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Oil Shale Dust Explosion

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COMMITTEE DEC ON

This thesis was defended successfully on 8th, May, 1996.

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DEDICATION

To My Parents Brothers and Sisters,

With Love and Appreciation.

ACKNOWLEDGMENTS

It gives me a great pleasure to express my deepest thanks to my supervisor Prof. Mohammed Ahmed Hamdan for his help, encouragement, and guidance during my research work.

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TABLE OF CONTENTS

LISTS OF FIGURES

LIST OF TABLES

ABSTRACT

Oil shale Dust Explosion

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This study aims at investigating the problem of oil shale dust explosion which is expected to arise, here in Jordan, in oil shale mines when they are put in operation in the next few years.

Two parameters were measured namely; the minimum ignition temperature and the minimum explosible concentration of oil shale dust when it was dispersed in air. Also, the effect of particle size on such parameters was investigated.

It was found that particles with fine size in the range of 63μm to 75μm are the most probable to explode among all other particle sizes. Such particles were found to have a minimum ignition temperature of 570°C and a minimum explosible concentration of 1.55 g/L.

Mixtures of coarse and fine particles were examined, and it was found that when coarse particles were used instead of fine ones, the minimum

CHAPTER ONE

INTRODUCTION

1.1 GENERAL:

Dust is formed in many industrial processes as major products or by-products. Many combustible dusts can burn with explosive severity if an ignition source is present. The conditions for burning are more favorable if the dust is dispersed in the form of a cloud, the large surface area in immediate contact with the air allows combustion to proceed much more rapidly than with deposits and a dust explosion may result. The characteristics of a dust explosion are the rapid propagation of combustion and the corresponding rapid generation of heat.

Dust explosions have been known for many years. The first incident to occur was in a flour factory in Turin in 1785. Years later, explosions especially in coal mines started to occur which made dust explosions a reality which could not be ignored.

Here in Jordan, during the period 1977-1982, the only period in which information about industrial fires and explosions are available, there were many fires and explosions which occurred in Jordan's industries, and according to the Public Fire Brigades records [1], 36 dust explosions were recorded during that period. The chemical industries (i.e. cement, sponge and battery manufacturing) had the most incidents, while food, textile and woodwork industries had smaller number of incidents.

1.2 OBJECTIVES OF THE PRESENT WORK:

This work is an experimental investigation directed towards studying the problem of oil-shale dust explosion which may occur in Jordan when oil-shale mines are put in operation .

Two parameters of oil-shale dust explosion will be investigated, which are: the minimum ignition temperature and the minimum explosible concentration, using the standard test apparatus given in the literature. Also the effect of particle size on such parameters will be investigated by using fine particles, coarse particles and mixtures of both. Finally, the methods for minimizing the occurrence of dust explosions will be studied, mainly using inert additives to decrease the hazards of dust explosion.

1.3 LAYOUT OF THE THESIS:

This thesis is divided into seven chapters, this introduction is the first. Literature review is presented in chapter two. In chapter three, the background of dust explosion phenomenon is introduced. Chapter four deals with combustion calculations. Chapter five presents the experimental setup and procedure. The results obtained are presented in chapter six and these results are discussed in the same chapter. Finally, conclusions and recommendations of this work are given in chapter seven.

CHAPTER TWO

LITERATURE REVIEW

This chapter contains a general review of some of the experimental and theoretical work that have been done in the field of dust explosions. In addition, a review of the explosion incidents in coal mines, which occurred during the last century, will be introduced.

2.1 PREVIOUS STUDIES:

Rose [2] in his work on the ignition of clouds of lycopodium dust using an electric spark as the source of ignition, suggested two processes required for an explosion to occur; both of which are dependent on the dust concentration, these two processes are:

1- The initiation process: where a small volume of the dust cloud is ignited by the electric spark.

2- The continuation process: where the combustion from the initially burning volume propagates to the remainder of the cloud.

He cocluded that if the initiation process does not occur within the duration of the spark ($\cong 10^{-3}$ sec), it will not occur at all. By using a heated surface as the source of ignition, the probability of initiation (ignition) increases with the time of exposure of the dust cloud to the hot surface.

In the same reference, it was suggested that the propagation of flame can occur if the initial volume of cloud, after combustion, release enough energy to raise the temperature of that volume to a minimum temperature necessary for the combustion of a neighboring volume.

Long and Murray [3] in their work in the pre-reaction zone have suggested that the way the chemical reaction starts depends to a large extent on the relative temperatures of the dust particles and that of the surrounding air. They have suggested two possibilities:

1- If the air surrounding the dust particles is at a higher temperature than it, then combustion starts by the ignition of the volatile matter and the inflammation of the solid particles occurs later.

