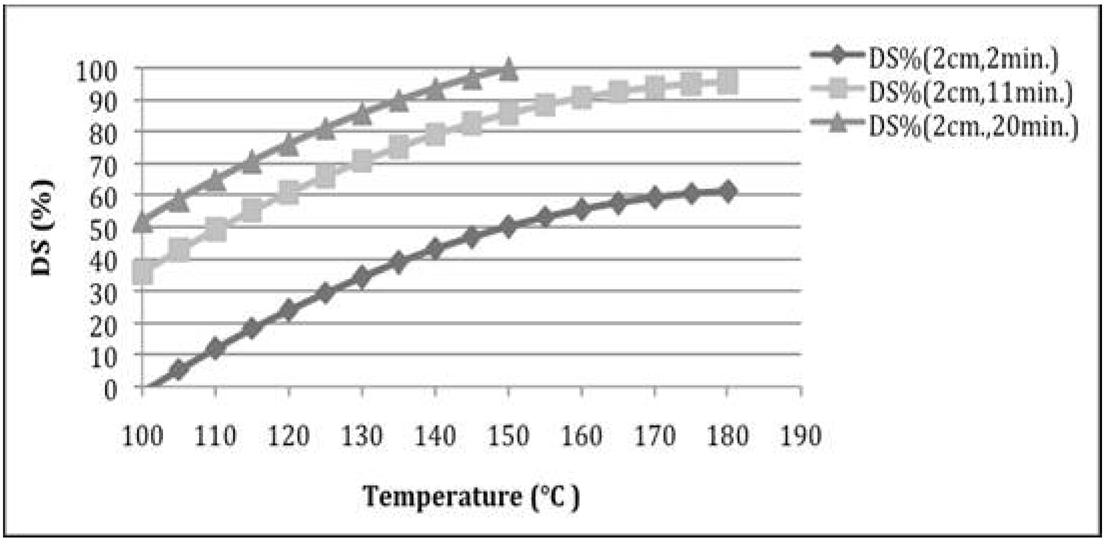

Figure 5.99 DS content curves for 2cm diameter samples fried sludge for three different process times.

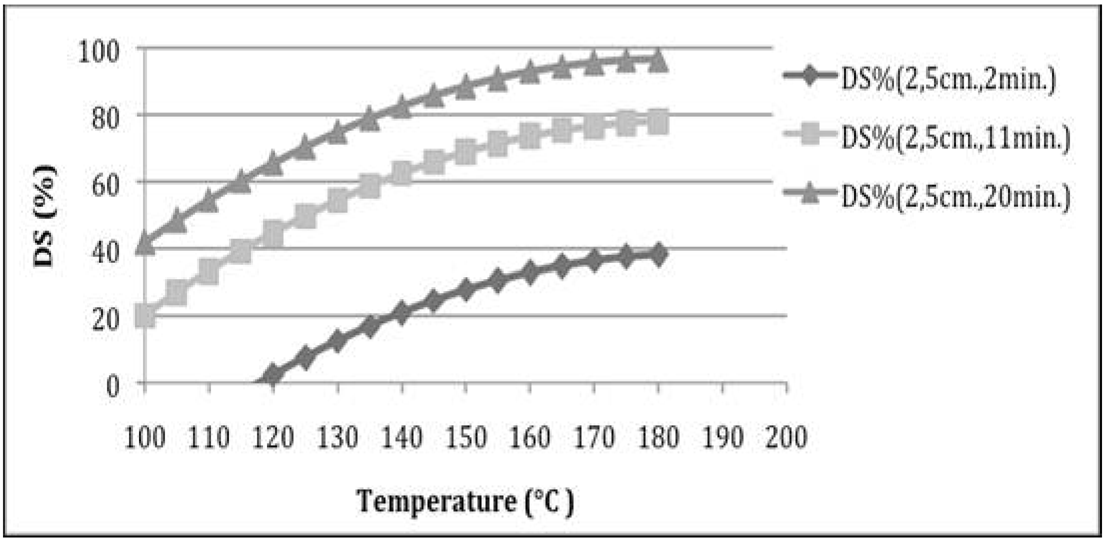

Figure 5.100 DS content curves for 2.5cm diameter samples fried sludge for three different process times.

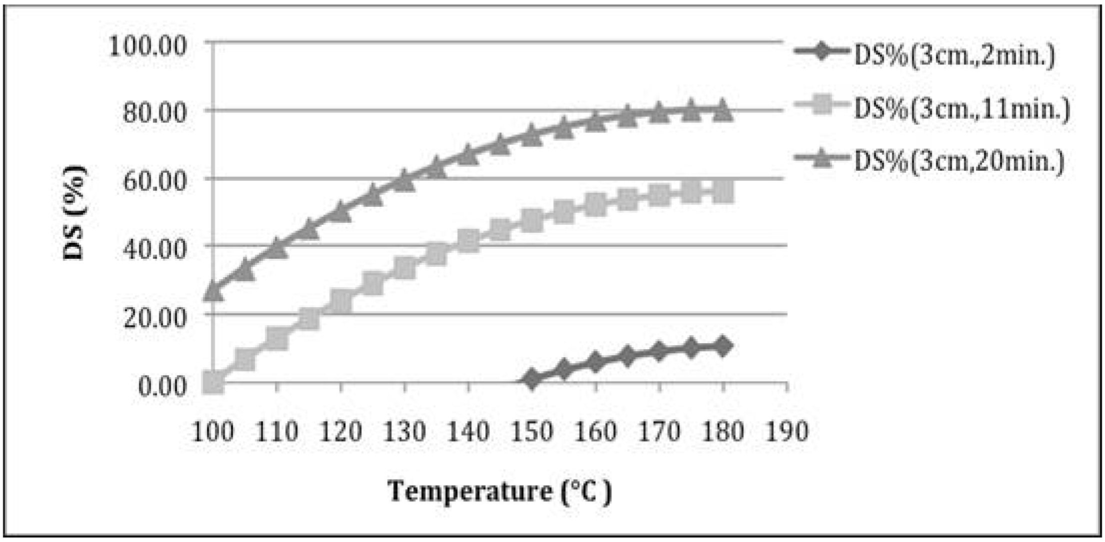

Figure 5.101 DS content curves for 3cm diameter samples fried sludge for three different process times.

Figures 5.102- 5.106 showed the DS results as a function of frying time at different temperatures and different sample diameters. For the samples having 1 and 1.5 cm diameter, a few minutes of frying time was enough to reach the DS higher than 90% at 180 °C of the oil temperature. Lowest temperature application at 100 °C did not produce higher DS content as well as the temperature range in 140-180 °C. Similar observations were obtained in the literature (e.g., Peregrina et al., 2006; Romdhana et al., 2009).

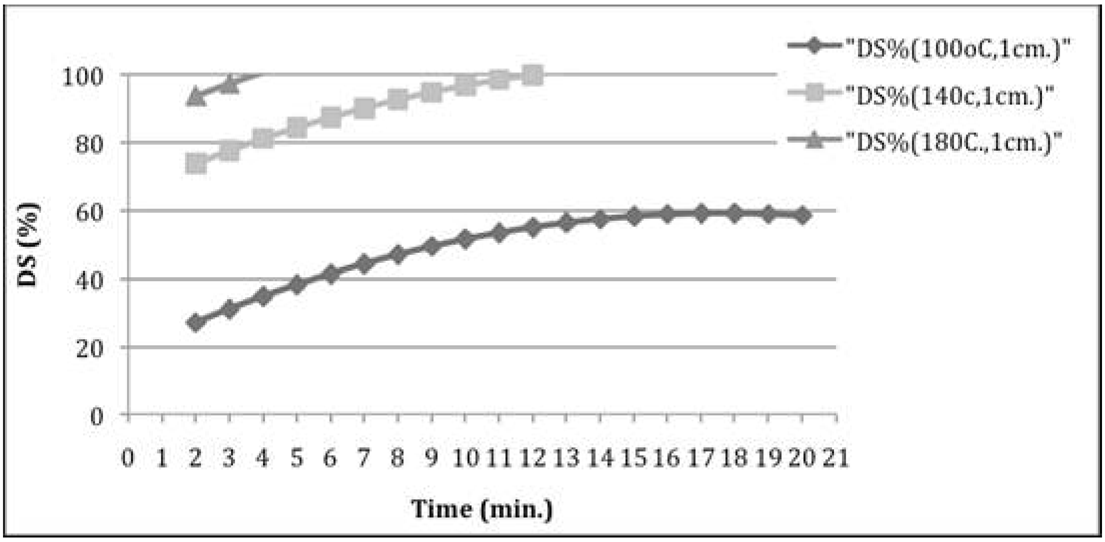

Figure 5.102 DS content curves for 1cm. diameter samples fried sludge at three different temperatures.

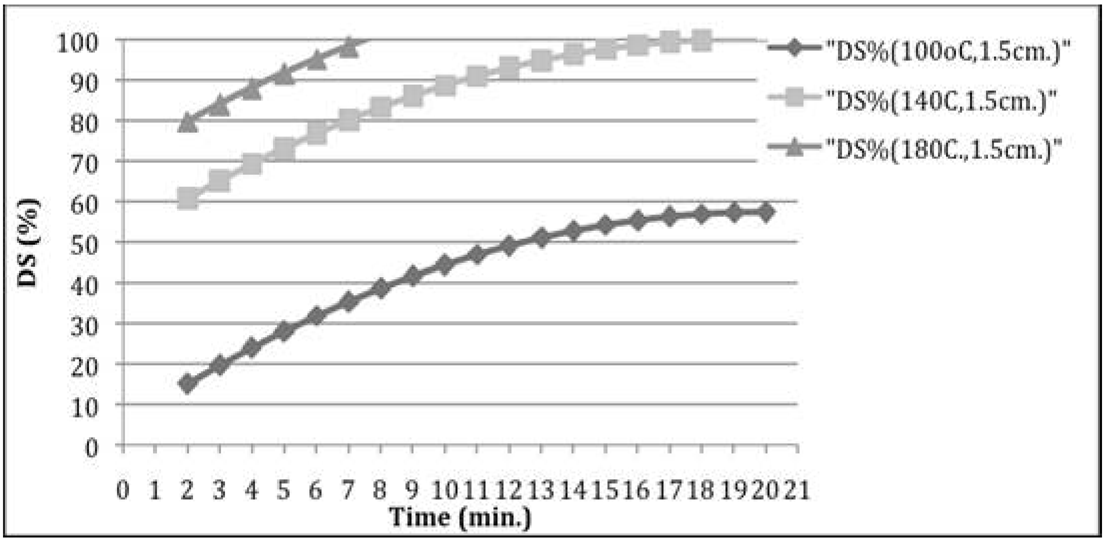

Figure 5.103 DS content curves for 1.5cm diameter samples fried sludge at three different temperatures.

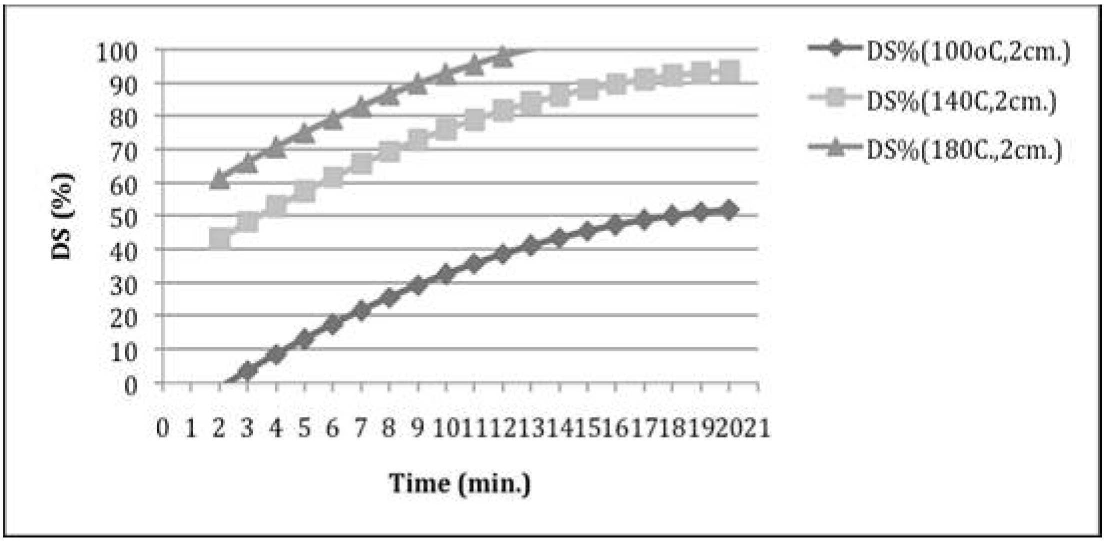

Figure 5.104 DS content curves for 2cm diameter samples fried sludge at three different temperatures.

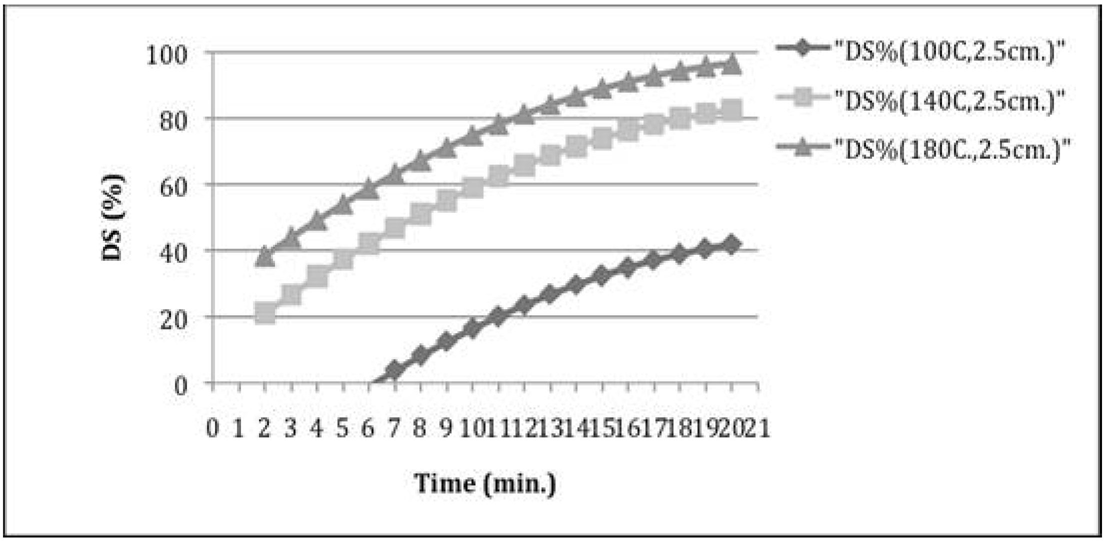

Figure 5.105 DS content curves for 2.5cm diameter samples fried sludge at three different temperatures.

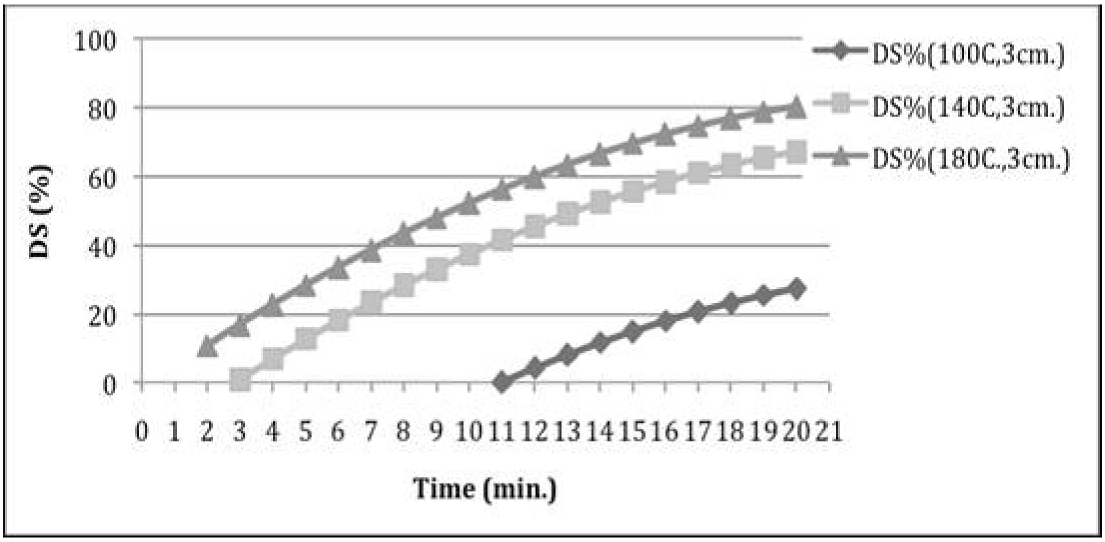

Figure 5.106 DS content curves for 3cm. diameter samples fried sludge at three different temperatures.

5.4.2 Volatile Solids Content (VS) Results of Fry-dried sludge with Waste Cooking Oil

VS contents of raw sludge and fry-dried sludge were determined at the data points calculated by Box-Wilson statistical design as shown Table 5.2. The experimental results are given in Table 5.19.

Table 5.19 VS results of sludge cake and fry-dried sludge with WCO.

Time (X_1), min	**Temperature (X_2), °C**	**Diameter (X_3), cm**	**VS (%)**
No frying time	25	Dewatered sludge cake	54.38
20	140	2	66.27
2	140	2	60.26
11	180	2	67.29
11	100	2	60.40
11	140	3	59.01
11	140	1	70.14
16	160	2.5	63.25
16	160	1.5	69.24
16	120	2.5	62.11
16	120	1.5	66.96
6	160	2.5	58.52
6	120	2.5	57.27
6	160	1.5	66.49
6	120	1.5	62.52
11	140	2	63.80
11	140	2	63.65
11	140	2	65.76

The effects of cylinder diameters on volatile solid results are given in Figure 5.107 and 5.108. Smaller diameter samples have higher VS contents than the bigger diameter samples.

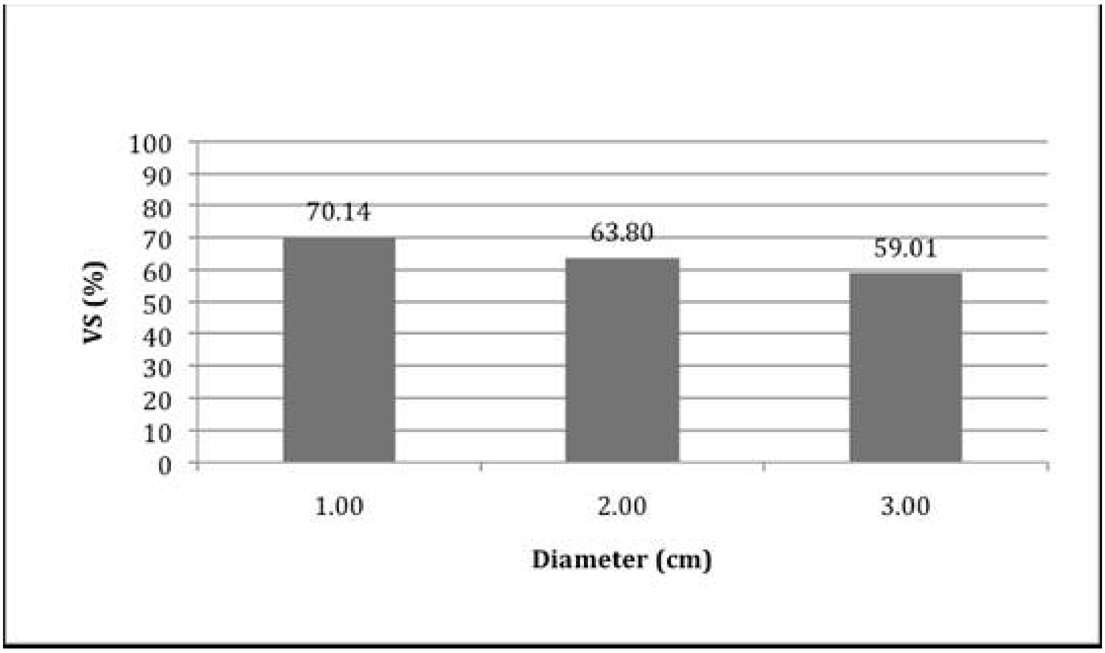

Figure 5.107 Effects of diameter on VS results at 140 °C for 11 minutes fry-drying.

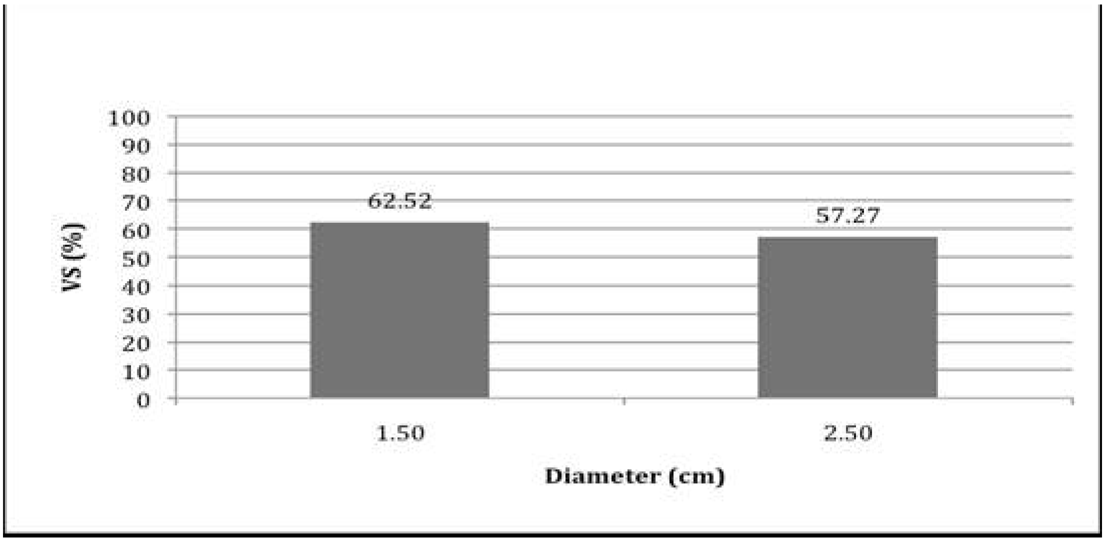

Figure 5.108 Effects of diameter on VS results at 120 °C for 6 minutes fry-drying.

Figure 5.109 shows VS results for the fry-drying applied samples having 2 cm diameter at different temperatures for 11 min. The higher oil temperatures led to lower VS contents. It might be due to volatile fraction of the material is vaporized at the high temperatures.

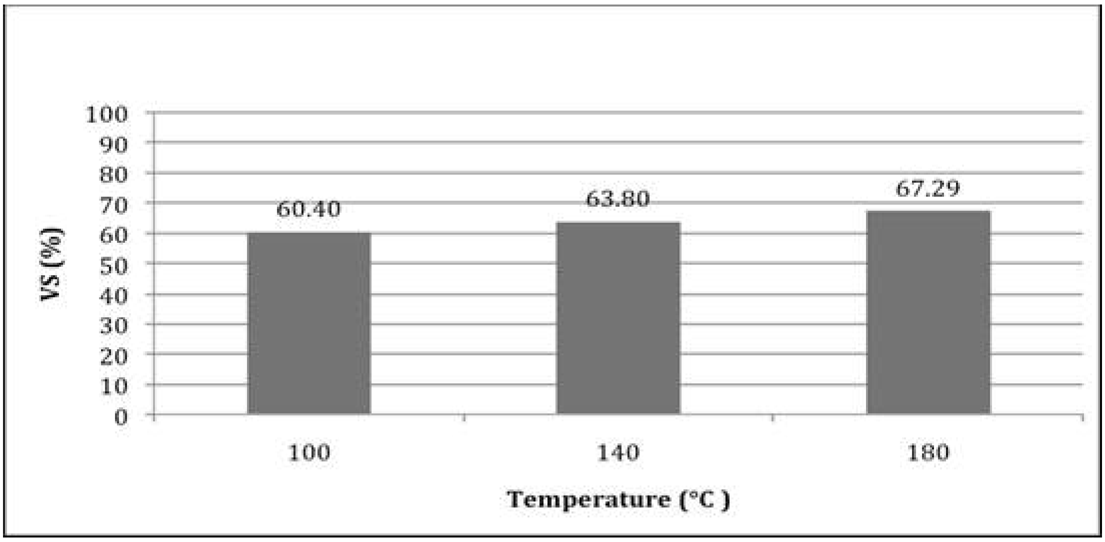

Figure 5.109 VS results fry-dried 2 cm. samples for 11 minutes at different temperatures.

Figure 5.110 presents the VS results of fry-dried 2 cm. samples at 140°C for 2, 11, and 20 min. As seen from the figure, VS results increase slightly for 11 min. of the frying time. Figure 5.111 shows the VS results of 1.5 and 2.5cm. samples fry-dried at 120°C and 160°C for 16 min. VS results are slightly increased by the temperature and are higher values for smaller diameters.

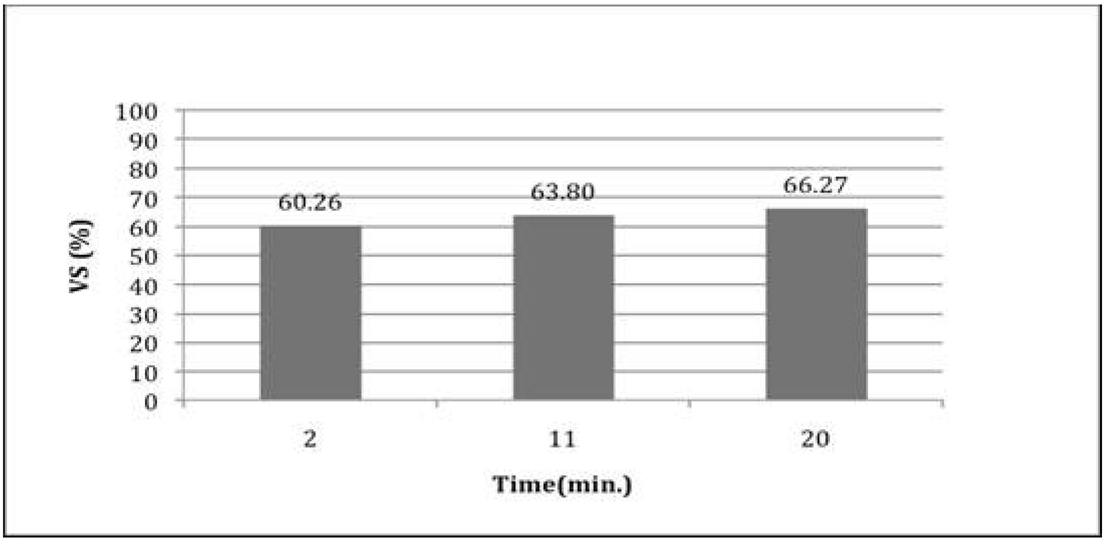

Figure 5.110 Effects of time on VS results on fry-dried 2 cm. samples at 140 °C.

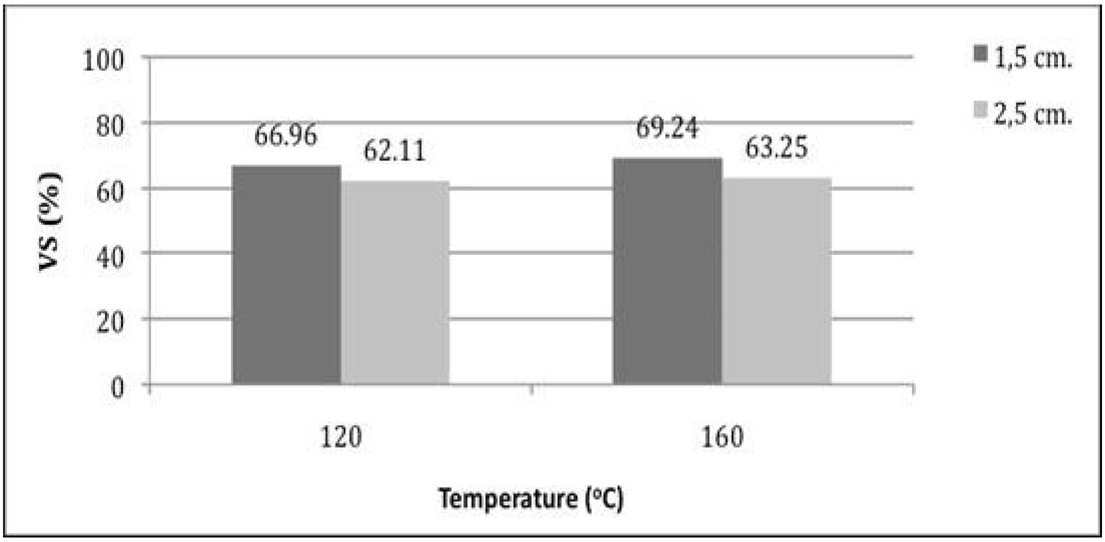

Figure 5.111 Effects of diameter and temperature on VS results fry-dried samples for 16 minutes.

Figure 5.112 shows the VS results of diameters 1.5 and 2.5 cm. samples fried for 6 and 16 min. at 120 and 160°C. It can be said that the frying time was not very effective on VS values on the contrary of temperature and sample's diameter.

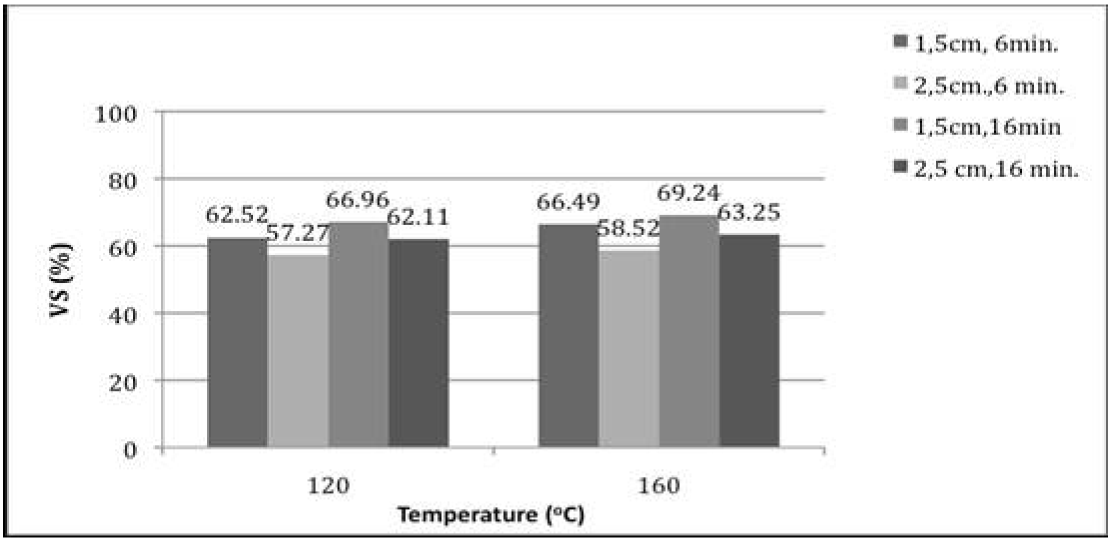

Figure 5.112 Effects of time, diameter and temperature on VS results..

Table 5.20 shows the estimated coefficients of the response function of VS values, calculated by Statistica 7 program with the experimental data. The predicted VS values were illustrated in Table 5.21. The regression coefficient was achieved as R^2=0. 9614156.

Table 5.20 VS response function coefficients.

bo	b1	b2	b3	b12
43.16431	0.89712	0.27245	-2.64427	-0.00617
b13	b23	b11	b22	b33
0.37233	-0.04057	-0.01561	-0.00016	-0.55354

Table 5.21 Predicted and residual values for volatile solids content of fry-dried samples with WCO.

Temperature (°C)	Time (min)	Diameter (cm)	Predicted	Residuals
20	140	2	68.60113	0.02146
2	140	2	60.77999	-0.03974
11	180	2	68.82993	1.34199
11	100	2	62.5647	-1.35679
11	140	3	58.9594	0.33718
11	140	1	71.84392	-0.352
16	160	2.5	65.78789	0.1448
16	160	1.5	71.17986	-1.50693
16	120	2.5	64.70061	-0.50213
16	120	1.5	68.46989	1.83879
6	160	2.5	60.81516	-1.82398
6	120	2.5	57.25991	1.52175
6	160	1.5	69.9304	0.51694
6	120	1.5	64.75246	-0.13
11	140	2	65.95519	-1.02726
11	140	2	65.95519	2.26783
11	140	2	65.95519	-1.25191

VS results as a function of temperature at different frying times for different sample diameters as 1, 1.5, 2, 2.5, 3 cm are shown in figures between 5.113 and 5.117. VS contents of the samples having 1 and 1.5 cm diameters were the highest values and also VS increased for all applications with the increasing time; however, it also decreased for the oil temperatures after 170 °C. 11 min. of the frying time gave the better results for all applications.

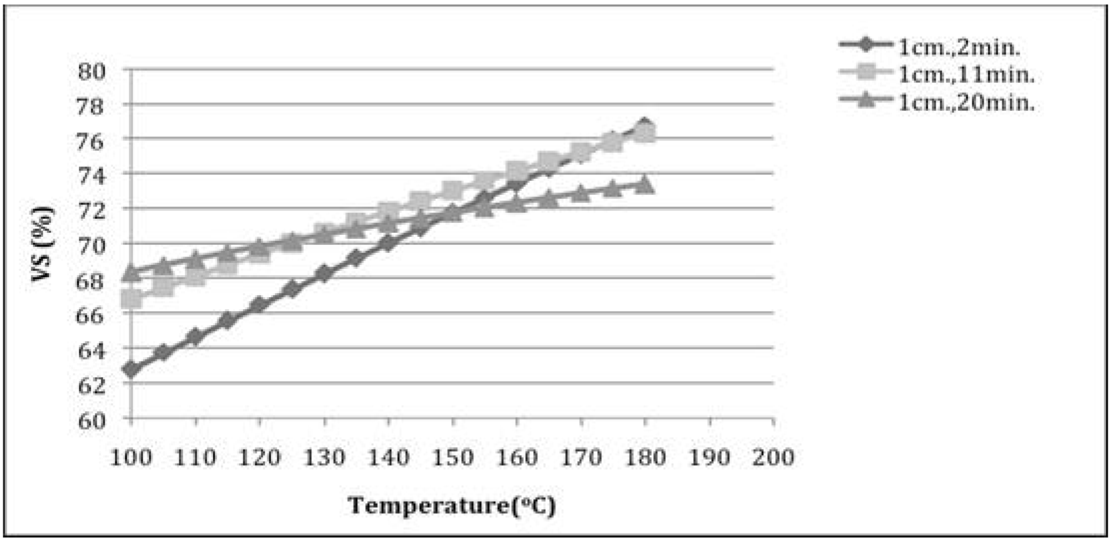

Figure 5.113 VS content curves for 1cm diameter samples fry-dried sludge for three different process times.

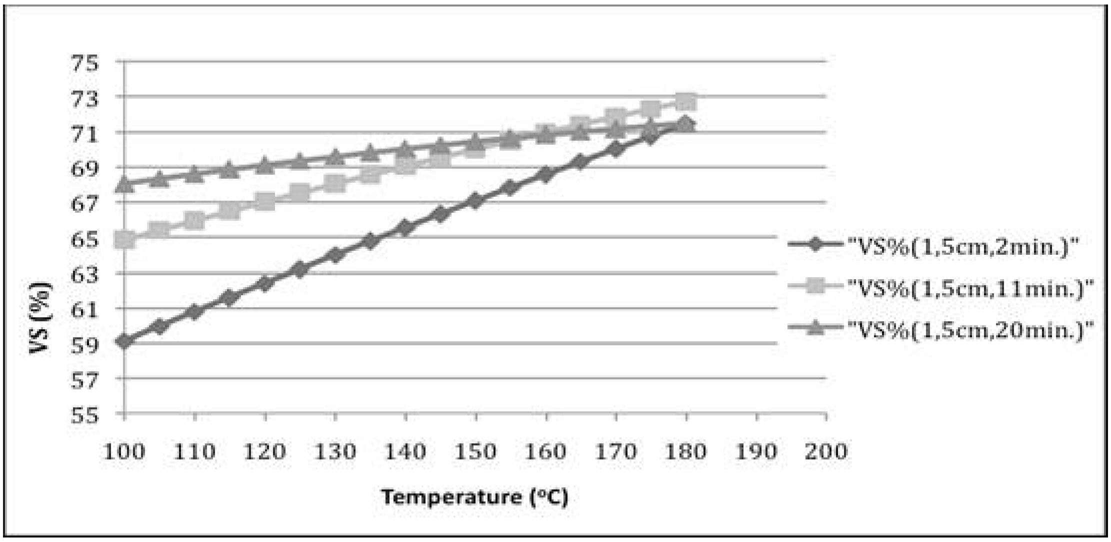

Figure 5.114 VS content curves for 1.5cm diameter samples fried sludge for three different process times.

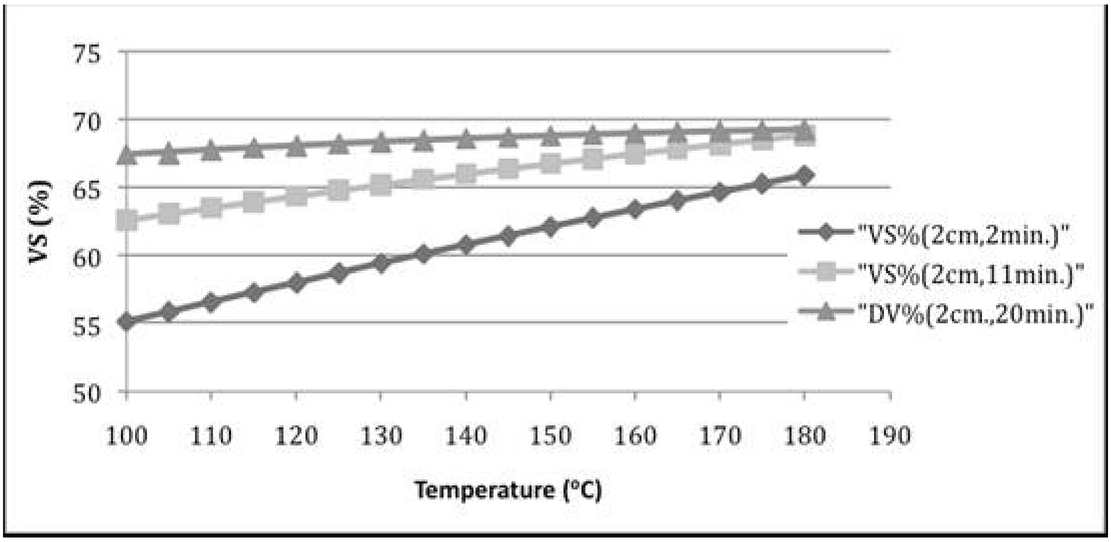

Figure 5.115 VS content curves for 2cm diameter samples fried sludge for three different process times.

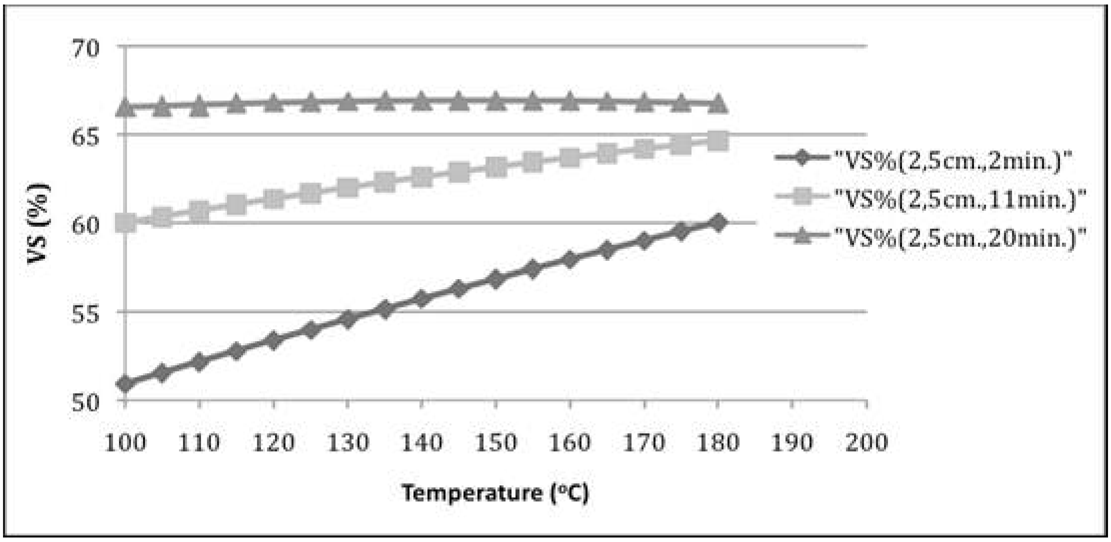

Figure 5.116 VS content curves for 2.5cm diameter samples fried sludge for three different process times.

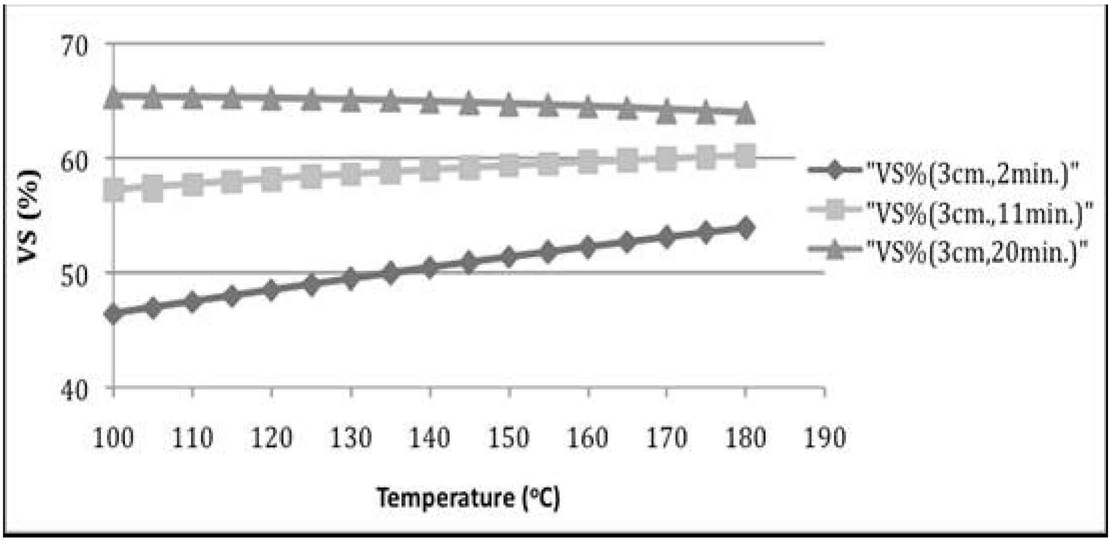

Figure 5.117 VS content curves for 3cm diameter samples fried sludge for three different process times.

Figures 5.118- 5.122 showed the VS results as a function of frying time at different temperatures and different sample diameters. For the samples having 1 and 1.5 cm diameter, approximately 11 minutes of frying time was enough to reach the VS higher than 80% at 140 °C of the oil temperature. Lowest temperature application at 100 °C did not produce higher VS content as well as the temperature range in 140-160 °C.

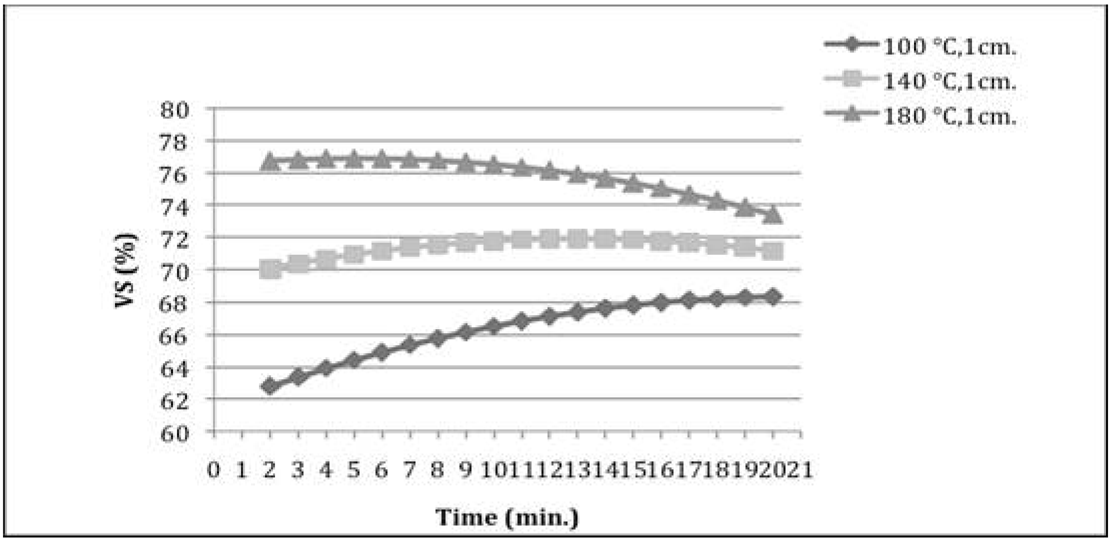

Figure 5.118 VS content curves for 1cm. diameter samples fried sludge at three different temperatures.

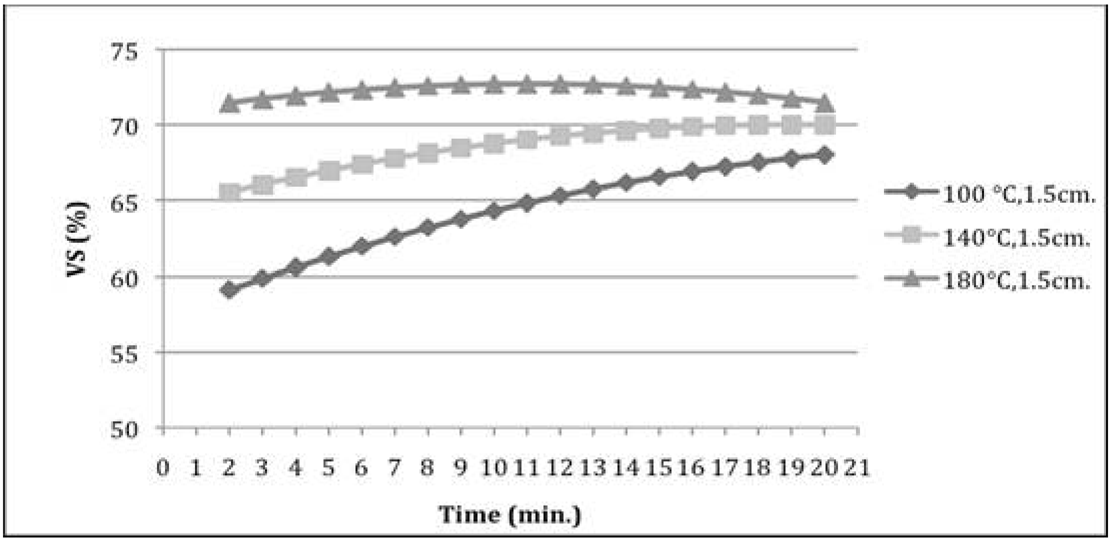

Figure 5.119 VS content curves for 1.5cm diameter samples fried sludge at three different temperatures.