2- If the dust particles are at a higher temperature than the surrounding air, then inflammation of the solid might occur first, and the dust particles will then behave as nuclei for igniting the surrounding gas mixture.

Cassel and Liebman [4] proved that the temperature required for ignition of a dust cloud is lower than the ignition temperature of a single particle. The ignition of a dust cloud in a heated environment has been investigated by extending the Frank Kamenetskii theory of steady state thermal ignition to a combustible dust cloud . An expression for the ignition of a dust cloud was proposed, which shows that the ignition temperature decreases as the dimensions of the dust cloud increases.

Sweis [5] had measured the dust explosion parameters of Adipic acid and Fumaric acid. He developed a primarily mathematical model explaining the initiation and continuation of flame propagation, but he did not compare his results with experimental data.

Amyotte et al. [6] investigated the effect of turbulence on dust explosion parameter. They found out that turbulence tends to decrease the ignitability of dust.

Hertzberg et al. [7] studied the lean limit of Pittsburg pulverized coal dust. They found out that the value of lean limit depends on the particle size and on the degree of dispersion.

Amyotte et al. [8] studied the ignitability of coal dust-air and methane-coal dust-air mixtures by conducting an experimental investigation of dust explosions in a 26 L sphere chamber. They found out that the ignitability of dust reduces with the presence of methane.

2.2 EXPLOSION INCIDENTS:

In spite of significant research world wide, the coal dust explosion hazard has not been eliminated. There have been serious explosion incidents in coal mines in Germany (June 1988), Yugoslavia (August 1990) and Czechoslovakia (October 1990). Nagy [9] reported that between 1880 and 1980 there were 500 major gas and dust explosions in coal mines in the

USA. There were also several thousand minor explosions and ignitions during this period; the number of fatalities from all these incidents exceeded 15000. Nagy gave data which show that although the frequency and magnitude of mine explosions in the USA (and the number of related fatalities) had been decreasing since 1910. explosions were continuing to occur

Since 1900 there have been 26 fires and/or explosions in Nova Scotia coal mines, which resulted in 294 fatalities. There were 1850 fatalities in coal mines in the province throughout that time; 16% of coal mine fatalities since 1900 have thus been caused by fires or explosions.

CHAPTER THREE

BACKGROUND

3.1 INTRODUCTION

An explosion is a phenomenon which results, from a sudden release of energy , and a dust explosion may be defined as the rapid transmission of a combustion wave through a cloud of solid particles. For most dust explosions it is the rapid chemical oxidation of the particles dispersed in air that supplies the sudden release of energy. This energy release increases the temperature of the system so fast that there is an accompanying increase in the pressure.

There is no agreed definition of the term 'dust'. In practice the terms 'dust' and 'powder' have been used indiscriminately, some industries favoring one term and some are favoring the other. For the present work the two terms will be regarded as interchangeable .

For convenience there need to be limitations on the diameters of particles entitled to be called dusts or powders. Following the British Standard [10], particles of diameter less than 1 micron can be termed 'smoke', so that dust particles have diameters greater that 1 micron (10^{-3} mm). It is also convenient to accept the definition of 'powder' as containing particles with a maximum dimension of less than 1000 microns. The term 'dust' was restricted to particles passing a 76 microns mesh sieve.

The term 'explosible' has been used to describe a dust which is able to cause a dust explosion, which has been preferred to 'explosive' to avoid confusion with high explosives, whose explosion properties are different from those of dusts dispersed as a cloud and ignited. A dust explosion propagates by the combustion of particles with surrounding gas, whereas explosives do not require a surrounding atmosphere. The properties of explosives are outside the scope of the present study. The term 'explosibility' indicates the extent to which a dust is explosible.

When a mass of solid flammable material is heated it burns away slowly, layer by layer, owing to the limited surface area exposed to the oxygen of the air. The energy produced is liberated gradually and harmlessly because it is dissipated as quickly as it is released. The result is quite different if the same mass of material is ground to a fine powder and intimately mixed with air in the form of a dust cloud. In these conditions the surface area exposed to the air is very great and if ignition now occurs the whole of the material will burn with great rapidity; the energy, which in the case of the mass was liberated gradually and harmlessly, is now released suddenly with the evolution of large quantities of heat.

3.2 CLASSIFICATION OF DUSTS:

Initially dusts were classified as follows:

Class I : Dusts which ignite and propagate flame readily, the source of heat required being small.

Class II : Dusts which ignite readily with flame but require a larger source of ignition.