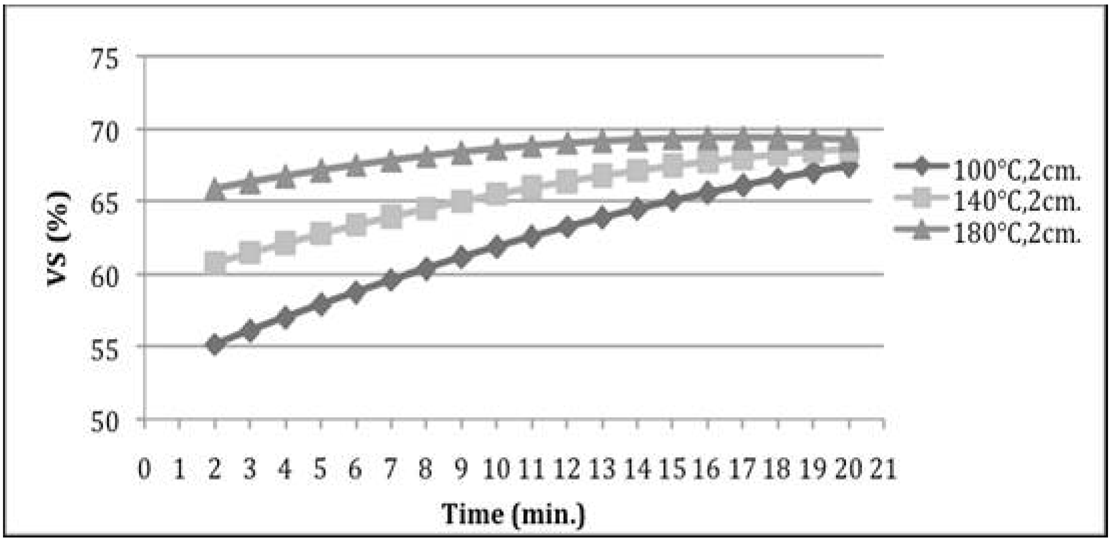

Figure 5.120 VS content curves for 2cm diameter samples fried sludge at three different temperatures.

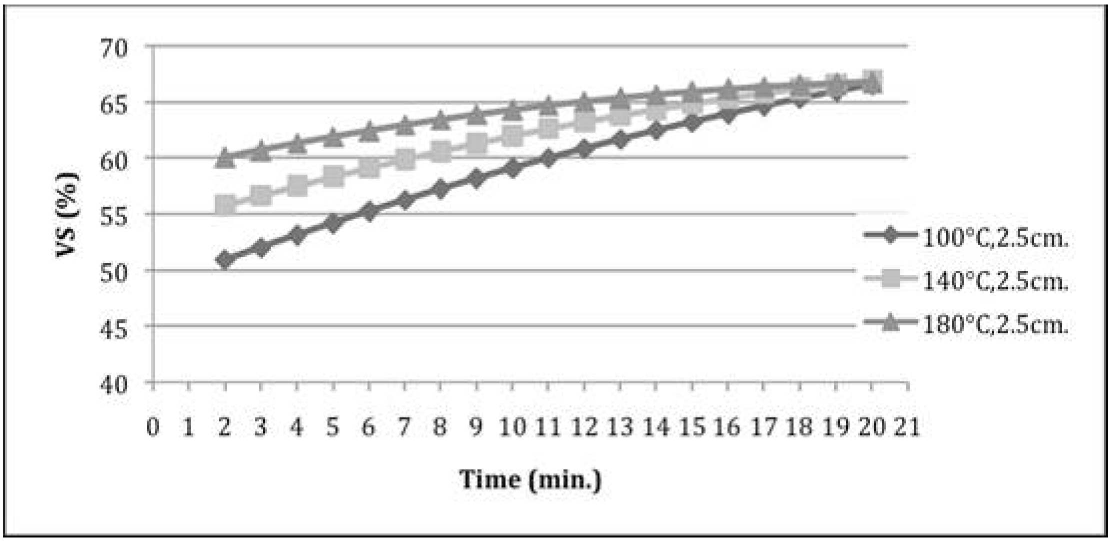

Figure 5.121 VS content curves for 2.5cm diameter samples fried sludge at three different temperatures.

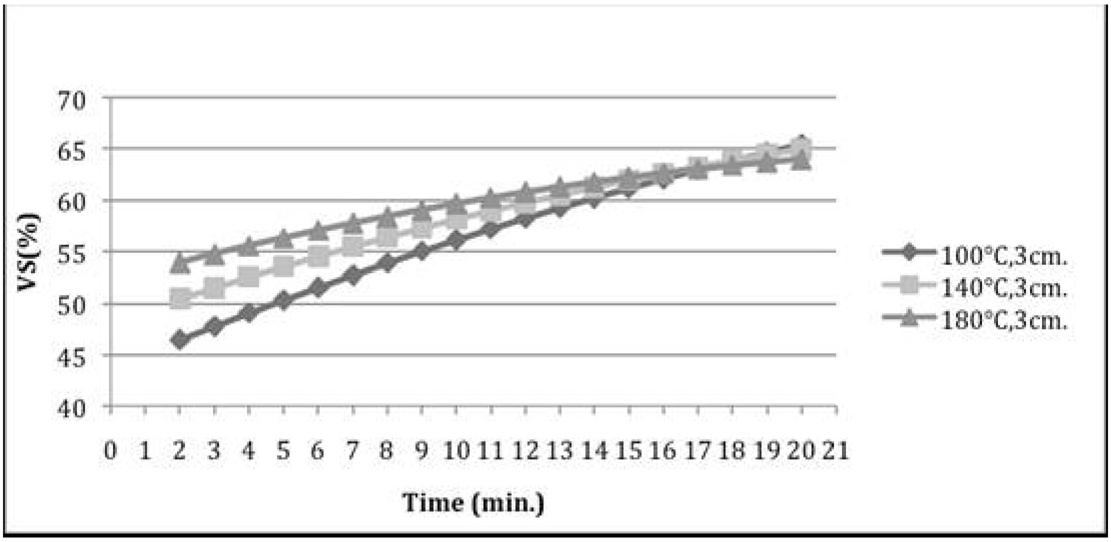

Figure 5.122 VS content curves for 3cm. diameter samples fried sludge at three different temperatures.

5.4.3 Heating Value (Calorific) of The Fried Sludge

The low and high heating values of the sludge were determined based on several original and dry base measurements. The same evaluation method was used as above sections with Statistica 7.0 program for the regression analysis. Response function coefficients were determined by using experimental data for each independent variable.

a) Low Heating (Calorific) Value (LHV) of The Fried Sludge in Original Base

Table 5.22 shows the estimated coefficients of the response function of LHV values, which calculated by Statistica 7 program with the experimental data. The predicted LHV values were given in Table 5.23. The regression coefficient was achieved as R^2=0.95821821.

Table 5.22 LHV in original base response function coefficients.

bo	b1	b2	b3	b12
-22251.8	528.5	269.4	2267.7	-1.4
b13	b23	b11	b22	b33
60.3	-17.0	-11.6	-0.6	-673.7

Table 5.23 Predicted and residual values for LHV in original base of fry-dried samples with WCO.

Time (min)	Temperature (°C)	Time (min)	Predicted	Residuals
20	140	2	5247.231	306.644
2	140	2	1682.574	-196.267
11	100	2	1349.189	38.677
11	140	3	1596.427	-62.264
11	140	1	5870.588	151.669
16	160	2.5	4521.901	555.035
16	160	1.5	6696.487	-876.775
16	120	2.5	3039.842	-763.783
16	120	1.5	4536.259	454.093
6	160	2.5	2518.835	-543.498
11	180	2	5549.233	50.727
6	120	2.5	479.02	787.37
6	160	1.5	5296.58	674.378
6	120	1.5	2578.595	-644.439
11	140	2	4407.162	-685.859
11	140	2	4407.162	591.154
11	140	2	4407.162	163.138

LHV in original base results are shown as a function of temperature at different frying durations and different sample diameter in Figures between 5.123 and 5.127. LHV in original base decreased with the increasing sample's diameter. These findings are also in accordance with the VS results.

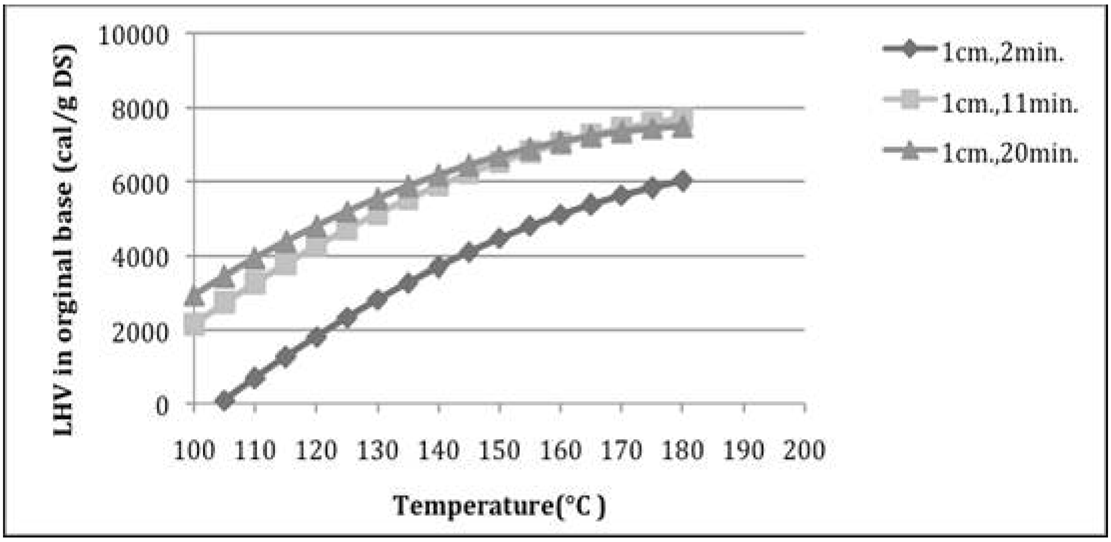

Figure 5.123 LHV in original base curves for 1cm diameter samples fry-dried sludge for three different process times.

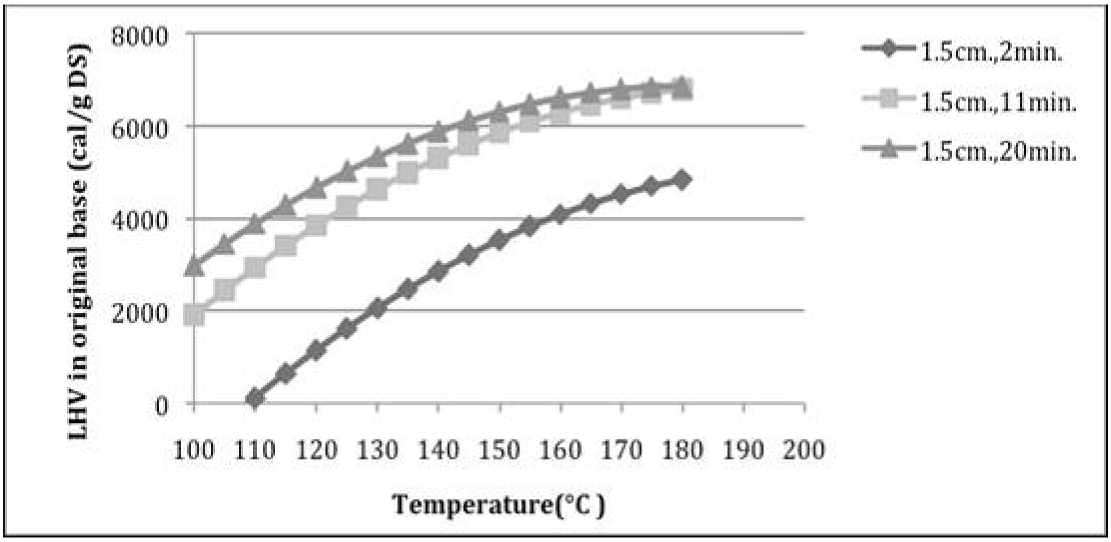

Figure 5.124 LHV in original base curves for 1.5cm diameter samples fry-dried sludge for three different process times.

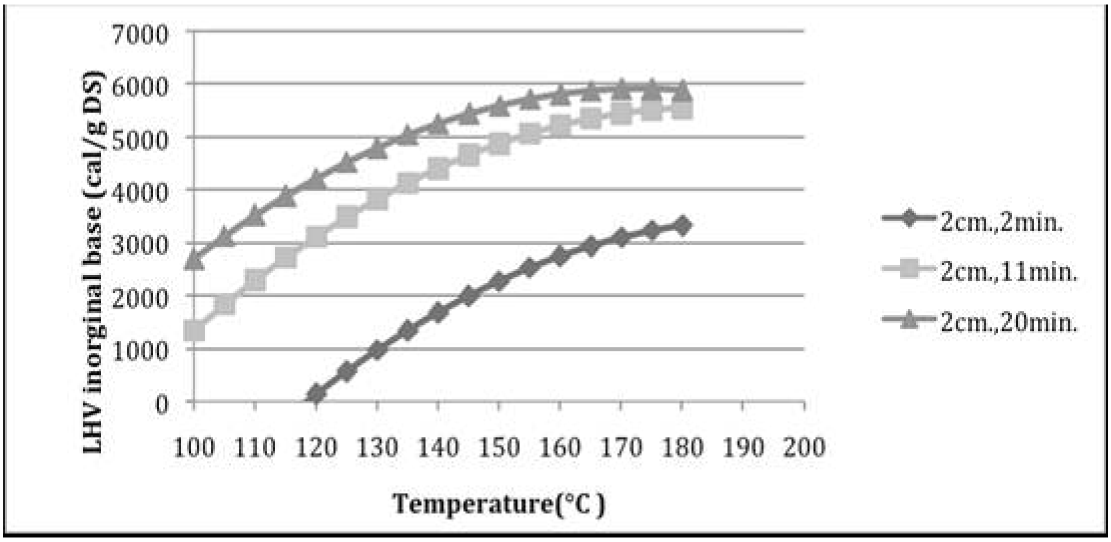

Figure 5.125 LHV in original base curves for 2cm. diameter samples fry-dried sludge for three different process times.

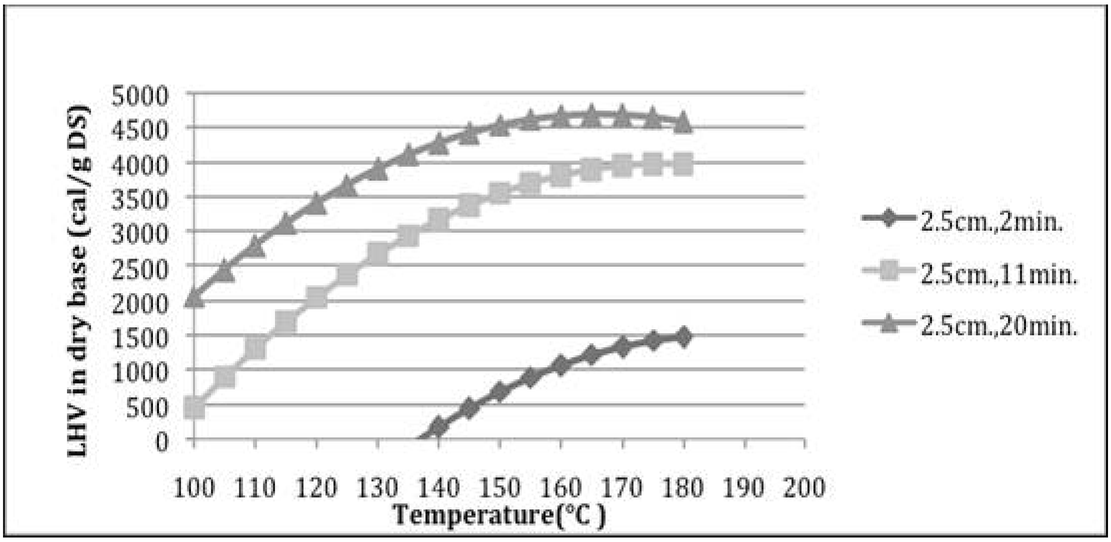

Figure 5.126 LHV in original base curves for 2.5cm diameter samples fry-dried sludge for three different process times.

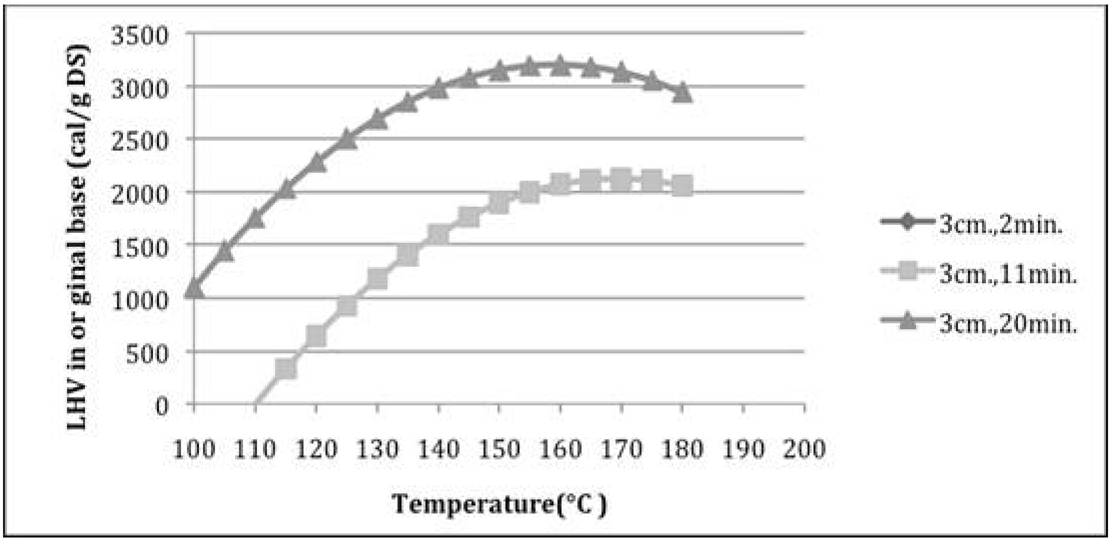

Figure 5.127 LHV in original base curves for 3cm diameter samples fry-dried sludge for three different process times.

Figures 5.128 and 5.132 also show LHV in original base results as a function of time at different temperatures and different sample diameters.

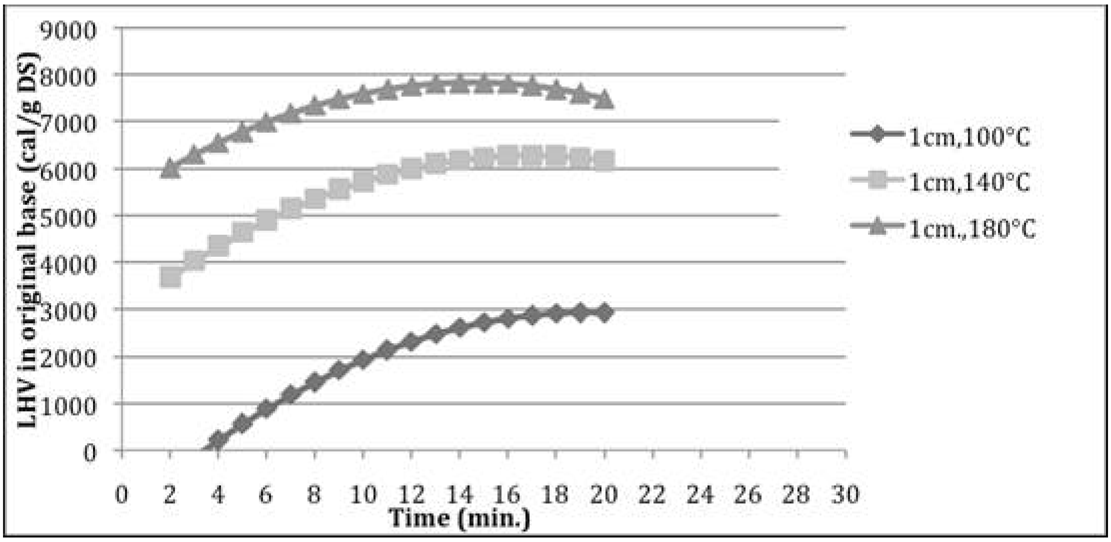

Figure 5.128 LHV in original base curves for 1cm. diameter samples fried sludge at three different temperatures.

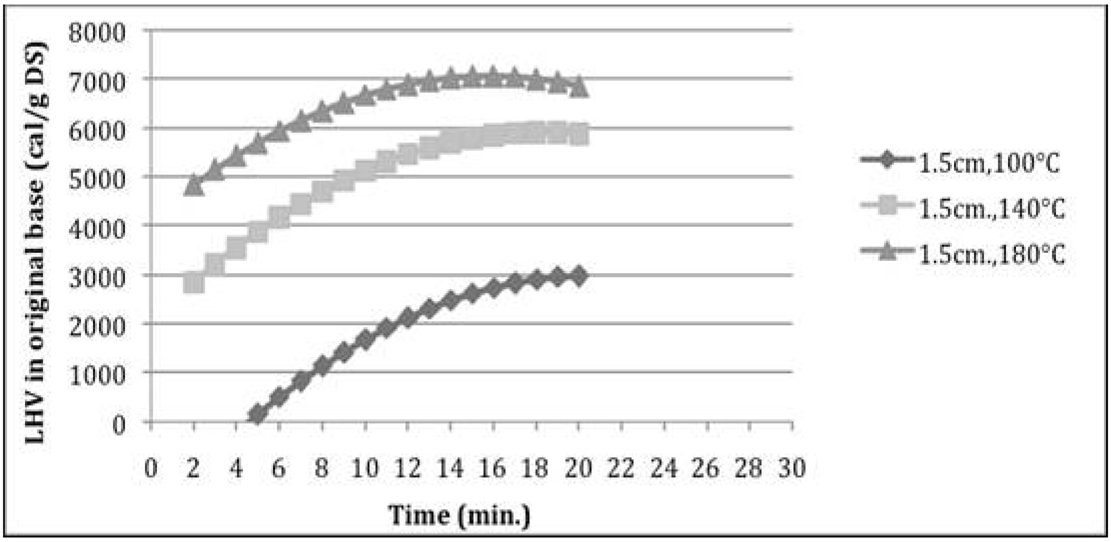

Figure 5.129 LHV in original base curves for 1.5cm. diameter samples fried sludge at three different temperatures.

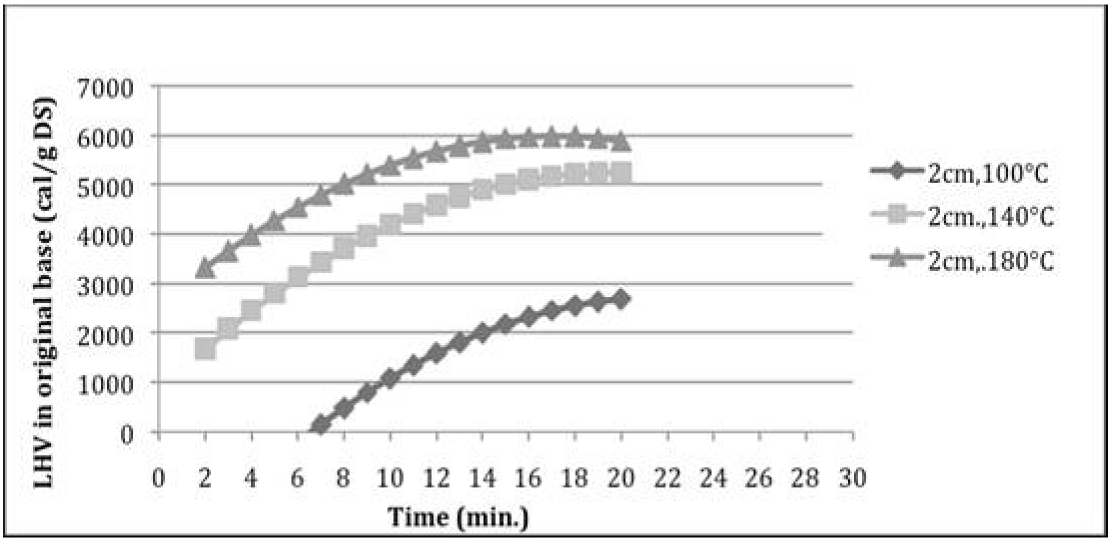

Figure 5.130 LHV in original base curves for 2cm. diameter samples fried sludge at three different temperatures.

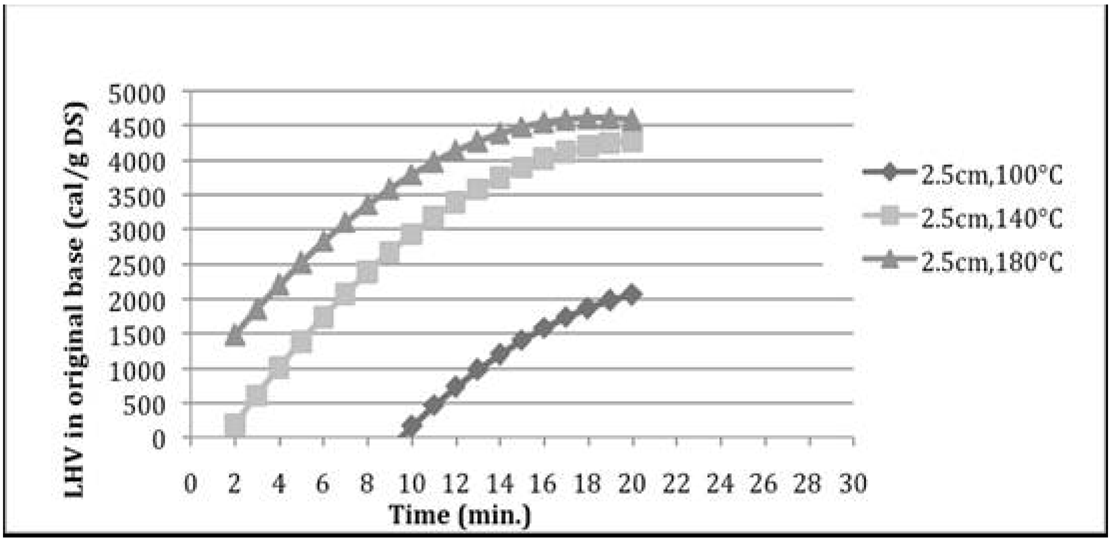

Figure 5.131 LHV in original base curves for 2.5cm diameter samples fried sludge at three different temperatures.

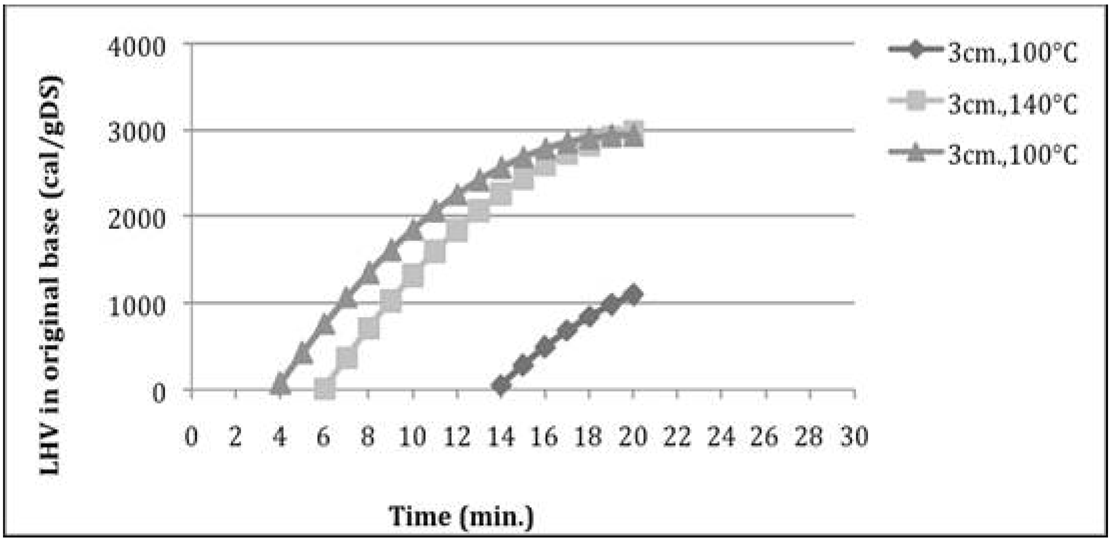

Figure 5.132 LHV in original base curves for 3cm. diameter samples fried sludge at three different temperatures.

b) Low Heating (Calorific) Value (LHV) of The Fried Sludge in Dry Base

Table 5.24 shows the estimated coefficients of the response function of LHV values, which was calculated by Statistica 7 program with the experimental data. The predicted LHV values were shown in Table 5.25. The regression coefficient was achieved as R^2=0.84853824.

Table 5.24 LHV in dry base response function coefficients.

bo	b1	b2	b3	b12
-10235.8	476.5	131.8	3576.5	-1.9
b13	b23	b11	b22	b33
-6.3	-17.8	-6.7	-0.2	-399.4

Table 5.25 Predicted and residual values for LHV in dry base of fry-dried samples with WCO.

Time(min)	Temperature(°C)	Diameter(cm)	Predicted	Residuals
20	140	2	5685.72	-32.632
2	140	2	4677.829	213.632
11	180	2	5811.381	99.619
11	100	2	4895.022	46.991
11	140	3	4740.905	-5.501
11	140	1	5901.241	152.111
16	160	2.5	5201.041	249.941
16	160	1.5	6168.453	-312.047
16	120	2.5	5472.214	-206.927
16	120	1.5	5728.333	197.45
6	160	2.5	5046.405	-344.059
6	120	2.5	4570.167	165.437
6	160	1.5	5950.622	60.317
6	120	1.5	4763.091	-396.552
11	140	2	5720.477	-400.623
11	140	2	5720.477	532.991
11	140	2	5720.477	-20.148

LHV in dry base results as a function of temperature at different frying times and different sample diameters are shown in Figures 5.133-5.137. Similar observations were obtained as in LHV in original base.

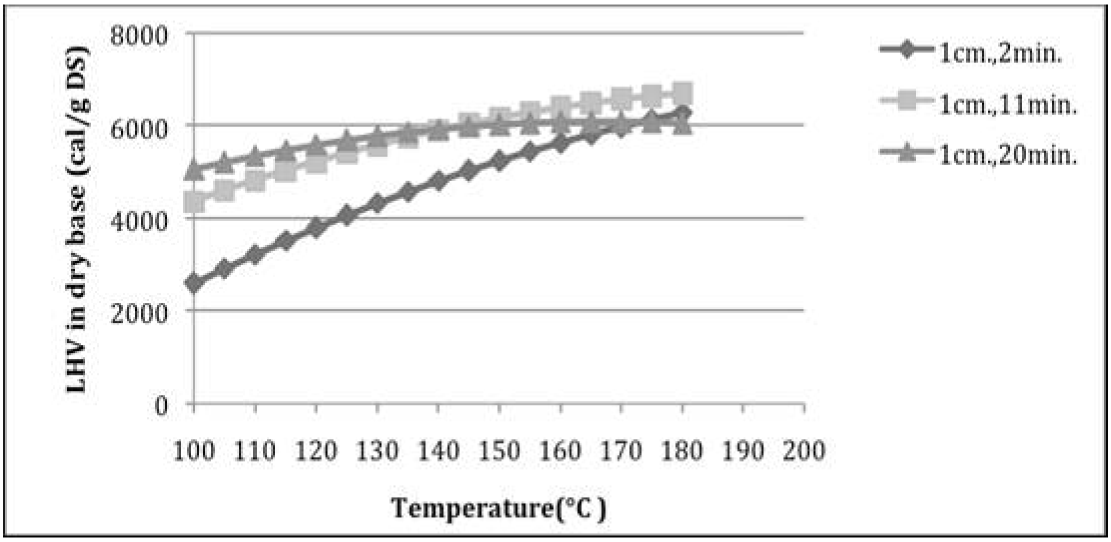

Figure 5.133 LHV in original base curves for 1cm. diameter samples fry-dried sludge for three different process times.

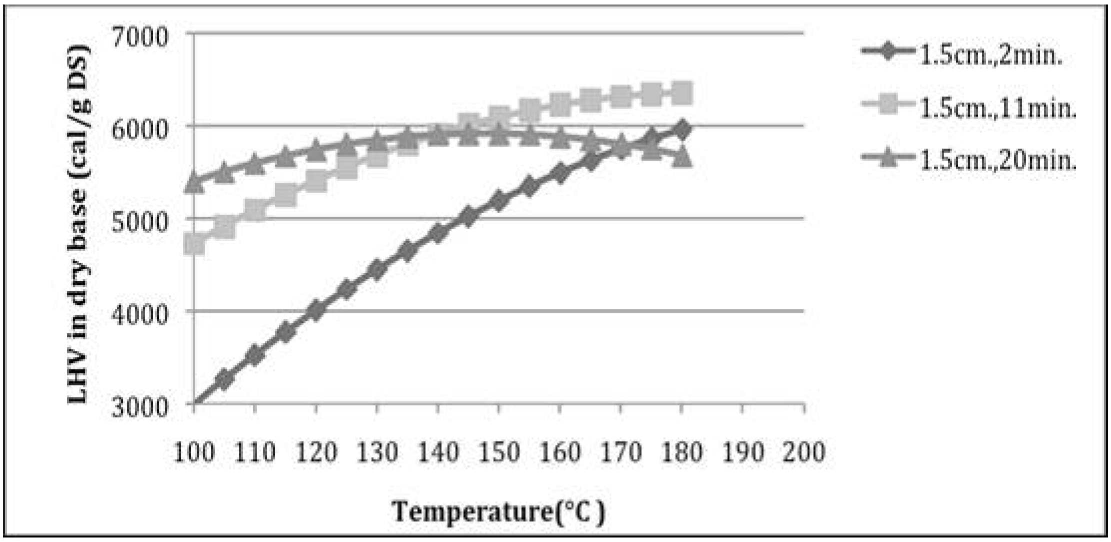

Figure 5.134 LHV in original base curves for 1.5cm diameter samples fry-dried sludge for three different process times.

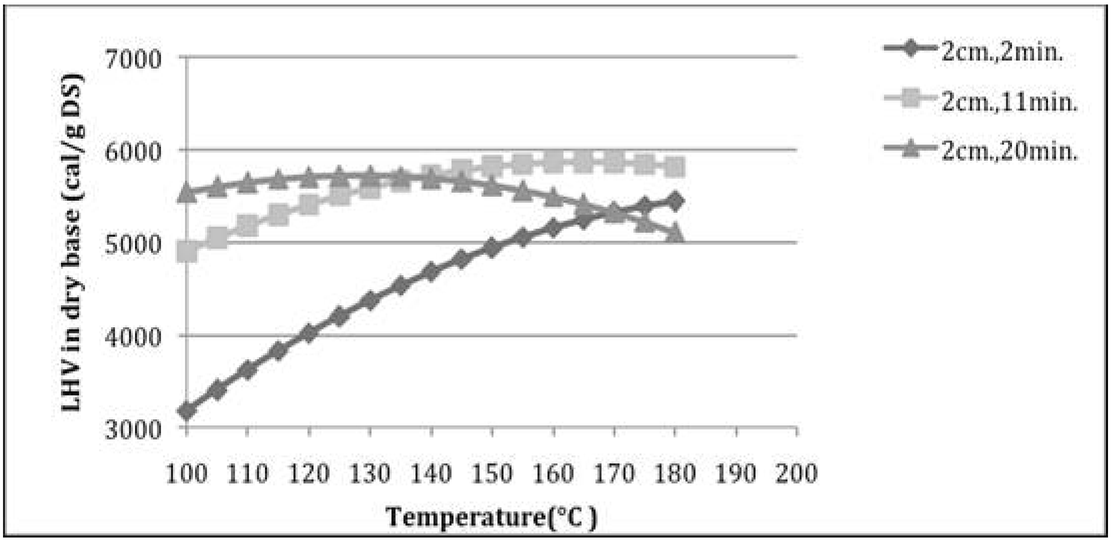

Figure 5.135 LHV in original base curves for 2cm diameter samples fry-dried sludge for three different process times.

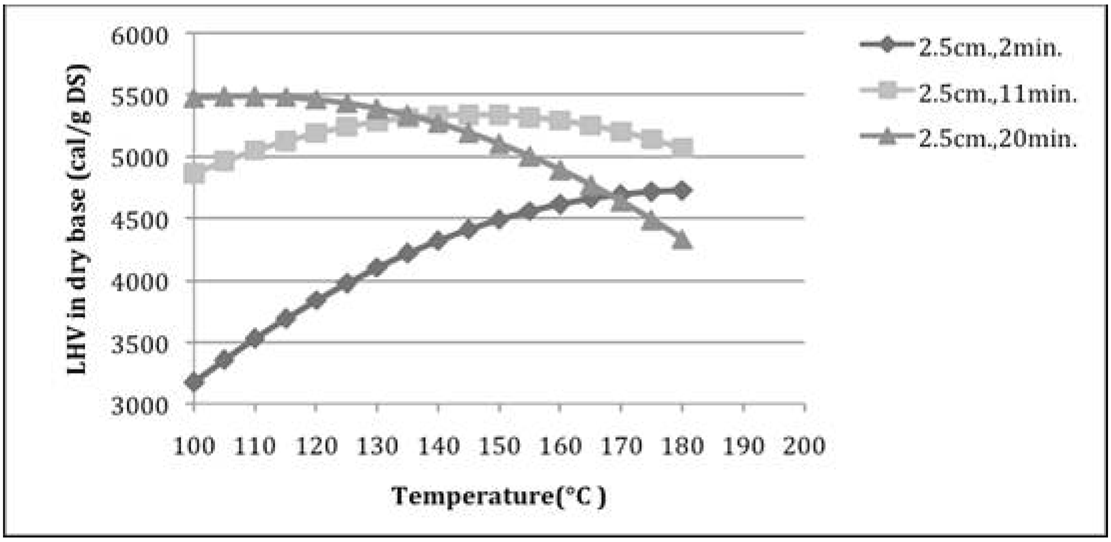

Figure 5.136 LHV in original base curves for 2.5cm diameter samples fry-dried sludge for three different process times.

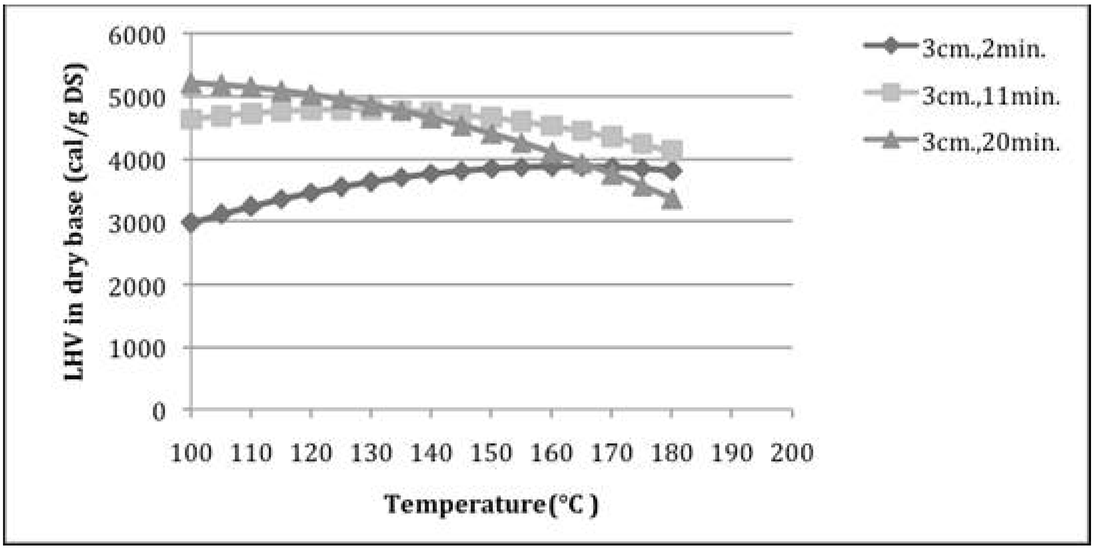

Figure 5.137 LHV in original base curves for 3cm diameter samples fry-dried sludge for three different process times.

Figures 5.138-5.142 show LHV in dry base results as a function of time at different temperatures and different sample diameters.

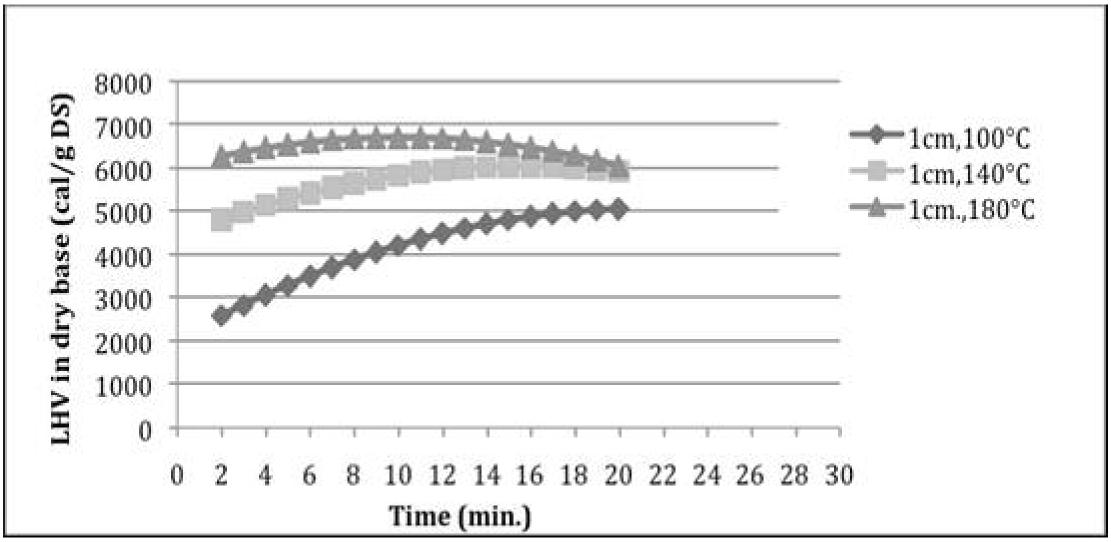

Figure 5.138 LHV in original base curves for 1cm diameter samples fried sludge at three different temperatures.

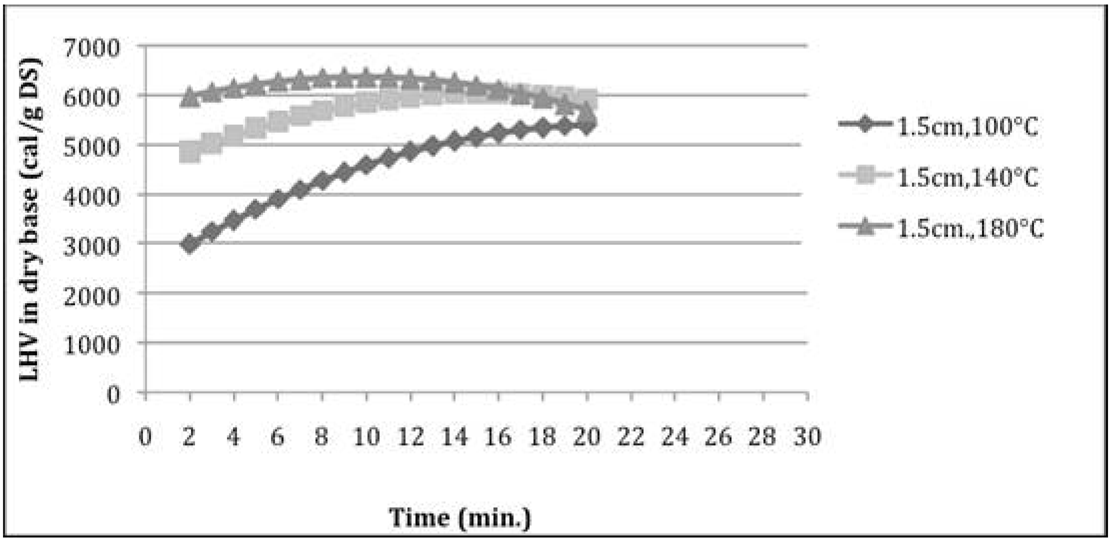

Figure 5.139 LHV in original base curves for 1.5cm diameter samples fried sludge at three different temperatures.

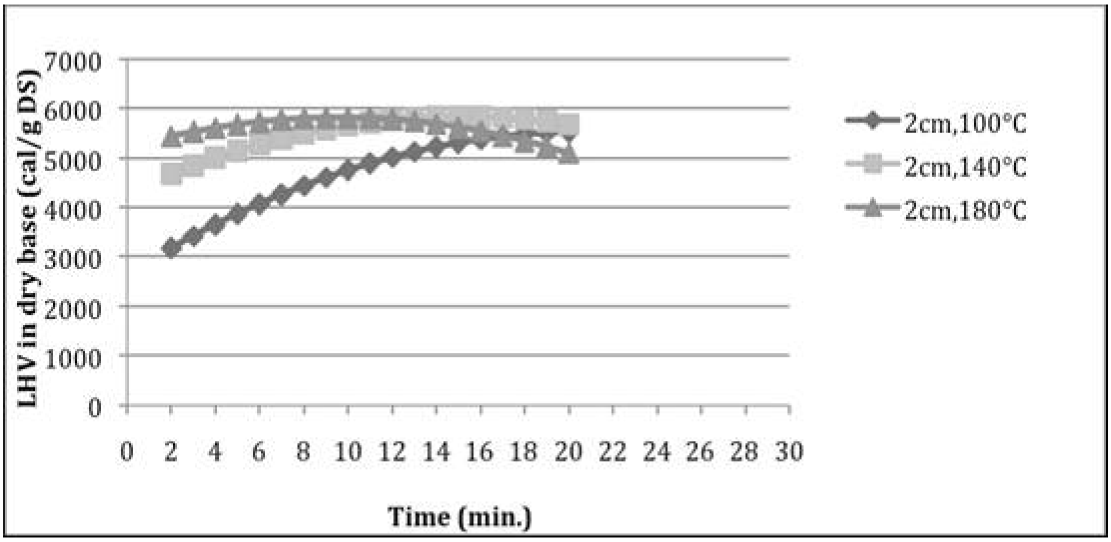

Figure 5.140 LHV in original base curves for 2cm diameter samples fried sludge at three different temperatures.

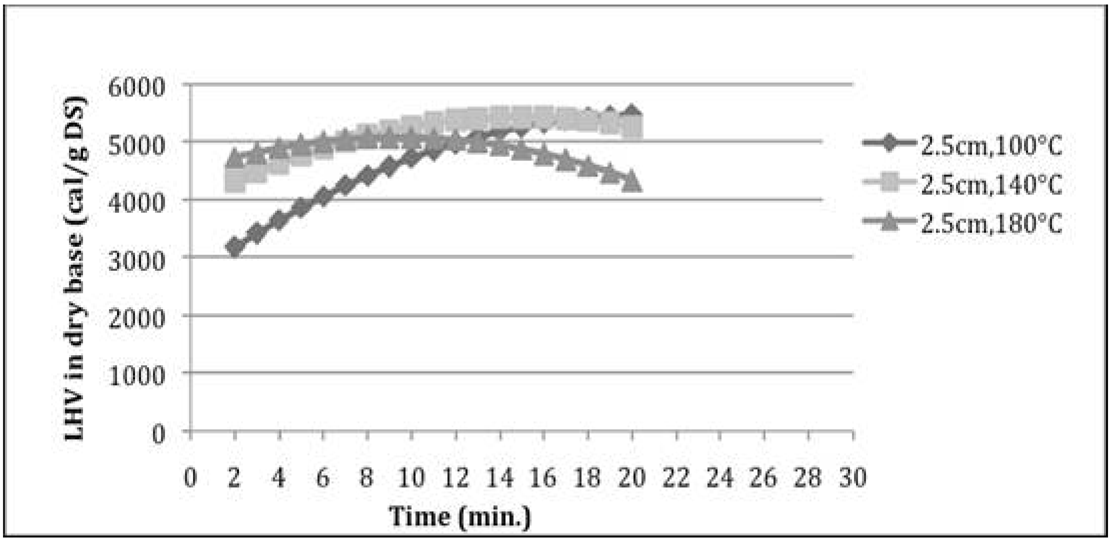

Figure 5.141 LHV in original base curves for 2.5cm diameter samples fried sludge at three different temperatures.