Class III : Dusts which do not ignite in the tests.

This classification has now been discarded, and the new and simpler criteria are listed as Group (a) or Group (b), as follow:

Group (a) : Dusts which, when tested, ignited and propagated flame in the test apparatus.

Group (b) : Dusts which, when tested, did not ignite and propagate flame in the test apparatus.

As a general guide, dusts which were previously classified as Class I may now be taken as Group (a), whereas those previously Class II and III are now regarded as Group (b).

3.3 EXPLOSION PARAMETERS OF DUSTS:

If a dust is shown to be explosible, further information on the extent of the explosion hazard may be required when considering suitable precautions for the safe handling of the dust. The following properties of the dust, or explosion parameters, can be determined:-

(1) Minimum ignition temperature.

(2) Maximum permissible oxygen concentration of the atmosphere to prevent ignition in a dust cloud.

(3) Minimum explosible concentration.

(4) Minimum ignition energy.

(5) Maximum explosion pressure and rate of pressure rise.

3.4 MECHANISM OF DUST FLAME PROPAGATION:

Many workers in the field of dust explosions have investigated the mechanism of dust flame propagation. Theories which have been developed to explain such a mechanism have not been applied fully to industrial purposes. This is due in part to the following [10] :-

1- No general theory has been developed to cover the entire combustion process, from the pre-flame reaction to the final combustion products.

2- The existed theories can be applied only to parts of the flame process, such as pre-flame reaction, predictions of burning velocity, combustion of a single particle, etc.

3- The available theories have been developed for specific dusts and may not be used in general.

4- Some specifications of the flame process are still vague, particularly the rate controlling process.

3.5 DEFLAGRATION AND DETONATION:

In dust explosions the rate of propagation of flame through the dust cloud is fast compared with rates of flame spread in fires. In explosions, in small enclosures, flame speeds range from hundred of meters per second to the slowest which are of the order one meter per second. The most rapid burning dust fires are below this speed range. The type of explosion usually occurring under industrial conditions is termed a 'deflagration' which is associated with a flame speed less than the velocity of sound in the gaseous products of combustion.

There is another mode of combustion, termed 'detonation', which has a flame speed equal or higher than the velocity of sound in the gaseous products and is accompanied by a shock wave. This velocity is of the order one thousand meters per second. Whether or not a true stable detonation can occur in a dust explosion in industrial plant has not yet been established. In theory, because of the energy released during the explosion, detonations should be possible and, indeed, explosions having velocities similar to those of detonations have been reported. The majority of evidence relates to explosions in coal-mine galleries, at least 100 m in length, but the explosions were initiated by powerful sources which in themselves were capable of generating strong shockwaves. Whether or not detonations can develop from relatively small ignition sources in industrial plant, has not yet been proved, but in any case a detonation would initially start as a deflagration.

It is general practice in considering protection against dust explosion hazards, in industrial plant, to assume that deflagrations rather than detonations occur. This procedure has proved to be satisfactory in practice, which is fortunate because deflagrations are simpler to deal with than are detonations.

3.6 FLAME SPEEDS:

The flame speed in a dust explosion is not constant but depends on a number of factors. Two of the principal factors are the chemical compositions of the dust and the oxidant, but with the present state of knowledge the flame speed cannot be related simply to composition, including moisture content, or to heat of combustion. Furthermore, the flame speed depends upon the particle size of the dust, the smaller the particles the higher the flame speed, providing that with fine particles the dust is evenly dispersed in suspension. The flame speed also depends on the turbulence of the gas in which the dust is dispersed; broadly, increased turbulence leads to higher flame speed. In addition, the flame speed is also influenced by the power of the ignition source.

3.7 EXPLOSIBILITY LIMITS:

If flame is to propagate through a dust cloud, the concentration of dust must lie within the lower and upper explosibility limits. The lower explosibility limit may be defined as the minimum concentration of dust in a cloud necessary for sustained flame propagation. It is a fairly well defined quantity, which can be determined reliably in small scale tests, and is often listed as the minimum explosible concentration. Values are usually in terms of weight of dust per unit volume of air or gas.

When the concentration of dust is raised above the lower explosibility limit and past the stoichiometric value, the flame speeds and vigor of the explosion increase as described above. As the dust concentration is further increased, however, the quenching effect of the surplus dust on the explosion becomes more marked and eventually a concentration is reached at which flame propagation no longer occurs. This concentration is the upper explosibility limit and may be defined as the dust concentration above which flame propagation does not occur. The upper explosibility limit is not easy to measure in practice, mainly because of the difficulty of ensuring that a dust is uniformly dispersed in the cloud and that regions of high concentrations do not form by chance movement of the dust particles.