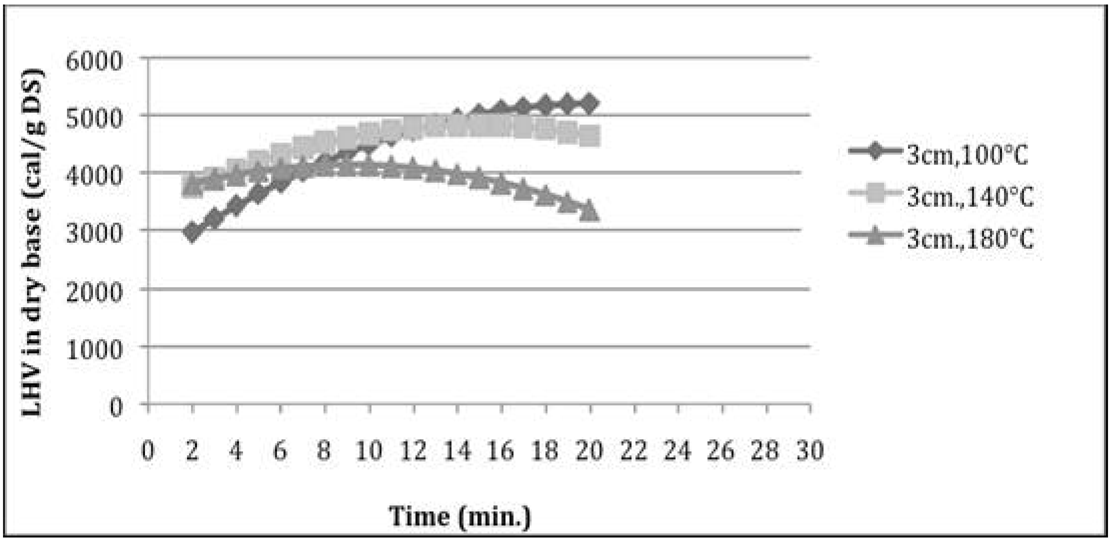

Figure 5.142 LHV in original base curves for 3cm. diameter samples fried sludge at three different temperatures.

*c) High Heating (Calorific) Value (*HHV*) of The Fried Sludge in Dry Base*

Table 5.26 shows the estimated coefficients of the response function of HHV values, which were calculated by Statistica 7 program with the experimental data. The predicted HHV values were illustrated in Table 5.27. The regression coefficient was achieved as R^2=0.89671117.

Table 5.26 HHV in dry base response function coefficients.

bo	b1	b2	b3	b12
-10112.8	478.4	3566.9	-2.64427	-1.9
b13	b23	b11	b22	b33
-5.3	-17.9	-6.7	-0.2	-400.7

Table 5.27 Predicted and residual values for HHV in dry base of fry-dried samples with WCO.

Time(min)	Temperature(°C)	Diameter(cm)	Predicted	Residuals
20	140	2	5868.803	-32.803
2	140	2	4839.384	213.584
11	100	2	5061.066	43.686
11	140	3	4898.061	-4.951
11	140	1	6092.117	151.383
16	160	2.5	5376.996	250.931
16	160	1.5	6358.103	-316.019
16	120	2.5	5644.22	-208.322
16	120	1.5	5910.185	202.294
6	160	2.5	5208.02	-348.726
11	180	2	5994.59	102.746
6	120	2.5	4722.413	169.587
6	160	1.5	6136.11	61.89
6	120	1.5	4935.363	-397.363
11	140	2	5895.749	-403.954
11	140	2	5895.749	530.251
11	140	2	5895.749	-14.213

High heating values in dry base are depicted as a function of temperature at different frying times and different sample diameters in Figures between 5.143 and 5.147.

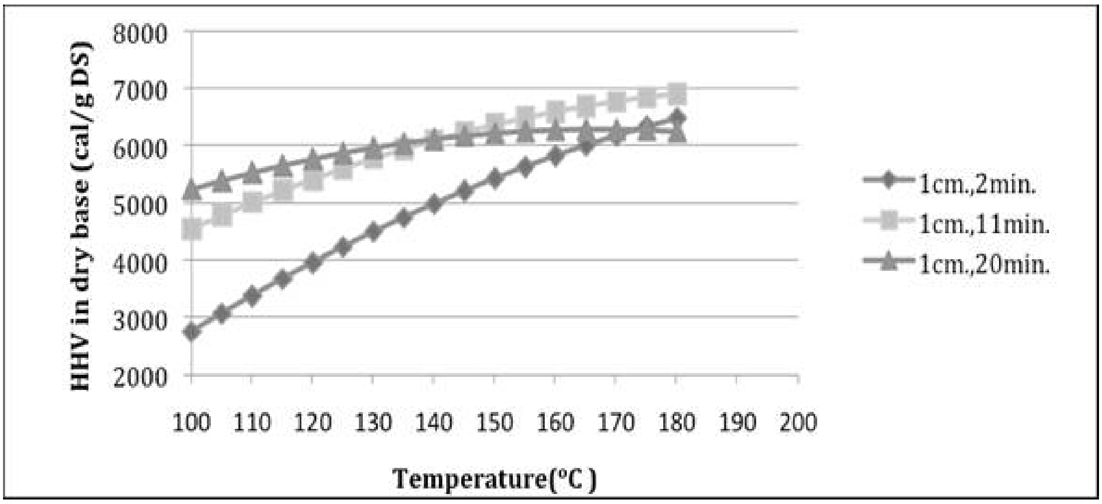

Figure 5.143 HHV in original base curves for 1cm diameter samples fry-dried sludge for three different process times.

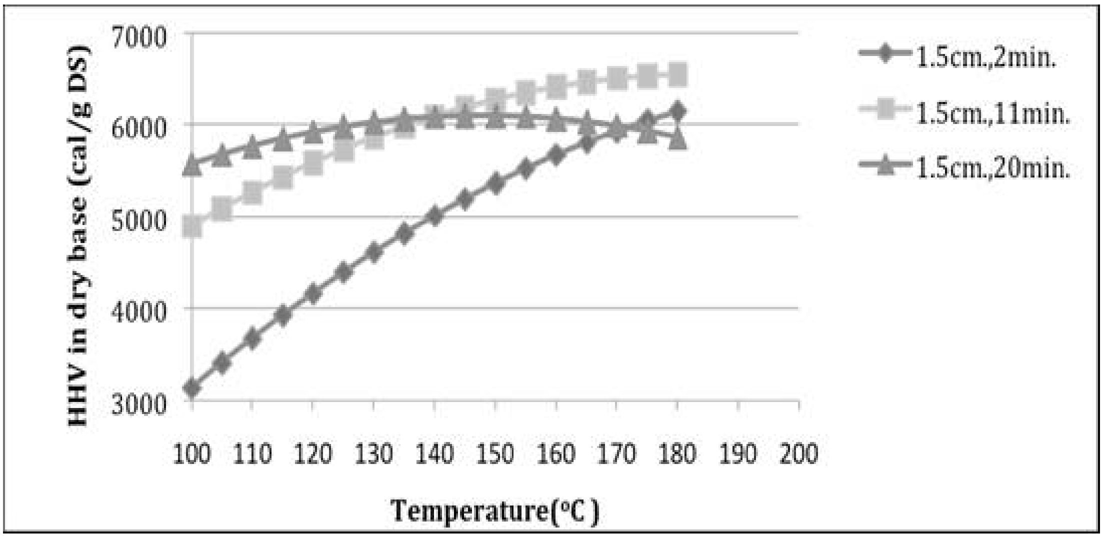

Figure 5.144 HHV in original base curves for 1.5cm diameter samples fry-dried sludge for three different process times.

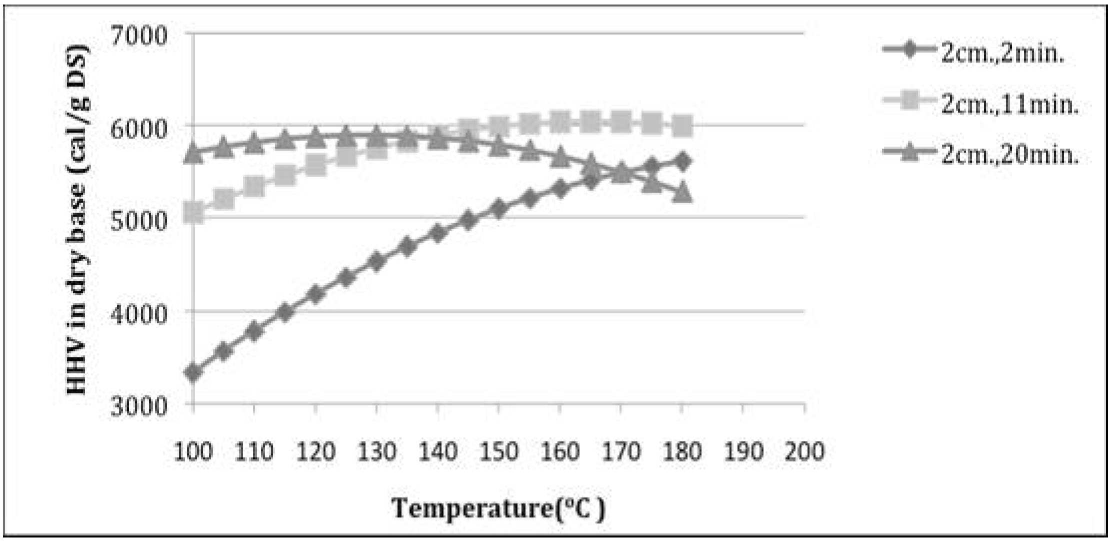

Figure 5.145 HHV in original base curves for 2cm diameter samples fry-dried sludge for three different process times.

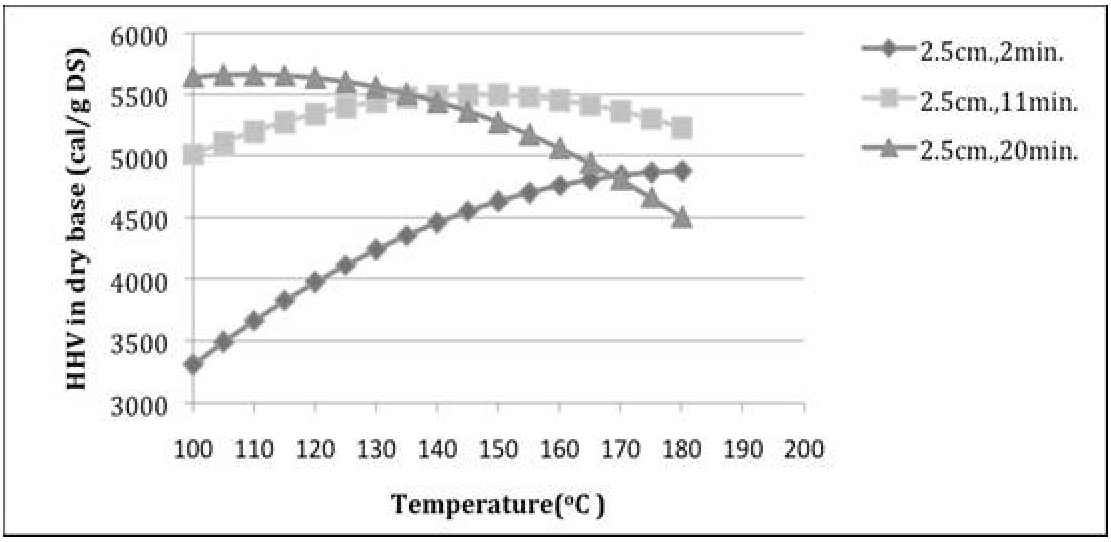

Figure 5.146 HHV in original base curves for 2.5cm diameter samples fry-dried sludge for three different process times.

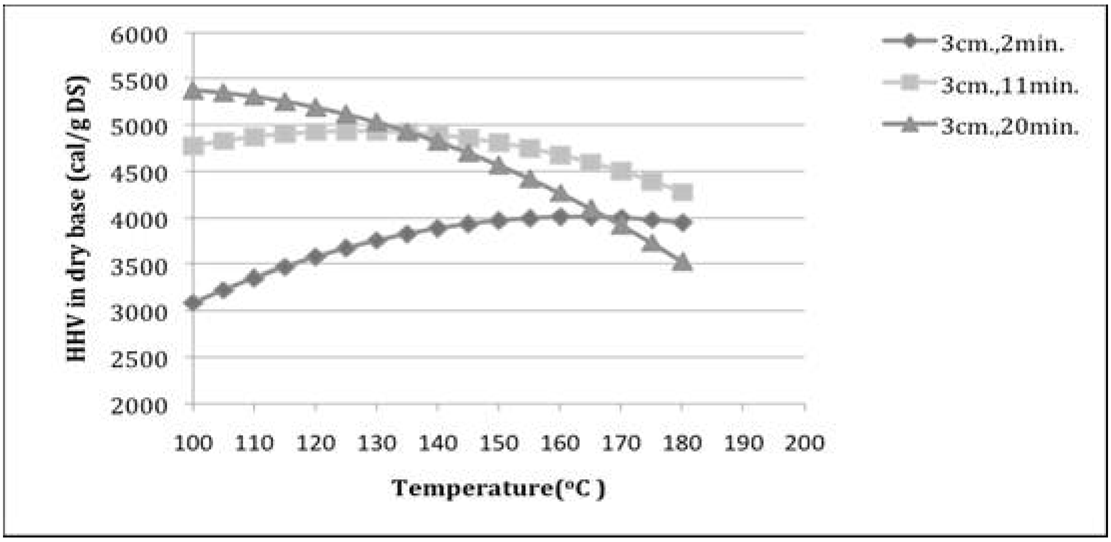

Figure 5.147 HHV in original base curves for 3cm. diameter samples fry-dried sludge for three different process times.

Figures 5.148- 5.152 show HHV in dry base results as a function of time at different temperatures and different sample diameters.

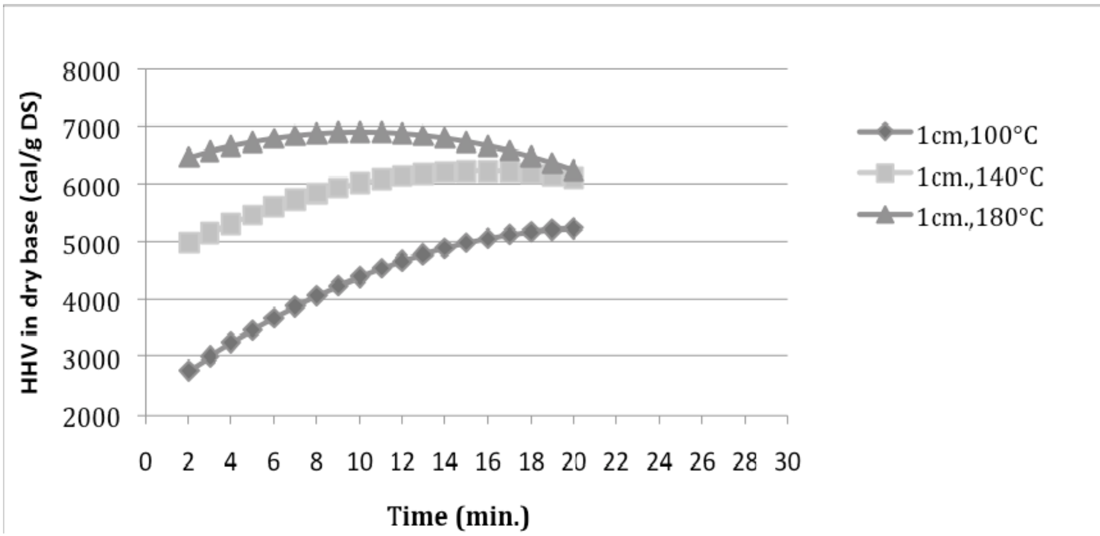

Figure 5.148 HHV in original base curves for 1cm. diameter samples fried sludge at three different temperatures.

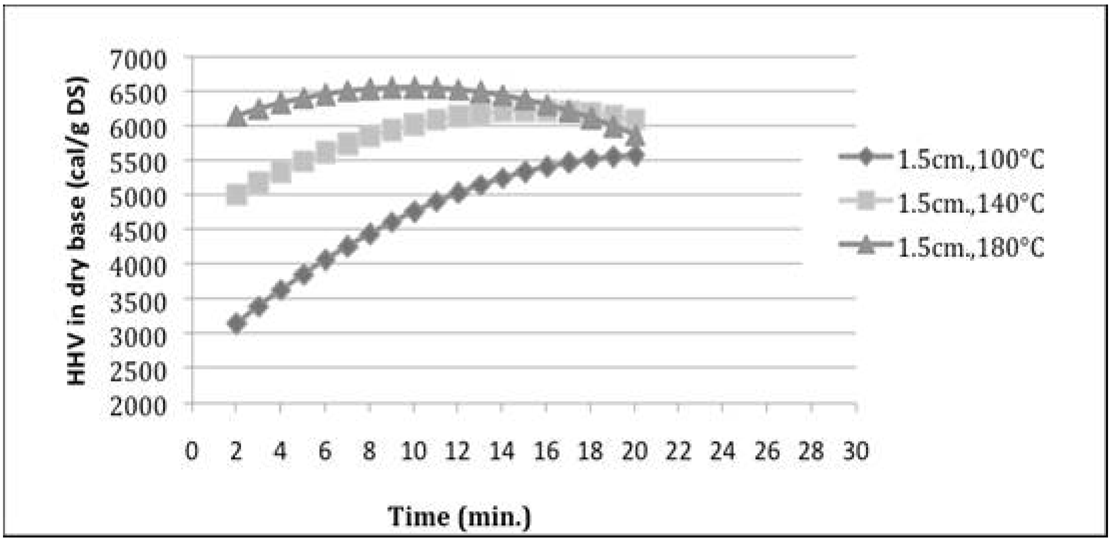

Figure 5.149 HHV in original base curves for 1.5cm diameter samples fried sludge at three different temperatures.

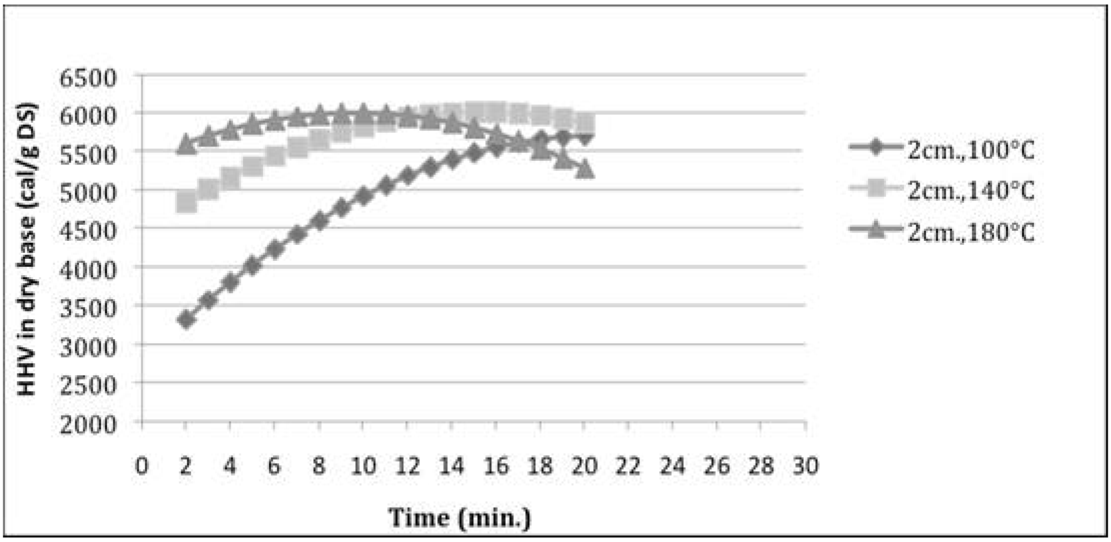

Figure 5.150 HHV in original base curves for 2cm. diameter samples fried sludge at three different temperatures.

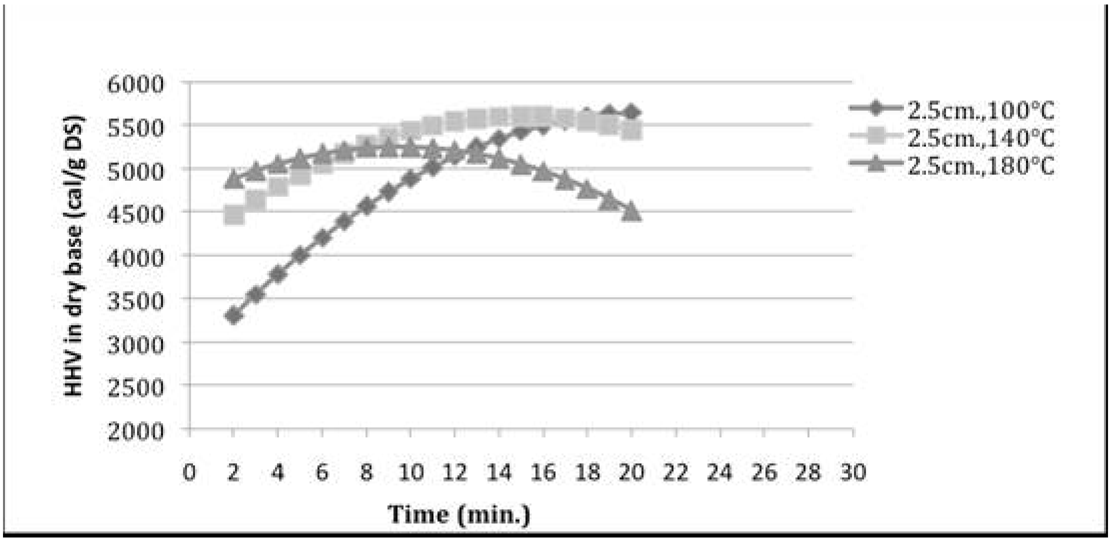

Figure 5.151 HHV in original base curves for 2.5cm diameter samples fried sludge at three different temperatures.

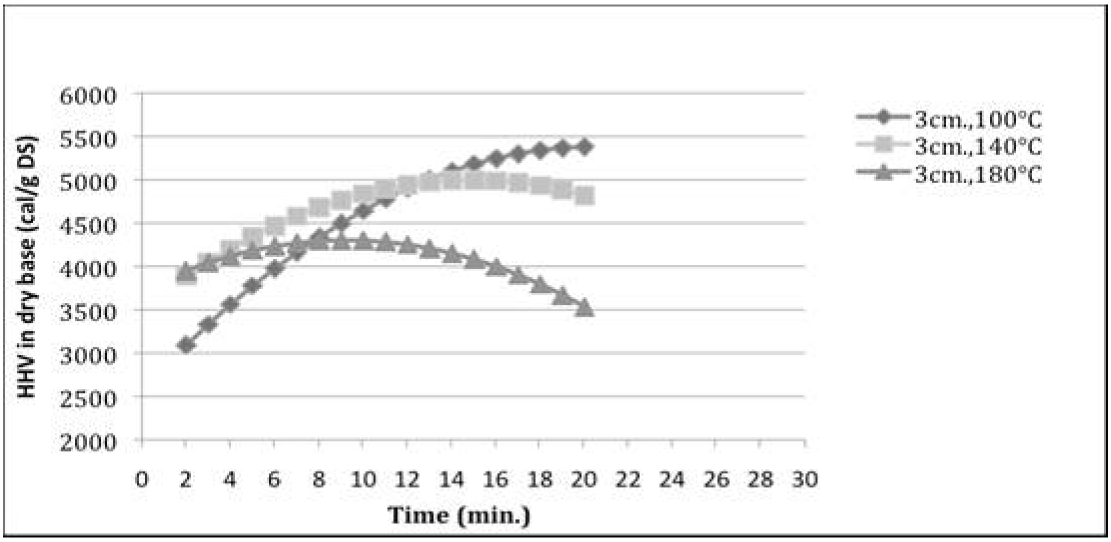

Figure 5.152 HHV in original base curves for 3cm. diameter samples fried sludge at three different temperatures.

d) High Heating (Calorific) Value (HHV) of The Fried Sludge in Original Base

Table 5.28 shows the estimated coefficients of the response function of HHV values, which were calculated by Statistica 7 program with the experimental data. The predicted HHV values were given in Table 5.29. The regression coefficient was achieved as R^2=0.95756989.