The lower and upper explosibility limits depend not only on the composition of the dust, but also on properties such as particle size, moisture content as well as on the type of ignition source used in the test. The particle size and shape also affect the dispensability of the dust; if this is poor due to cohesive forces or to entanglement of fibrous particles, then the explosibility limits are also modified.

3.8 IGNITION:

For an explosion of a dust cloud to occur, two conditions must be achieved:-

1) The concentration of the dust in air falls within the explosive limits, and

2) A source of ignition to raise the temperature of the dust cloud to the ignition temperature of that dust.

Apart from a few special instances where the act of dispersion of dust may ignite it, a separate source of ignition must be present and the concentration of dust in the cloud must be favorable. As the main stimulus for the measurement of dust explosion properties has been the need to provide information on the safe use and handling of dust, the laboratory tests of ignitability of dust have been designed to incorporate sources of ignition contact of the dust with the surface is greater, permitting a slower rate of rise in temperature to lead to ignition than would be possible in a dust cloud which is usually in motion past the hot surface.

Another frequent source of ignition of dust clouds is a spark. There are a number of ways by which these can be produced, e.g. by electricity, friction, impact, or by hot cutting or welding. A characteristic of all these forms of spark is that a small particle or volume of gas at a high temperature, is produced for a short interval of time. Although the temperatures of sparks are well above the minimum ignition temperatures for dust clouds, the size of the spark is much smaller than that of the hot surface used for ignition temperature measurement. Because of the smallness of the source, and its short duration, much higher temperatures are necessary to transfer the energy necessary to ignite dust clouds.

3.9 STANDARD TEST APPARATUS:

Laboratory tests have been set up in various countries to enable investigations of dust explosion properties to be made and these tests have become formalized . The test procedures accepted at present differ between countries because they have developed independently, however they have certain points in common. Those concerned particularly with explosibility properties provide for a small sample of dust to be dispersed in the presence of a source of ignition.

The assessments of dust explosions in the united Kingdom is now being carried out at the Fire Research Station, Boreham Wood. An extensive report of the standard test apparatus and the methods used for assessing the explosibility of dusts have been published by Raftery [11].

The standard test apparatus, which are used in the United Kingdom to determine the explosibility of dust cloud are:-

1) The Vertical Tube apparatus :

It is the Hartmann apparatus, shown in figure (3.1). It consists of a perspex combustion tube of 30.5 cm long, and 6.4 cm inside diameter, mounted over a brass dispersion cup, of 6.4 cm diameter and 1.6 cm deep in the center. The volume of the apparatus is 1.2 litters. The dust under test is placed in the cup, and is dispersed by air passing upwards through a tube on the axis of the cup. To improve dispersion a mushroom-shaped deflector is mounted in the cup over the end of this tube. The dispersing air is released from a reservoir of 460 cm^3 capacity at gauge pressures up to 280 kN/m^2, either as a momentary or a continuous blast. The ignition source is a pair of brass electrodes mounted at various positions in the perspex tube, with a spark gap of approximately 0.6 cm. The spark is obtained from an induction coil. Observations are made as to whether flame propagation through the dust cloud occurs away from the source of ignition.