High heating values in original base are shown as a function of temperature at different frying times and different sample diameters in Figures 5.153 and 5.157.

Table 5.28 HHV in original base response function coefficients.

bo	b1	b2	b3	b12
-20824.0	514.1	256.3	2257.7	-1.4
b13	b23	b11	b22	b33
55.5	-16.9	-11.1	-0.6	-632.7

Table 5.29 Predicted and residual values for HHV in original base of fry-dried samples with WCO.

Time(min)	Temperature(°C)	Diameter(cm)	Predicted	Residuals
20	140	2	5455.742	287.425
2	140	2	2085.652	-175.238
11	100	2	1784.704	36.702
11	140	3	2004.372	-56.127
11	140	1	6067.253	146.998
16	160	2.5	4751.096	528.009
16	160	1.5	6843.471	-835.812
16	120	2.5	3383.378	-725.516
16	120	1.5	4798.963	435.18
6	160	2.5	2878.485	-526.051
11	180	2	5751.172	54.169
6	120	2.5	956.523	744.94
6	160	1.5	5525.781	634.644
6	120	1.5	2927.03	-618.88
11	140	2	4668.515	-663.733
11	140	2	4668.515	577.873
11	140	2	4668.515	155.415

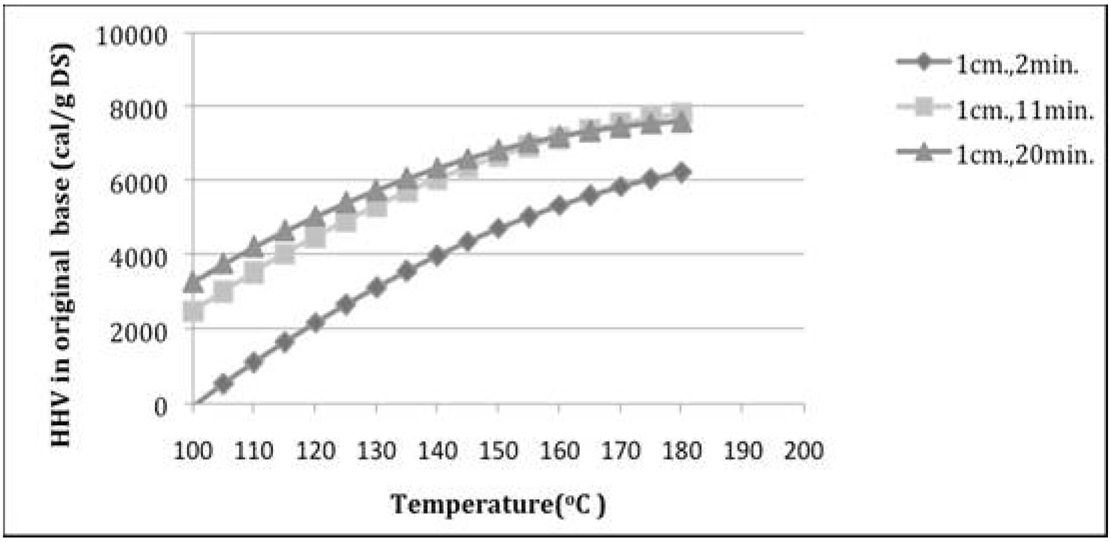

Figure 5.153 HHV in original base curves for 1cm diameter samples fry-dried sludge for three different process times.

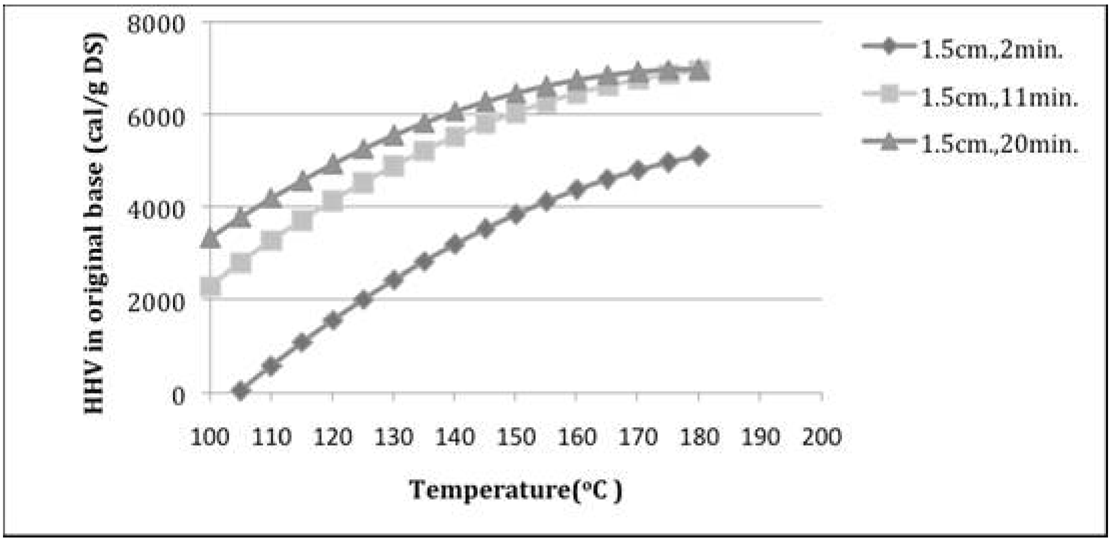

Figure 5.154 HHV in original base curves for 1.5cm diameter samples fry-dried sludge for three different process times.

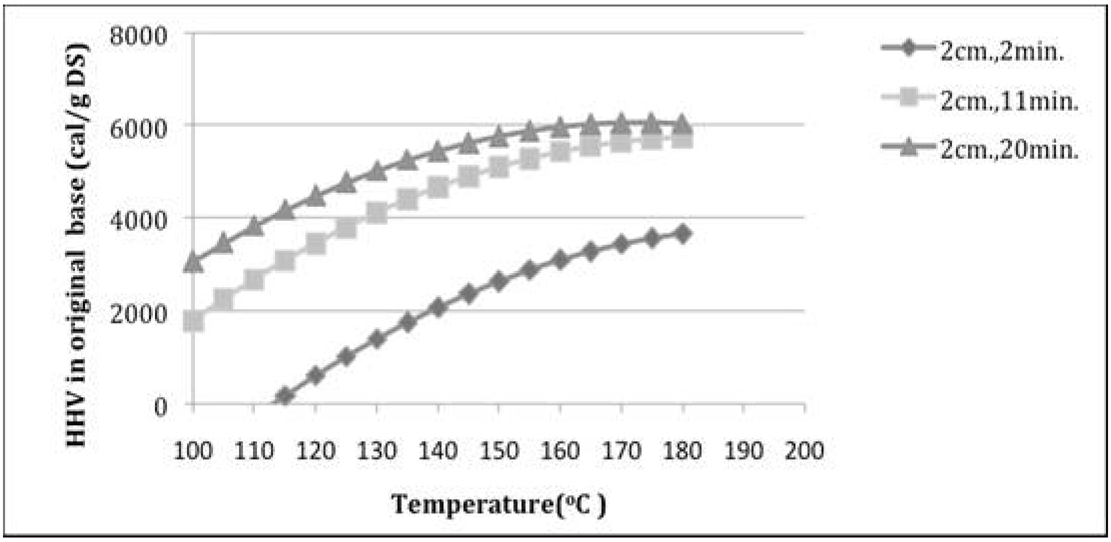

Figure 5.155 HHV in original base curves for 2cm diameter samples fry-dried sludge for three different process times.

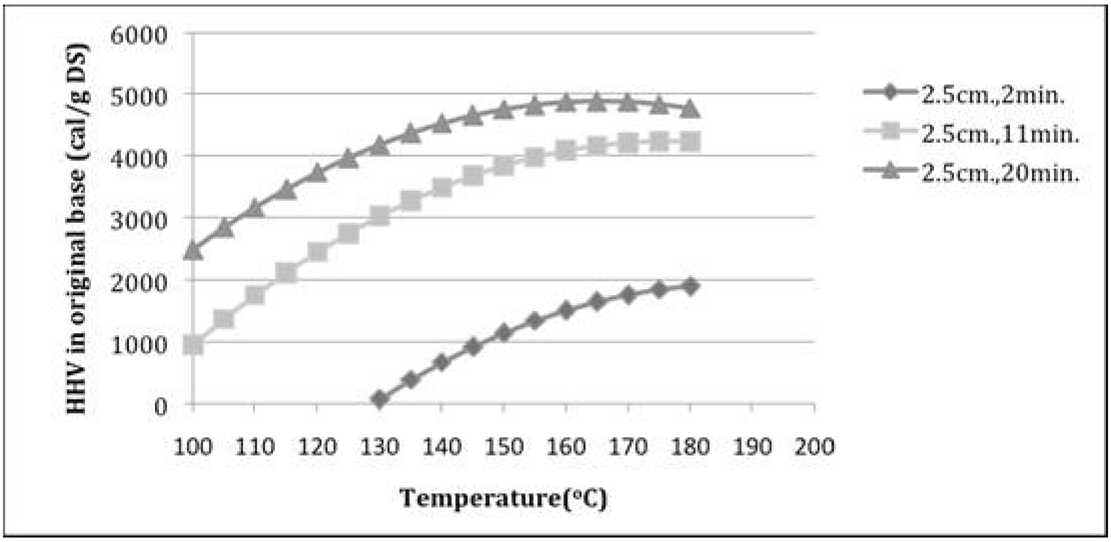

Figure 5.156 HHV in original base curves for 2.5cm diameter samples fry-dried sludge for three different process times.

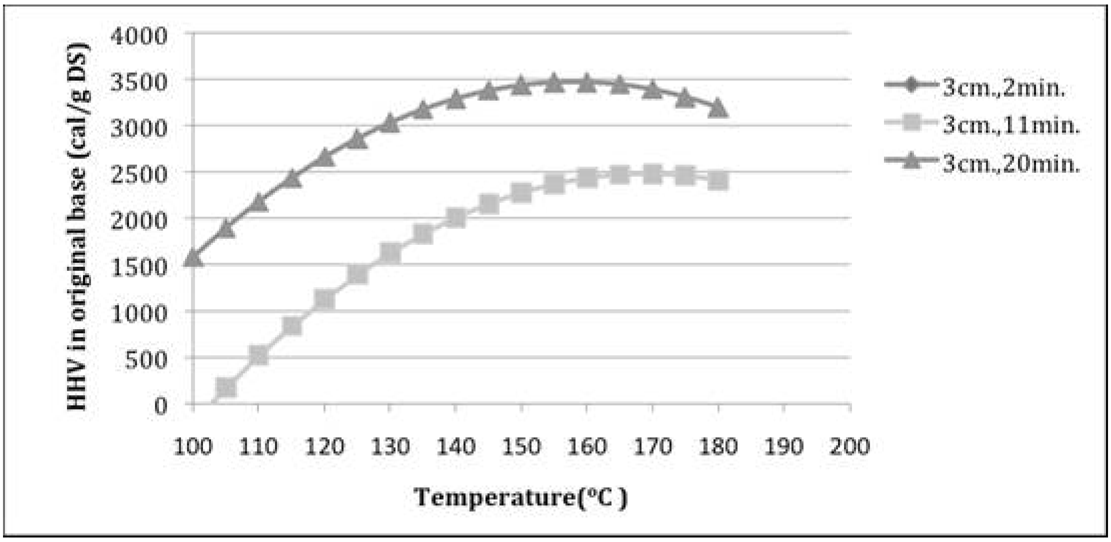

Figure 5.157 HHV in original base curves for 3cm. diameter samples fry-dried sludge for three different process times.

Figures 5.158- 5.162 show high heating values in dry original results as a function of fry-drying time at different temperatures and different sample diameters.

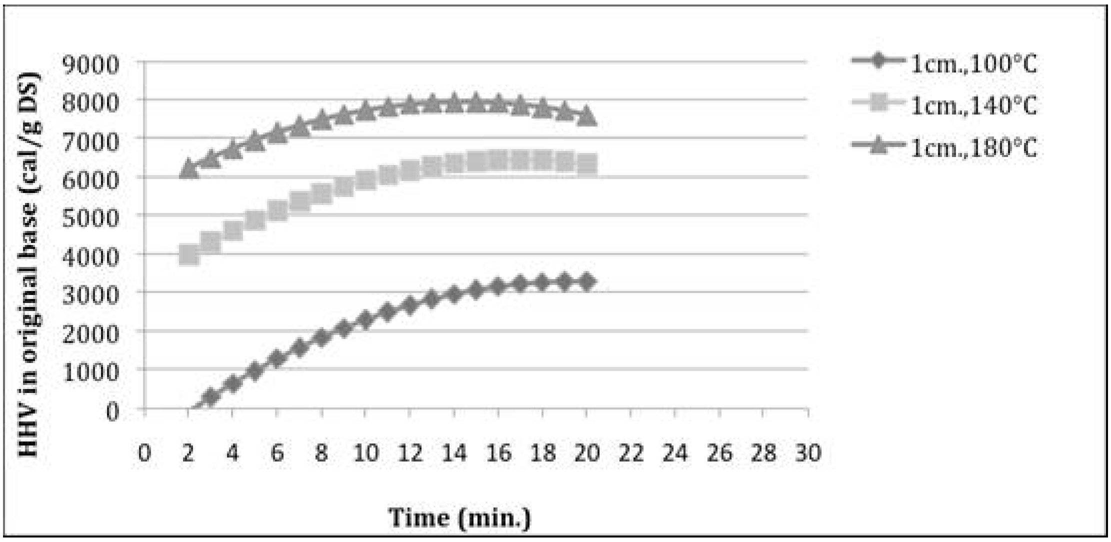

Figure 5.158 HHV in original base curves for 1cm diameter samples fried sludge at three different temperatures.

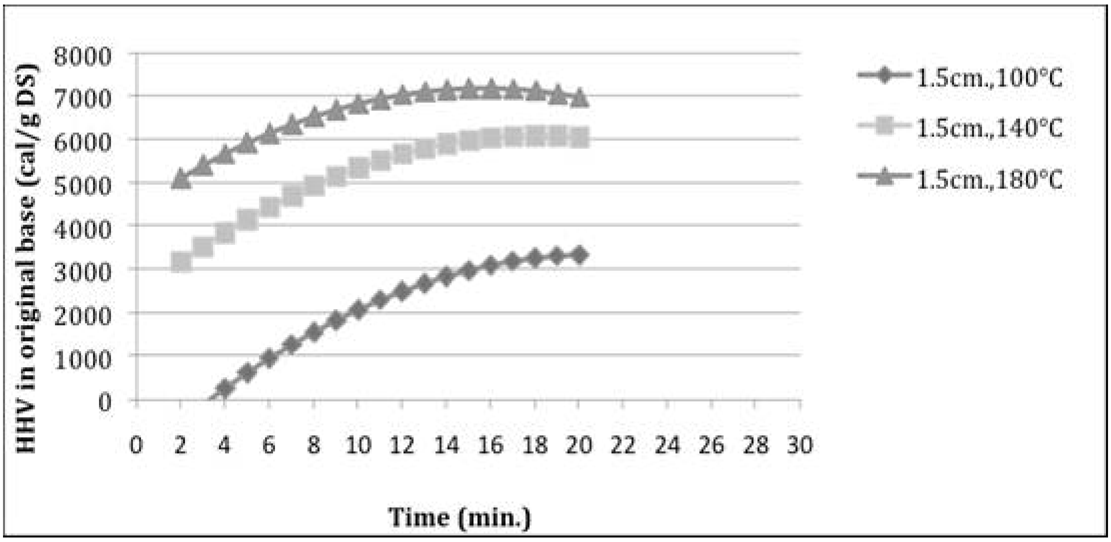

Figure 5.159 HHV in original base curves for 1.5cm diameter samples fried sludge at three different temperatures.

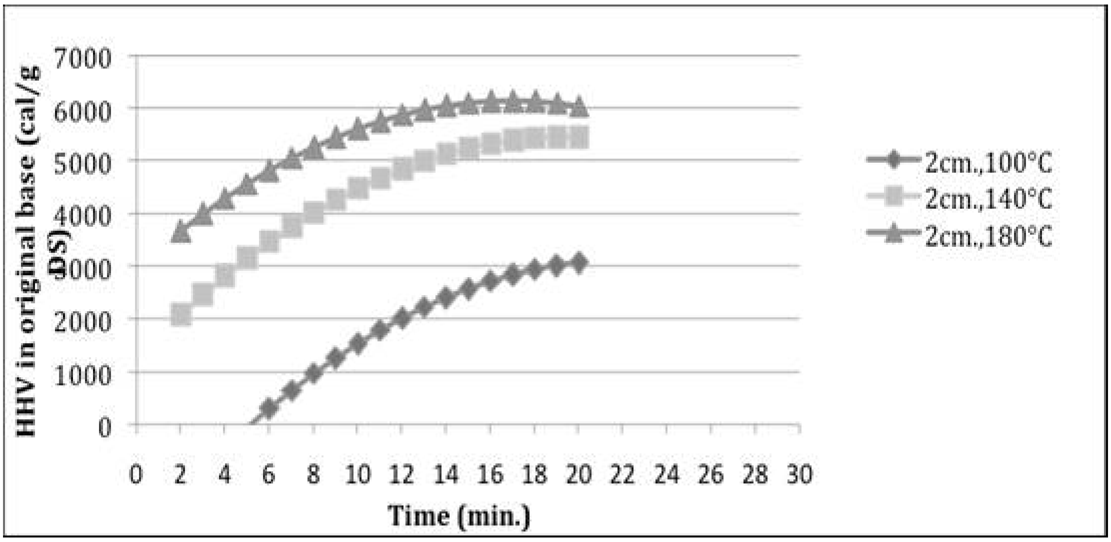

Figure 5.160 HHV in original base curves for 2cm diameter samples fried sludge at three different temperatures.

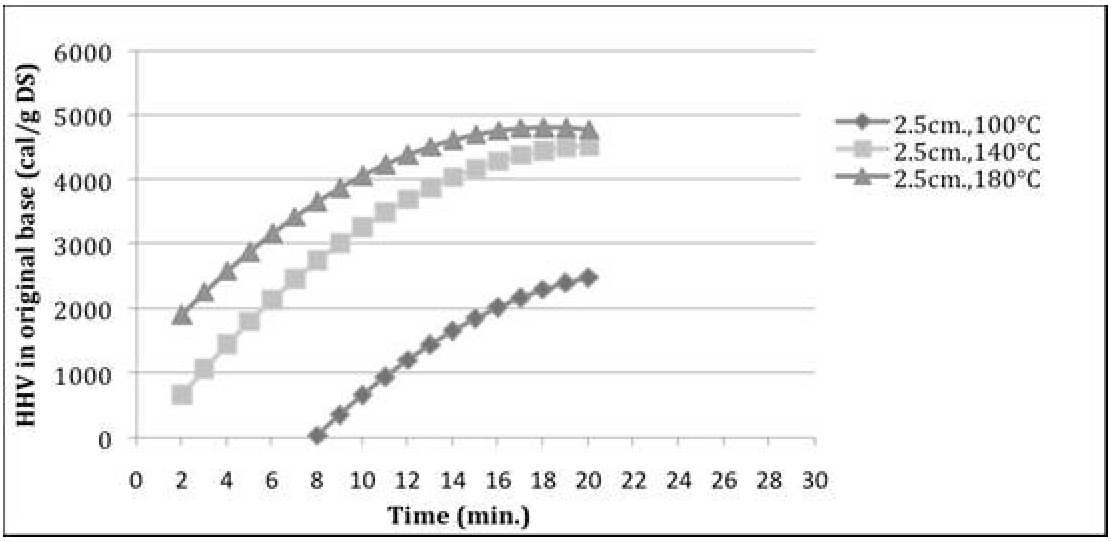

Figure 5.161 HHV in original base curves for 2.5cm diameter samples fried sludge at three different temperatures.

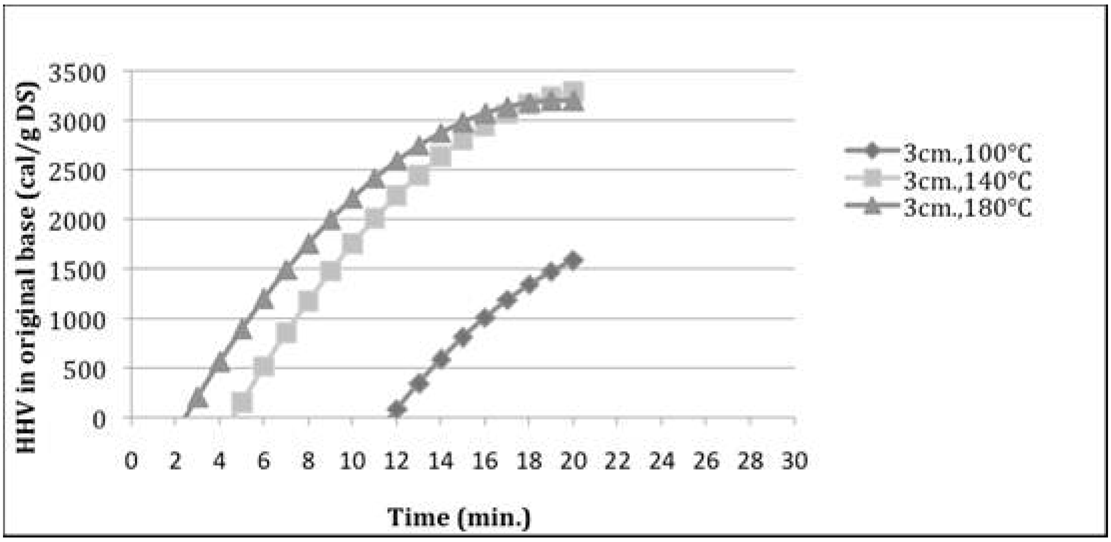

Figure 5.162 HHV in original base curves for 3cm diameter samples fried sludge at three different temperatures.

5.4.4 Oil Uptake Performance of Fry-dried sludge with Waste Cooking Oil

During the frying process sludge uptakes oil while loses moisture. Relationships between oil uptake and cylinder diameters are shown in Figures 5.163 and 5.164. Frying different diameters at the same conditions showed that the 2 cm diameter sample has higher oil uptake than smaller diameter samples. However, it was surprisingly for the sample having 3 cm diameter.

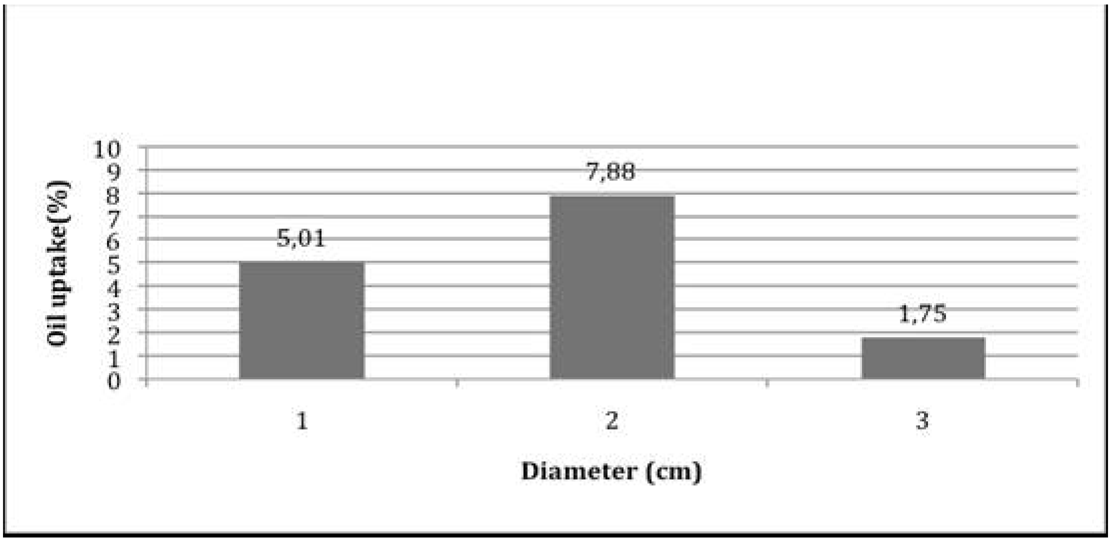

Figure 5.163 Effects of diameter on oil uptake results at 140 °C for 11 minutes fry-drying.

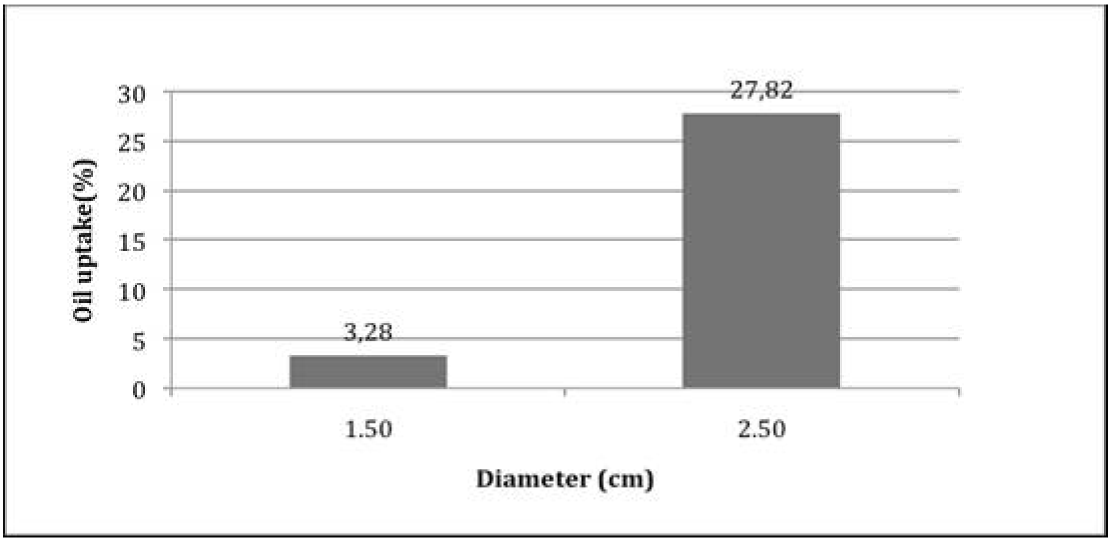

Figure 5.164 Effects of diameter on oil uptake results at 120 °C for 6 minutes fry-drying.

Figure 5.165 shows the oil uptakes of the fried 2cm. diameter samples for 11 min. at different temperatures. The higher oil temperatures led to higher oil uptakes.

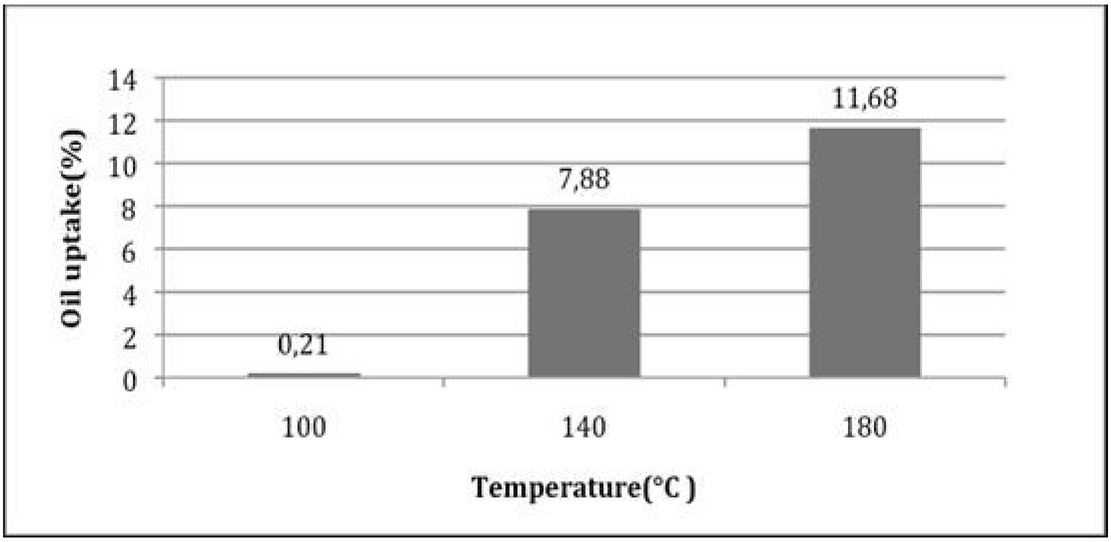

Figure 5.165 Oil uptake results fry-dried 2 cm. samples for 11 minutes at different temperatures.

Figure 5.166 presents the oil uptake results of fry-dried 2 cm. samples at 140°C for 2, 11, and 20 min. As seen from the figure, oil uptakes increased for 11 min. application; but it decreased for higher drying times.

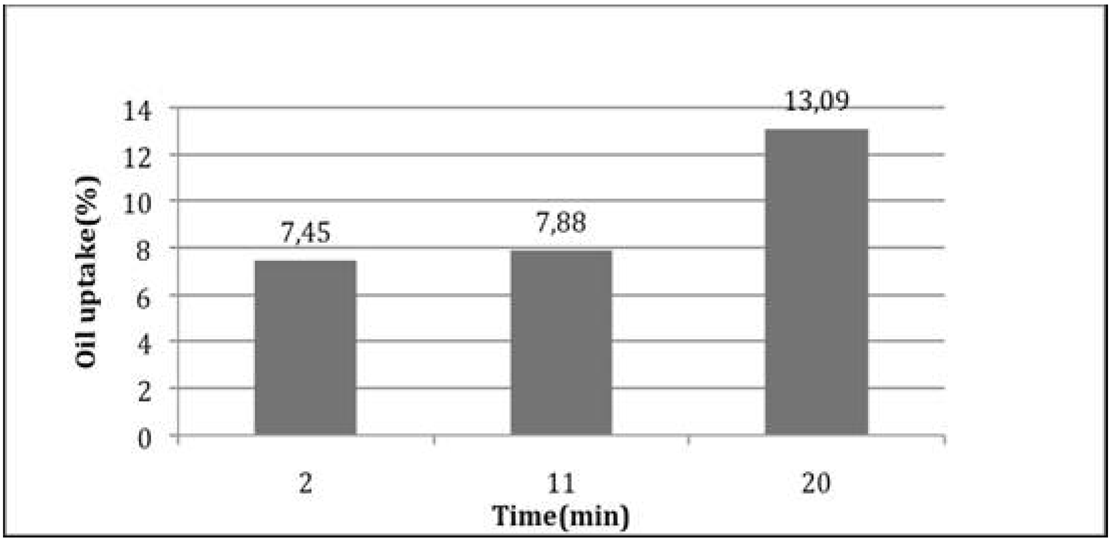

Figure 5.166 Effects of time on oil uptake results on fry-dried 2 cm. samples at 140 °C.

Figure 5.167 shows oil uptakes of 1.5 and 2.5 cm. samples fry-dried at 120°C and 160°C for 16 min. Higher diameter samples up took oil much more than smaller diameter samples.

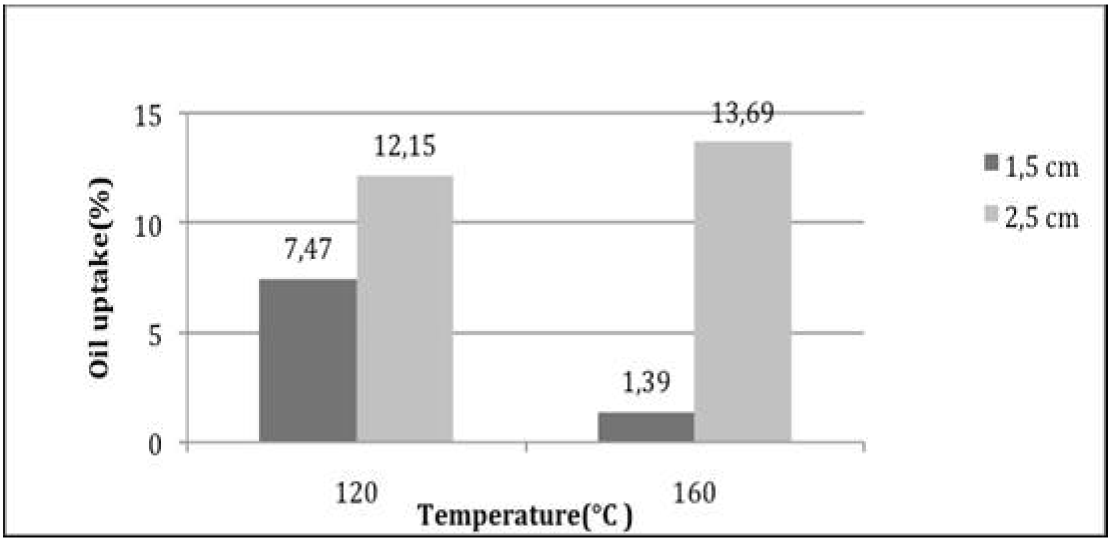

Figure 5.167 Effects of diameter and temperature on oil uptake results fry-dried samples for 16 minutes.

Figure 5.168 shows the oil uptakes for the 1.5 and 2.5 cm. diameter samples fried for 6 and 16 min. at 120 and 160°C.

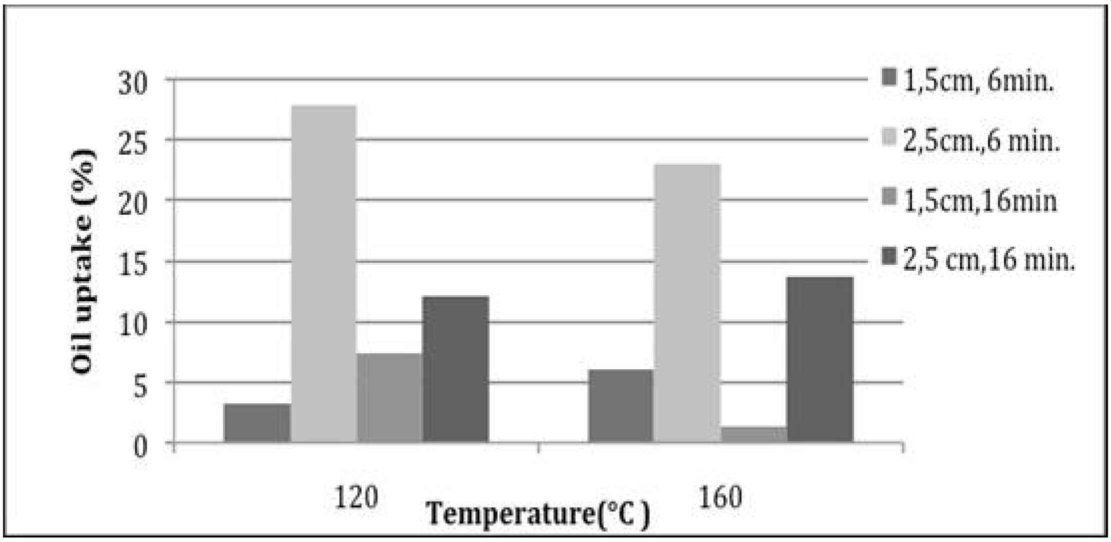

Figure 5.168 Effects of time, diameter, and temperature on oil uptake results.

Table 5.30 shows the estimated coefficients of the response function of oil uptake calculated by Statistica 7 program with the experimental data. The predicted oil contents were given in Table 5.31. The regression coefficient was obtained as R^2=0.62388803.

Table 5.30 Oil uptake response function coefficients.

bo	b1	b2	b3	b12
-22.4798	1.0042	-0.1386	25.0397	-0.0032
b13	b23	b11	b22	b33
-1.2293	0.0011	0.0767	0.0008	-1.2931

Table 5.31 Predicted and residual values for oil uptake of fry-dried samples with WEO.

Time(min)	Temperature(°C)	Diameter(cm)	Predicted	Residuals
20	140	2	11.61843	1.4703
2	140	2	15.43387	-7.9801
11	100	2	6.53083	-6.3223
16	120	2.5	7.62463	4.5291
11	140	1	-0.48887	5.4951
16	160	2.5	9.06205	4.6227
16	160	1.5	8.67961	-7.2883
16	120	1.5	7.28805	0.1769
11	140	3	12.52287	-10.768
6	160	2.5	17.96517	5.0961
11	140	2	7.31009	-1.8447
6	120	2.5	15.25361	12.5611
6	160	1.5	5.29	0.7437
6	120	1.5	2.62431	0.6503
11	140	2	7.31009	0.5691
11	180	2	10.63394	1.0494
11	140	2	7.31009	-2.7605

Oil uptake curves are shown as a function of temperature at different frying times and different sample diameters in between the Figures 5.169 and 5.173.

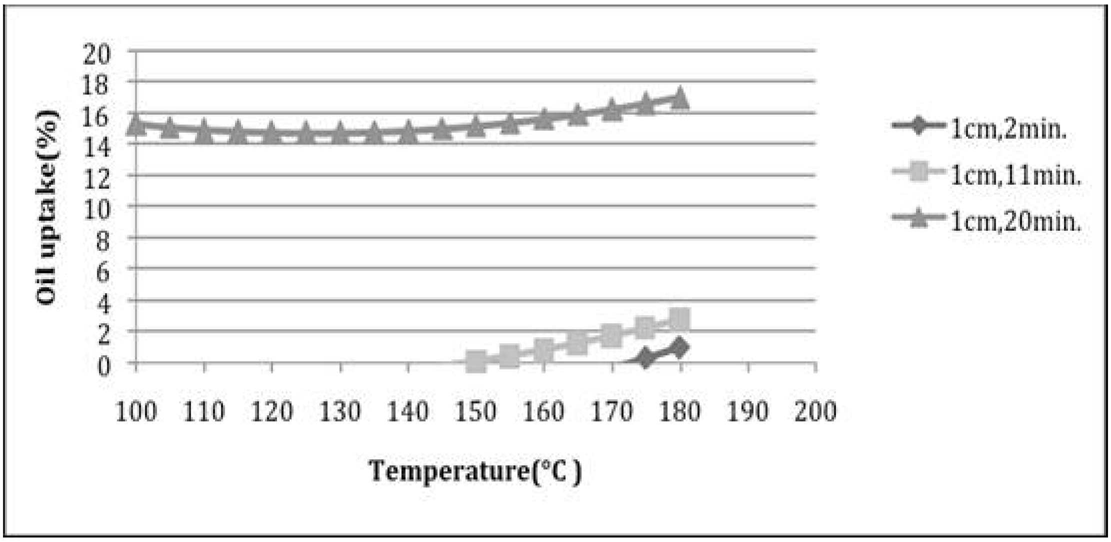

Figure 5.169 Oil uptake curves for 1cm diameter samples fry-dried sludge for three different process times.

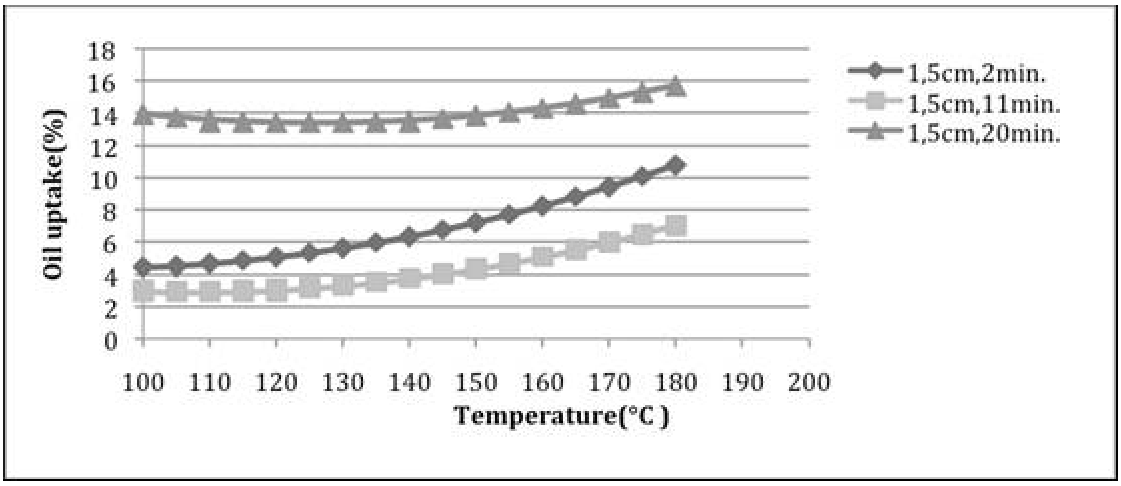

Figure 5.170 Oil uptake curves for 1.5cm diameter samples fry-dried sludge for three different process times.

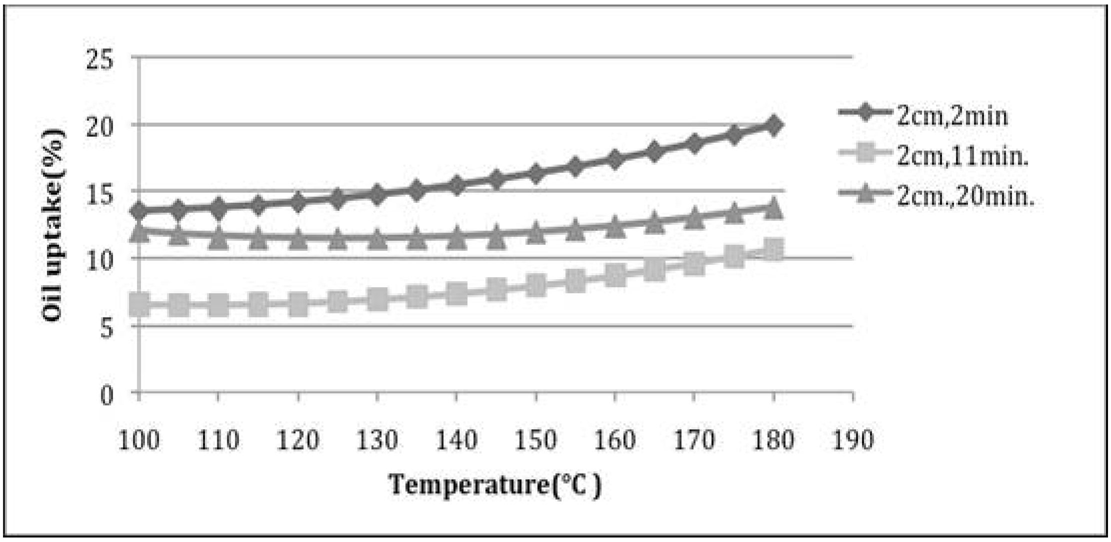

Figure 5.171 Oil uptake curves for 2cm diameter samples fry-dried sludge for three different process times.

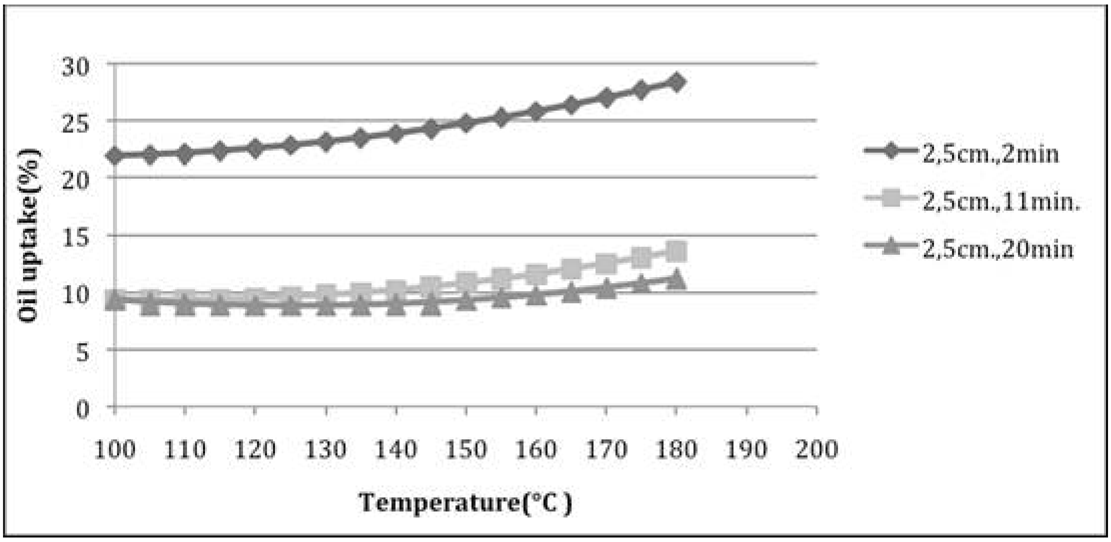

Figure 5.172 Oil uptake curves for 2.5cm diameter samples fry-dried sludge for three different process times.

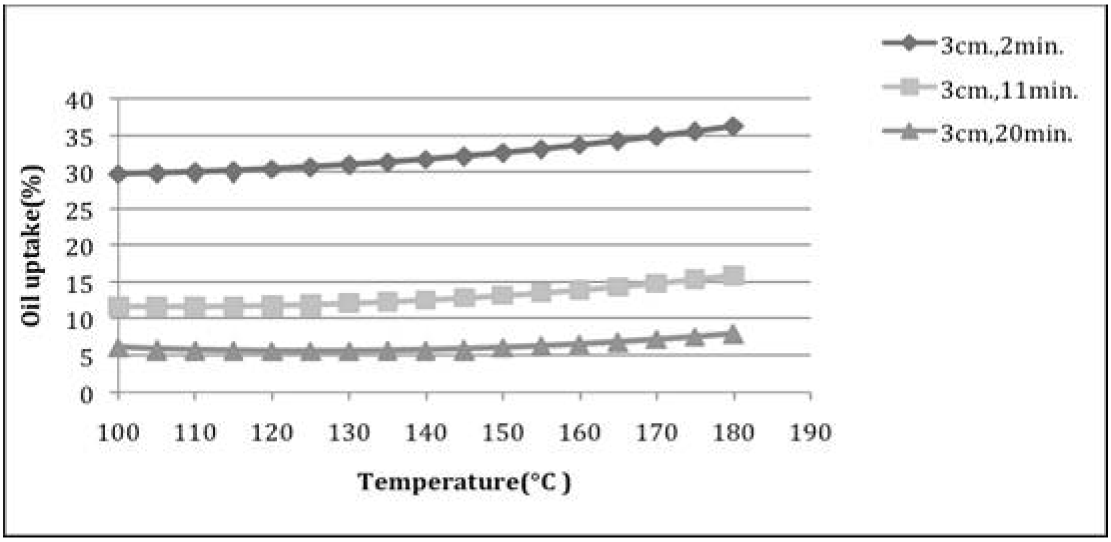

Figure 5.173 Oil uptake curves for 3cm diameter samples fry-dried sludge for three different process times.

Figures 5.174-5.178 show oil uptake curves as a function of time at different temperatures and different sample diameters.

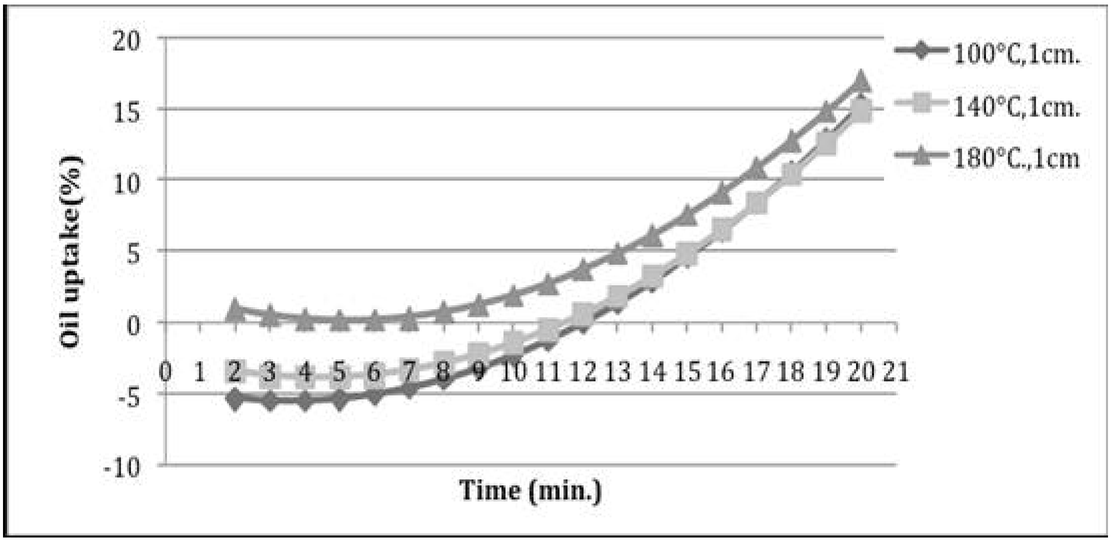

Figure 5.174 Oil uptake curves for 1cm. diameter samples fried sludge at three different temperatures.