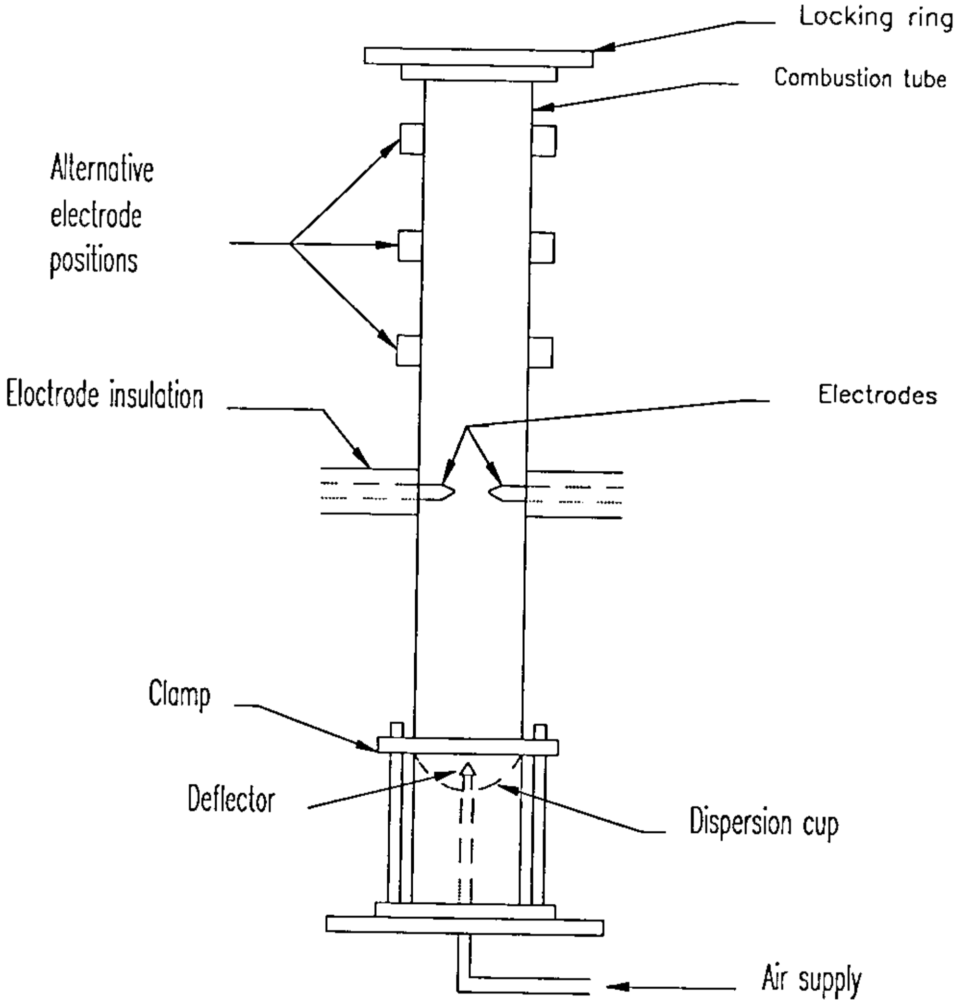


Figure 3.1 Vertical tube apparatus

The vertical Tube apparatus is suitable for testing all types of dust, but particularly materials which are adherent, or of high density are available only in limited quantity.

2) The Horizontal Tube apparatus

The horizontal tube apparatus as shown in figure (3.2) is constructed of glass, which is 1.38 m long and with internal diameter 7.6 cm.

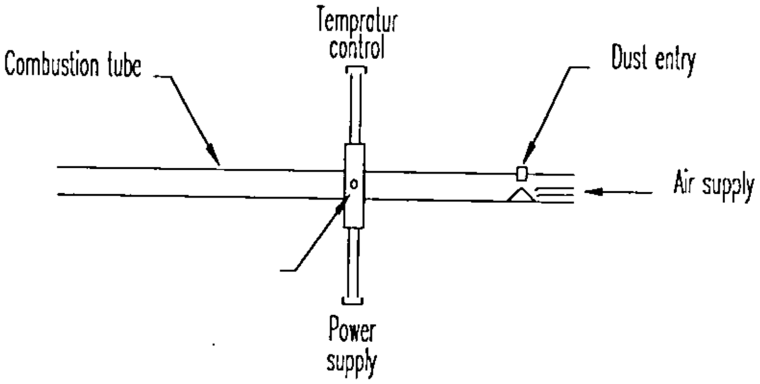


Figure 3.2 Horizontal tube apparatus

As appears in the figure, the tube is open at both ends and the dust is introduced through a hole in the upper surface of the tube 13 cm from one end, and deposited as a loose heap in the tube. The ignition coil is mounted 64 cm from the same end of the tube, and consists of a helix 18 mm long and 2.5 mm internal diameter. It is constructed from 32 SWG platinum wire, and is mounted on a ceramic former horizontally across the diameter of the tube. The dust is dispersed by a metered blast of air, applied for 2 seconds, which carries the dust down the tube past the igniter. The temperature of the coil is maintained thermostatically at 1300°C, and observations are made as to whether or not propagation of flame away from the source of ignition takes place.

The apparatus is suitable for testing all types of carbonaceous materials, particularly if easily dispersed, but is not suitable for metal dusts which could damage the coil igniter.

3) The Inflammator Apparatus:

With the Inflammator apparatus the dust fails vertically downwards on to the igniting source, as shown in figure (3.3).