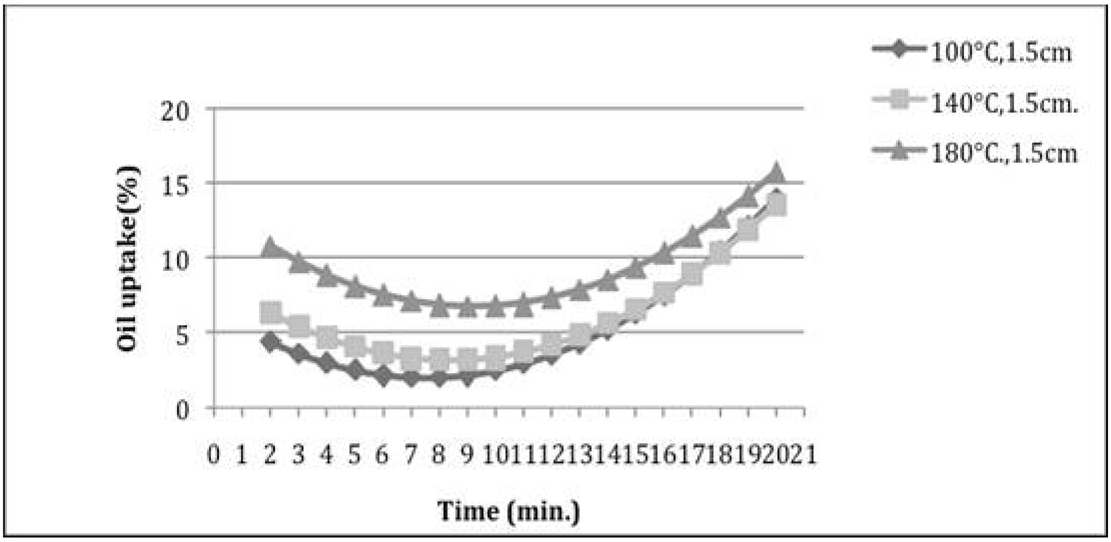

Figure 5.175 Oil uptake curves for 1.5cm diameter samples fried sludge at three different temperatures.

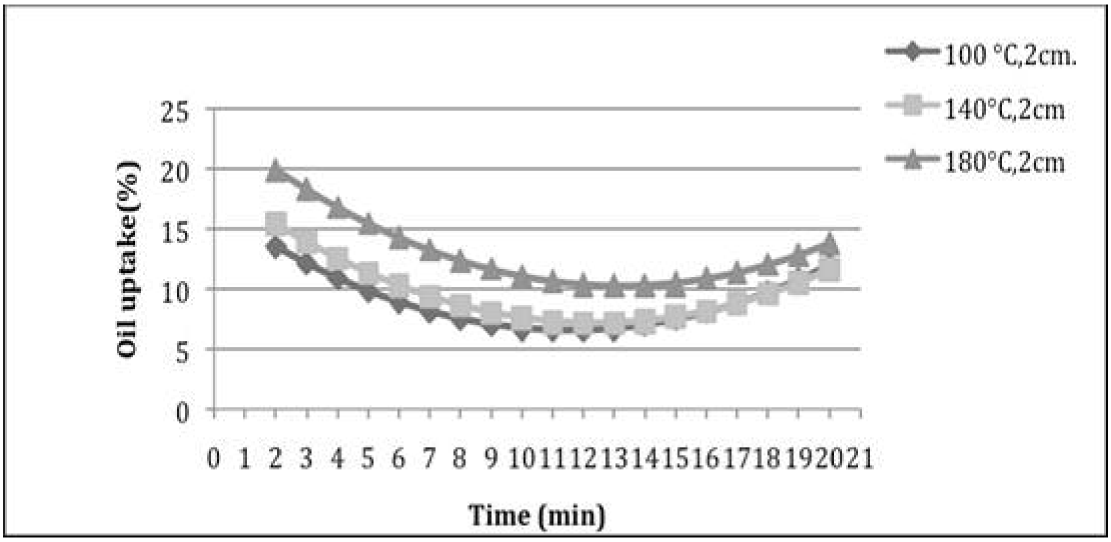

Figure 5.176 Oil uptake curves for 2cm diameter samples fried sludge at three different temperatures.

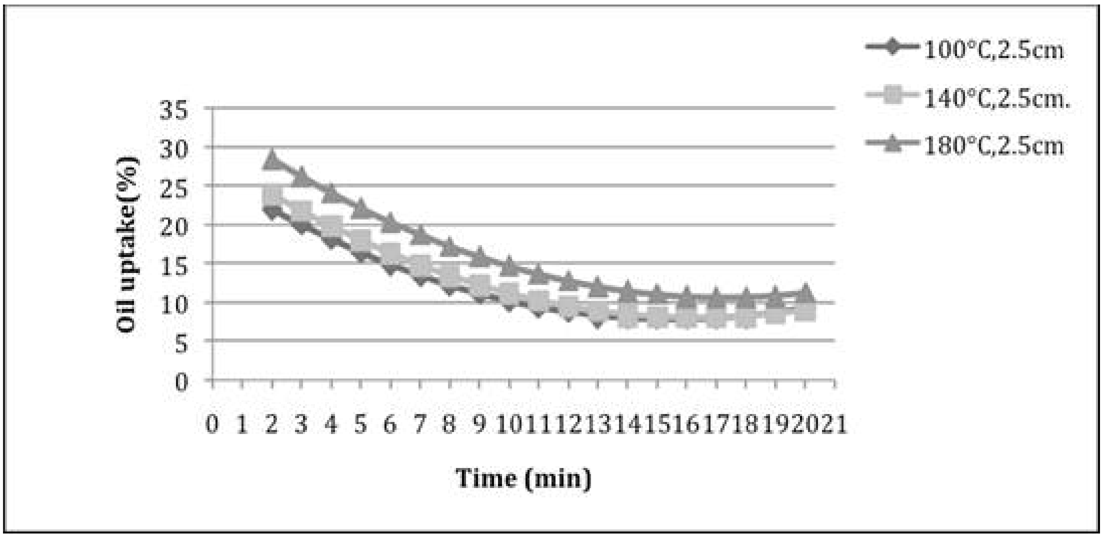

Figure 5.177 Oil uptake curves for 2.5cm diameter samples fried sludge at three different temperatures.

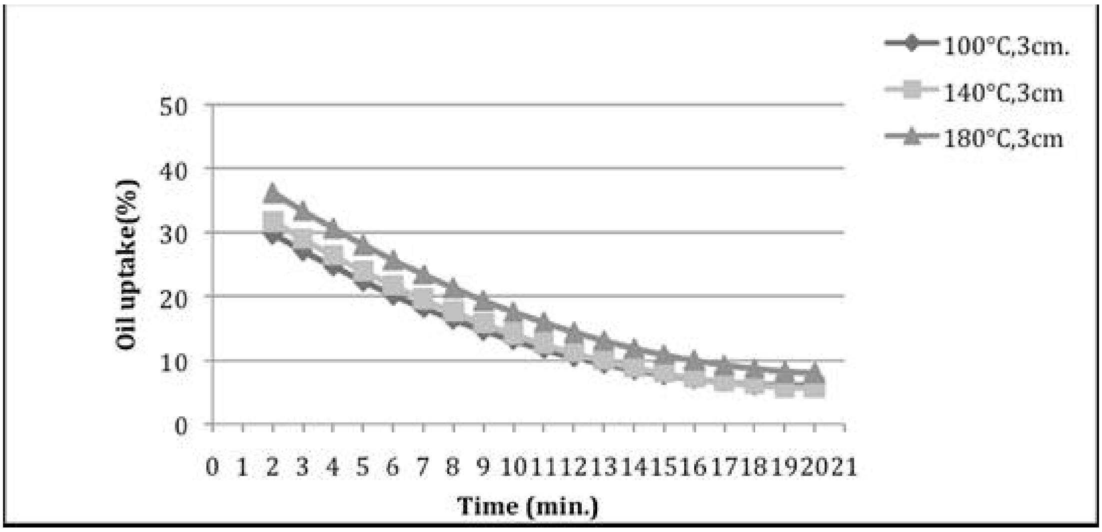

Figure 5.178 Oil uptake curves for 3cm. diameter samples fried sludge at three different temperatures.

During the fry-drying applications, the sludge samples having different thickness gained an additional heating value. Increased DS contents of the samples were obtained and similarly VS contents of the samples increased in the temperature range of 120- 160 °C. Some pictures from the experimental studies showing the dewatered sludge cake and fry-dried sludge samples with WCO are given in Figure 5.179. This application was also done using waste cooking oil.

Figure 5.179 Some pictures from the experimental studies showing the dewatered sludge cake and fry-dried sludge samples with WCO.

CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The fry-drying method was used to dry sewage sludge in this study. Two experimental studies were carried out at the same operational conditions; but different oils were used in these series. The experiments were done by using the both waste cooking oil and waste engine oil. The effects of frying time, frying temperature and the sludge's diameter on sludge drying and its calorific value were examined. In the experimental studies, sludge used as cylindrical samples at five different diameters between 1cm and 3 cm, at five different oil temperatures ranged between 100°C and 180 °C, and at five different frying times ranged between 2 min and 20min. In both of these studies, the Box Wilson statistical method was used to determine the operational conditions in which the experiments were done. Experimental results showed that the usage of the fry-drying process as a final treatment or improved is an effective method. The concluding remarks from this thesis can be given as follows:

- The dry solid content of dewatered sludge cake was increased from 24% to 97.26% using fry-dried method with waste engine oil for 16 min. at 160°C in 1.5 cm diameter. The maximum dry solid content of fry-dried sludge with waste cooking oil was achieved at 140°C fried for 11 min and in shape 1cm. diameter; increased from 22.99% to 99.53%.
- Drying performance regarding the dry solids content was greater for long frying times at higher temperatures with smaller diameters. The optimal conditions were determined as 6-11-16min. of frying time, 140-160°C of frying temperature, and 1-1.5-2 cm of sample's diameter.
- The dry solids content of fry-dried samples with waste cooking oil was higher than fry-dried samples with waste engine oil at optimum operation conditions.

- The volatile solids content of sewage sludge fry-dried with waste engine oil for 16 min. at 160^{o}C in 1.5 cm diameter was increased from 53.49% to 73.80%. The maximum volatile solids content of fry-dried sludge with waste cooking oil was achieved at 140^{o}C fried for 11 min and in shape 1cm. diameter; increased from 54.38% to 70.14%.
- Both experimental study results were run in the statistical program (Statistica 7) and the results showed that long frying times, higher temperatures, and bigger diameters have negative effect on volatile solids contents.
- Low heating values of the sludge after fry-drying increased significantly. LHV's in dry base of sludge samples fry-dried was increased from approximately 2900 cal/g DS to 5779 cal/g DS with waste engine oil and from 3100 cal/g DS to 6168 cal/g DS with waste cooking oil.
- LHV in dry base was range between 5090 cal/g DS and 5779 cal/g DS at optimum operation conditions for waste engine oil experimental set.
- LHV in dry base was range between 5720 cal/g DS and 6168 cal/g DS at optimum operation conditions for waste cooking oil experimental set.
- The maximum LHV in dry base results were achieved for fry-dried sample 1.5cm diameter at 160^{o}C for 16min with both WCO and WEO.
- For the WEO and WCO applications using fry-drying of dewatered sludge cake samples, the optimum operational conditions based on the DS, VS, and LHV in dry base results are summarized below. Depending on the results, WCO looks more efficient than the WEO regarding the DS and LHV_{dry}. However, VS values for WEO were higher than those obtained from WCO application.

WEO				WCO			
Time (X_1), min	**Temperature (X_2), °C**	**Diameter (X_3), cm**	**DS (%)**	**Time (X_1), min**	**Temperature (X_2), °C**	**Diameter (X_3), cm**	**DS (%)**
16	160	1.5	97.26	11	140	1	99.53
11	140	1	86.84	16	160	1.5	99.43
6	160	1.5	81.98	6	160	1.5	99.4
16	120	1.5	80.1	16	120	1.5	85.67
11	140	2	68.4	11	140	2	82.06

WEO				WCO			
Time (X_1), min	**Temperature (X_2), °C**	**Diameter (X_3), cm**	**VS (%)**	**Time (X_1), min**	**Temperature (X_2), °C**	**Diameter (X_3), cm**	**VS (%)**
16	160	1.5	73.8	16	160	1.5	69.24
11	140	1	70.82	16	120	1.5	66.96
16	120	1.5	69.65	6	160	1.5	66.49
11	100	2	68.91	11	140	2	65.76
6	160	1.5	67.72	11	140	2	63.80
11	140	2	67.21	11	140	2	63.65
11	180	2	64.33				
6	120	1.5	63.73				

WEO				WCO			
Time (X_1), min	**Temperature (X_2), °C**	**Diameter (X_3), cm**	**LHV_{dry} (cal/g)**	**Time (X_1), min**	**Temperature (X_2), °C**	**Diameter (X_3), cm**	**LHV_{dry} (cal/g)**
16	160	1.5	5779.14	16	160	1.5	6168.45
11	140	1	5668.65	6	160	1.5	5950.62
16	120	1.5	5296.37	11	140	1	5901.24
11	140	2	5227.52	16	120	1.5	5728.33
6	160	1.5	5224.85	11	140	2	5720.48
6	120	1.5	5090.50				

6.2 Recommendations

The applicability of fry-drying technology for dewatered sludge cake taken from a municipal WWTP sludge were examined in this study. The results showed the fry-drying method is an alternative fast process for sludge drying. This makes fry-dried sludge as a product that can also be used as soil-fuel with its high heating value. In order to improve this study, the following future work can be done:

- Drying kinetics, water loss and oil uptake kinetic models can be determined.
- Experimental studies were done in laboratory scale; for future work, a pilot scale reactor might be designed. A full-scale trial can be done.
- Energy consumptions can be determined in laboratory scale.
- It may be beneficial to carry out a cost analysis in addition to investigation of sludge fry-drying properties.
- Different operational conditions may be applied to sludge samples in order to find out the optimum conditions.
- Emission characteristics can be investigated and which operation conditions effects on emission rates can be determined.

REFERENCES

Andritz Group, (n.d.). *Fluid bed drying system*, Retrieved December, 01, 2009, from http://www.andritz.com/ep-thermal-brochure-fds-e.pdf

APHA, (2005). *Standard Methods for the examination of water and wastewater*. 19th ed. American Public Healt Association, American Water Works Association and Water Environment Federation, Washington, USA.

Arcadis/CH2M Hill, (2008), *Technical Memorandum: Evaluation of Sludge Dryer and Dewatering Facilities at the Western Wake Regional Water Reclamation Facility,* Retrieved April, 09, 2011, from http://www.westernwakepartners.com/docs/reportamendments/appendices/App%20H--Evaluation%20of%20Sludge%20Dryer%20and%20Dewatering%20Facilities.PDF

Arlabosse, P., (2001a) Study on Thermal Drying Processes of Municipal and Industrial Sewage Sludges; *Report no. 99-0217=1A; Ecole des Mines d'Albi Carmaux & Association RE.CO.R.D., Albi, France.*

Arlabosse, P., Peregrina, C., Lecomte, D., Rudolph, V., (2001b), The Environmental Performance of an Alternative Fry-Drying Process for Sewage Sludge: a Life Cycle Assessment Study., Laboratoire de Génie des Procédés des Solides Divisés (*UMR 2392*), Ecole des Mines d'Albi Carmaux, Route de Teillet, 81013 Albi CT Cedex 09, France

Arlabosse, P., Peregrina, C., Lecomte, D., (2004), Thermal Efficiency in Sewage Sludge Fry Drying.

Ayhan D., (1996), Calculation of higher heating values of biomass fuels. *Fuel, 76, 431-434.*

Bresters, A. R, Coulomb, I., Deak, B., Matter, M., Saabye, A., Spinosa, L., Utvik, A. O., (1997), Sludge Treatment and Disposal Management Approaches and

Experiences, Environmental *7,* Retrieved April, 09, 2011 from http://www.eea.europa.eu/publications/GH-10-97-106-EN-C/sludge.pdf

Catallo, W.J., Comeaux, J.L., (2008). Reductive hydrothermal treatment of sewage sludge. *Waste Manage. 28* (11*)*, 2213–2219.

Chen, G., Yue, P. L., Mujumdar, A., (2002). Sludge dewatering and drying. Drying Technology – *International Journal, 20* (4&5*)*, 883–916.

Council Directive 86/278/EEC of 12 June 1986 on *the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture*

Faghri, A., Zhang, Y., and Howell, J.,(2010). *Advanced heat and mass transfer*, chapter nine, fundamentals of thermal radiation. Retrieved December 20, 2010, from https://www.thermalfluidscentral.org/e-books/book-viewer.php?b=37&s=10

Flaga, A. (2009), Water Science and Technology, *60* (5), 1145-1154.

Filibeli, A. and Ayol, A., (2011). Evaluation of Stabilized Treatment Plant Sludges for Land Application. *V. Turkish-German Symposium*, 27-30 September, 2011, 211-231, ISBN:978-3-8356-3269-1, Stuttgart, Germany.

Furness, D.T., Hogget, L.A., Judd, S.J., (2000), *Thermochemical treatment of sewage sludge. Water Environ. J.* 14 (1), 57–65.

Fytili, D., Zabaniotou, A., (2008). Utilization of sewage sludge in EU application of old and new methods—A review, *Renewable and Sustainable Energy Reviews 12* 116–140.

Gruter, H., Matter, M. andOehlmann, K.H. (1990). Drying of sewage sludge – an important step in waste disposal. *Water Science & Technology*, *22* (12), 57-63

Hasserbrauck, M., Ermel, G., (1996), Two examples of thermal drying of sewage sludge. *Water Science and Technology*. Proceedings of the 1995 7th IAWQ Conference on Design and Operation of Large Wastewater Treatment Plants, Aug 27-Sep 1 1995. *33*(12), 235-242.

Izmir Water Works Authority, *Izmir Municipal WWTP*. (n.d.). Retrieved February 28,2011 from

http://www.izsu.gov.tr/pages/standartPage.aspx?id=225,28.02.2011

Lienhard V, J.H., Lienhard IV, J. H., (2008). *A Heat Transfer Textbook* (3rd ed.). NY; Phlogiston Press.

Lowe, P. (1995) Developments in the Thermal Drying of Sewage Sludge. *Water and Environment Journal 9* (3). 306–316

Metcalf & Eddy (Eds.). (2003). *Wastewater Engineering: Treatment, Disposal, Reuse.* New York, USA: McGraw Book Company.

Moreira, R.G., Castell-Perez, M.E., Barrufet, M.A., (1999), *Deep-Fat Frying and Application*. US Edition. Maryland: Aspen Publisher, Inc.

Ohm T.I, Jong-Seong Chaea, Jeong-Eun Kima, Hee-kyum Kima, Seung-Hyun Moonb , The evaporative drying of sludge by immersion in hot oil: Effects of oil type and temperature, *Journal of Hazardous Materials*, 2010

Ohm T.I, Jong-Seong Chaea, Jeong-Eun Kima, Hee-kyum Kima, Seung-Hyun Moonb, (2009). A study on the dewatering of industrial waste sludge by fry-drying technology, *Journal Of Hazardous Materials 168*, 445-450.

Ogada, T., Werther, J, 1996. Combustion Characteristics of Wet Sludge in a Fluidised Bed. *Fuel* 75, 617-626.

Ogada, T., Werther, J, (1999). Sewage Sludge Combustion. *Prog. Energ. Combust*. *25*, 55–116.

Öztürk, İ., (2010), *Atık Sektörü Mevcut Durum Değerlendirmesi Raporu*, Ankara: T.C. Çevre ve Orman Bakanlığı Çevre Yönetimi Genel Müdürlüğü

Park, K., Lim, B., Lee, S., (2010), Drying characteristics of sewage sludge using vacuum evaporation and frying, *Journal of Material Cycles and Waste Management*, *12* (3), 235-239.

Peregrina, C., Arlabosse, P., Lecomte, D. and Rudolph, V.(2006) 'Heat and Mass Transfer During Fry- Drying of Sewage Sludge', *Drying Technology*, 24 (7), 797-818.

Peregrina, C., 2005. Traitement des boues par friture: Des mécanismes physiques à l'éco-conception d'un procédé. *Thèse: Ecole des mines d'Albi*, France.

Peregrina, C., Lecomte D., Arlabosse P., V. Rudolph (2001). Laboratoire de Génie des Procédés des Solides Divisés (UMR 2392), Ecole des Mines d'Albi Carmaux, Route de Teillet, 81013 Albi CT Cedex 09, France

Pires da Silva, D., (2003). Study of Sewage Sludge Drying Using Immersion Frying; Ph.D. Thesis. Universidade Estadual de Campinas: Campinas, SP, Brazil, (in Portuguese).

Romdhana M. H., Hamasaiid A., Ladevie B., Lecomte D., (2009). Energy valorization of industrial biomass: Using a batch frying process for sewage sludge. *Biores. Tech*, *100,* 3740-3744.

Saguy, I. S., G. Ufheil, S. (1998), Livings, Oil uptake in deep fat frying-review. *Oléagineux Corps Gras Lipides, 5* (1), 30-35.

Silva D. P., Rudolph V., Taranto O. P., (2005), The Drying of Sewage Sludge by Immersion Frying. *Brazilian Journal of Chemical engineering 22,* 271-276.

Thamer, D., Jenewein, W., (n.d.)., *Thermal Drying: An Attractive and Sustainable Answer to the Sludge Utilisation under the Light of EU-Legislation*. Retrieved April 09,2011 from http://www.idswater.com/Common/Paper/Paper_246/Article_Thermal-Drying.htm

Turkish Statistical Institute Report. (n.d.). Retrieved 2008 from www.tuik.gov.tr

Turovskiy, I. S., Mathai, P. K., (2006), *Wastewater Sludgeprocessing*, Hoboken, New Jersey: John Wiley & Sons, Inc.

U. S. Department of Energy, (1992). *Fundamentals handbook* - Thermodynamics, Heat Transfer, and Fluid Flow, 2.

U. S. Environmental Protection Agency, (1979), *Process Design Manual For Sludge Treatment and Disposal*, Retrieved April, 10, 2011 from http://www.epa.gov/nrmrl/pubs/625179011/625179011prel.pdf

Vaxelaire, J., Cezac, P., (2004). Moisture distribution in activated sludges: a review. *Water Research 38*, 2215–2230.

Vesilind P. A. (1994) The role of water in sludge dewatering. *Water Environ. Res*. *66*, 4–11.

Wang, L. K., Williford,, C., Chen, W., Shammas, N. K., (2005), Low-Temperature Thermal Treatment Processes, *Handbook of Environmental Engineering, 3, Physicochemical Treatment Processes,* Totowa, New Jersey: The Humana Press.

Water Environment Federation Residuals and Biosolids Committee Bioenergy Technology Subcommittee**, (**2004), *Thermal Drying of Wastewater Solids,* Working document.

Water Siemens Technologies, (nd). *Sludge Dryers*. Retrieved August 30, 2011, from http://www.water.siemens.com/SiteCollectionDocuments/Product_Lines/Industrial_Wastewater_Systems/Brochures/Dryer_Draft_Manuscript.pdf

Welty, J. R., Wicks, C. E.; Wilson, R. E., (1976), *Fundamentals of momentum, heat, and mass transfer* (2 ed.). New York: Wiley.

Wendewolf sewage sludge dryer by Ist ,*Solar drying systems*.(n.d.). Retrieved April 09,2011 from http://www.wendewolf.com/klssystem.php?lang=en