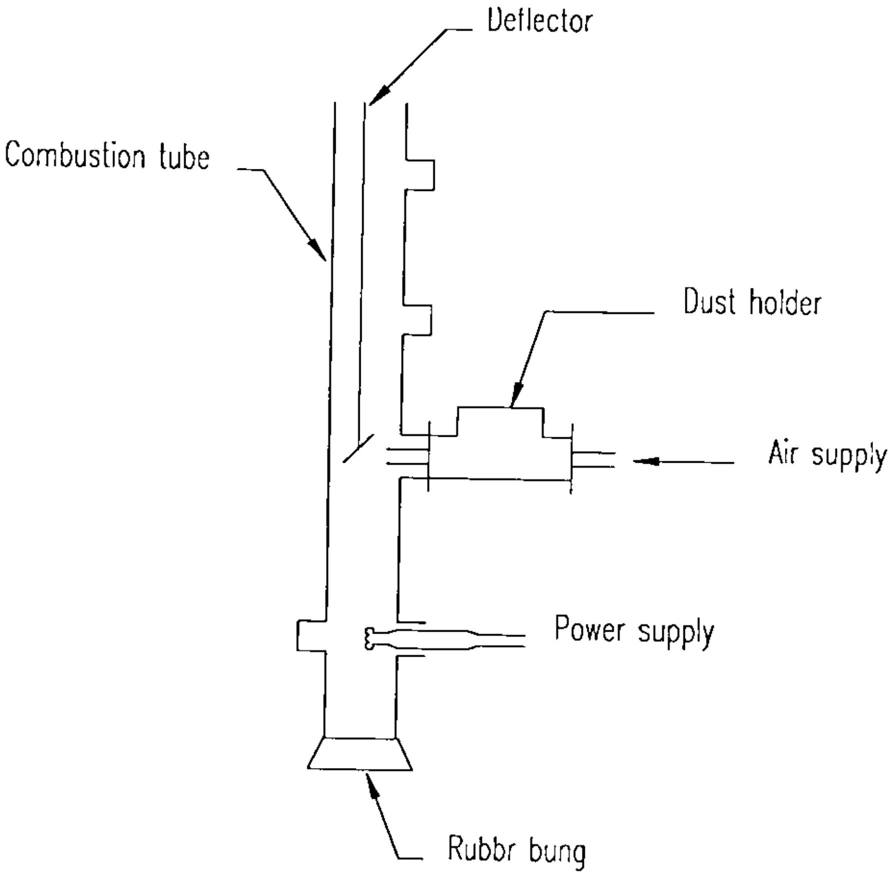


Figure 3.3 Inflammator apparatus

This apparatus consists of a vertical glass tube, of length 1.02 m and diameter 7.6 cm, it is open at the top and closed at the bottom with a rubber bung. The tube is fitted with three side arms, at 25 cm intervals, for the position of the dust holder to be varied. Two further side arms, 13 cm from the bottom of the tube, enable a spark electrode or heated wire coil igniter to be inserted. The dust holder is 15 cm in length and 1.8 cm internal diameter, and is connected to an air reservoir of 460 cm^3 capacity. The reservoir can be pressurized up to 280 kN/m^2. When the dust is dispersed from the holder by the air it strikes a deflector plate mounted on the axis of the tube and then falls under gravity past the igniter. Observations are made as to whether flames propagate away from the source of ignition.

$2C + O_2 \rightarrow 2CO$

If there is sufficient oxygen available, carbon monoxide will then be oxidized to carbon dioxide with the release of additional energy:

$2CO + O_2 \rightarrow 2CO_2$

Therefore, 2.66 kg of oxygen are required to completely burn 1 kg of carbon. This ratio is quite useful in evaluating the oxygen requirements for hydrocarbon fuels:

$$\boxed{2.66\ \text{kg}\ O_2/\text{kg}\ C}$$

Hydrogen has the highest ignition temperature (582°C) of the three combustible elements, but since it is a gas the kinetics are such that the combustion of hydrogen proceeds very rapidly. Consequently, if there is sufficient air, hydrogen will burn completely to water according to the reaction

$2H_2 + O_2 \rightarrow 2H_2O$

Thus, the mass of oxygen required to completely burn a unit mass of hydrogen is 7.94:

$$\boxed{7.94\ \text{kg}\ O_2/\text{kg}\ H_2}$$

Sulfur has an ignition temperature of 243°C , which is the lowest ignition temperature of the three combustible elements. While the oxidation of sulfur does release chemical energy in the following reaction, the combustion product , sulfur dioxide (SO2), is a major atmospheric pollutant:

$S+O_2 \rightarrow SO_2$

Thus, 0.998 kg of oxygen is required to burn 1 kg of sulfur:

$$\boxed{0.998 \text{ kg } O_2\text{/kg S}}$$

While this completes the combustion chemistry for the three elements, a brief discussion of the source of oxygen is warranted. Almost all combustion processes rely on air as the source of oxygen. Air is composed of approximately 21 percent oxygen, by volume or by mole, and the remaining 79 percent consists primarily of nitrogen with a small amount of argon, carbon dioxide, and other gases. As far as combustion calculations are concerned, it will be assumed that air consists of 21 percent oxygen and 79 percent nitrogen on a volumetric or molar basis. These values translate to 23.2 percent oxygen and 76.8 percent nitrogen on a gravimetric or mass basis. The molecular weight of air is 28.97 kg/kg mole.

4.3 THEORETICAL AIR-FUEL RATIO:

The theoretical or stoichiometric air-fuel ratio gives the minimum air requirements for complete combustion of a fuel. It may be expressed in terms of mass of air per mass of fuel, in terms of moles of air per mole of fuel or in terms of volume of air per volume of fuel. All values should normally be reported on the basis of the "as - burned " fuel analysis.

The gravimetric, theoretical air-fuel ratio of a fuel is determined from the as-burned ultimate analysis of the fuel. This ratio is evaluated by performing an oxygen mass balance on the combustible reactants, as follow:

(C mass fraction) (2.66) = _______ kg of O_2 to burn C in 1 kg fuel

(H_2 mass fraction) (7.94) = _______ kg of O_2 to burn H_2 in 1 kg fuel

(S mass fraction) (0.998) = _______ kg of O_2 to burn S in 1 kg fuel

---

Total = ______ kg of O_2 to burn the combustible elements in 1 kg of fuel

However, the fuel itself may contains a certain mass percent of oxygen (O_2), which should be subtracted from the total required amount of oxygen, thus:

$$\begin{array}{l} \text{mass of } O_2 \text{ required} \\ \text{from the air per 1 Kg} \\ \text{of fuel} \end{array} = \begin{array}{l} \text{total mass of } O_2 \text{ to} \\ \text{burn the combustible} \\ \text{elements in 1 Kg fuel} \end{array} - \begin{array}{l} \text{mass of } O_2 \text{ in the} \\ \text{fuel per 1 Kg of} \\ \text{fuel} \end{array}$$

gravimetric (mass), theoretical air-fuel ratio = $(\frac{A}{F})_{th,m}$

$$= \frac{kg\ O_2 \text{ needed from the air per kg of fuel}}{0.232} \qquad (4.1)$$

All the mass fractions in the above accounting system are from the as-burned ultimate fuel analysis. The factor of 0.232 in the denominator of Equation (4.1) is the mass fraction of oxygen in the air and the ratio obtained from (4.1) can be expressed in units of kilograms of air per kilogram of fuel. This rather complex calculational procedure for determining the theoretical air-fuel ratio can be condensed into one simple equation , as follows [12]:

$$(\frac{A}{F})_{th,m} = \frac{2.66C + 7.94H_2 + 0.998S - O_2}{0.232} \qquad (4.2)$$

4.4 THEORETICAL AIR-FUEL RATIO FOR OIL-SHALE

The ultimate analysis of oil-shale samples as reported by the Natural Resources Authority is given in the following table:

content	Wt.%
Moisture Content	1.44
Ash	54.68
CO2 (mineral)	20.88
Total sulfur	3.12
C	15.83
H	1.64
N	0.38
O	1.87

Table (4.1): ultimate analysis of oil-shale

Based on the above analysis and using equation (4.2) it may be obtained:

$$(\frac{A}{F})_{th,m} = \frac{2.66 \times 0.1583 + 7.94 \times 0.0164 + 0.998 \times 0.0312 - 0.0187}{0.232} = 2.429878 \text{ g air / g fuel}$$

$$\rightarrow \frac{F}{A} = \frac{1}{(A/F)} = \frac{1}{2.429878} = 0.41154\ g\ fuel\ /\ g\ air$$

And for air density 1.2 g/L

$$(F/A)_{th,m} = 0.41154\ \frac{\text{g fuel}}{\text{g air}} \times 1.2\frac{g\ \text{air}}{\text{L air}}$$
$$= 0.49385\ \text{g fuel / L air}$$

CHAPTER 5

EXPERIMENTAL SETUP AND PROCEDURE

This chapter describes in detail the experimental setup and the apparatus used to perform the experimental investigation. Also, the procedure that was followed throughout the experiment will be outlined.

5.1 EXPERIMENTAL EQUIPMENTS:

In the present work, two different equipments will be used, both of which are designed and constructed for such work. These equipments are:

5.1.1 The Godbert-Greenwald furnace apparatus:

It is used to measure the minimum ignition temperature. The general layout of the Godbert-Greenwald Furnace apparatus is shown diagrammatically in figure (5.1). A photograph of the apparatus is shown in figure (5.2).

The furnace apparatus consists of a silica furnace tube 21.6 cm long and 3.75 cm inside diameter. The furnace tube is heated externally by an electric winding of 20 SWG, 80/20 nickel/chrome wire with a resistance of 1.3 ohm. A thin layer of heat resisting cement (Alsrax) was used to cover the electric winding. The furnace tube is mounted vertically in a mild steel case lined with asbestos wood and filled up with bulkwool (Triton Kaowool) to act as a thermal insulation. The top of the furnace tube

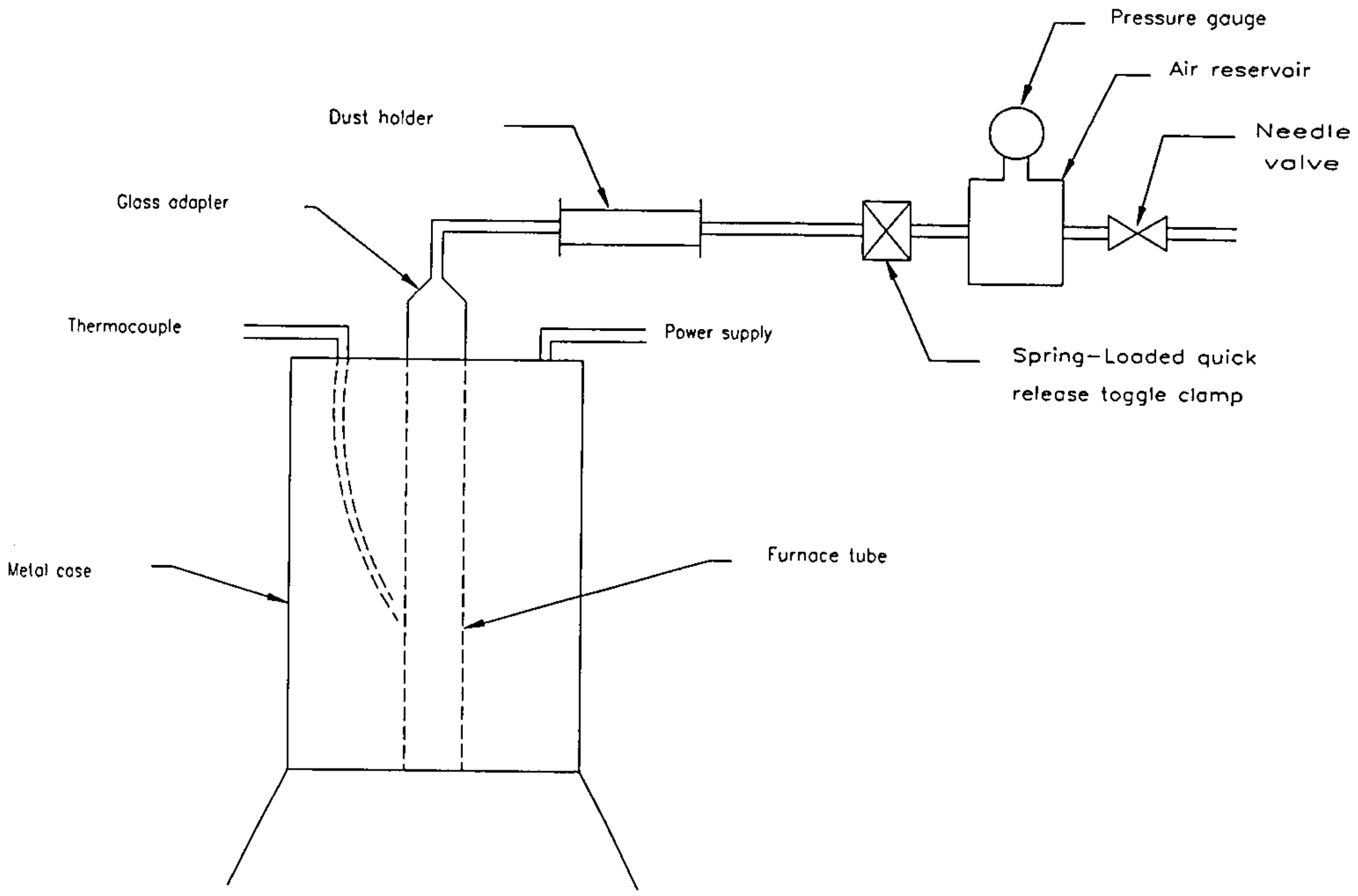


Figure 5.1 Furnace apparatus

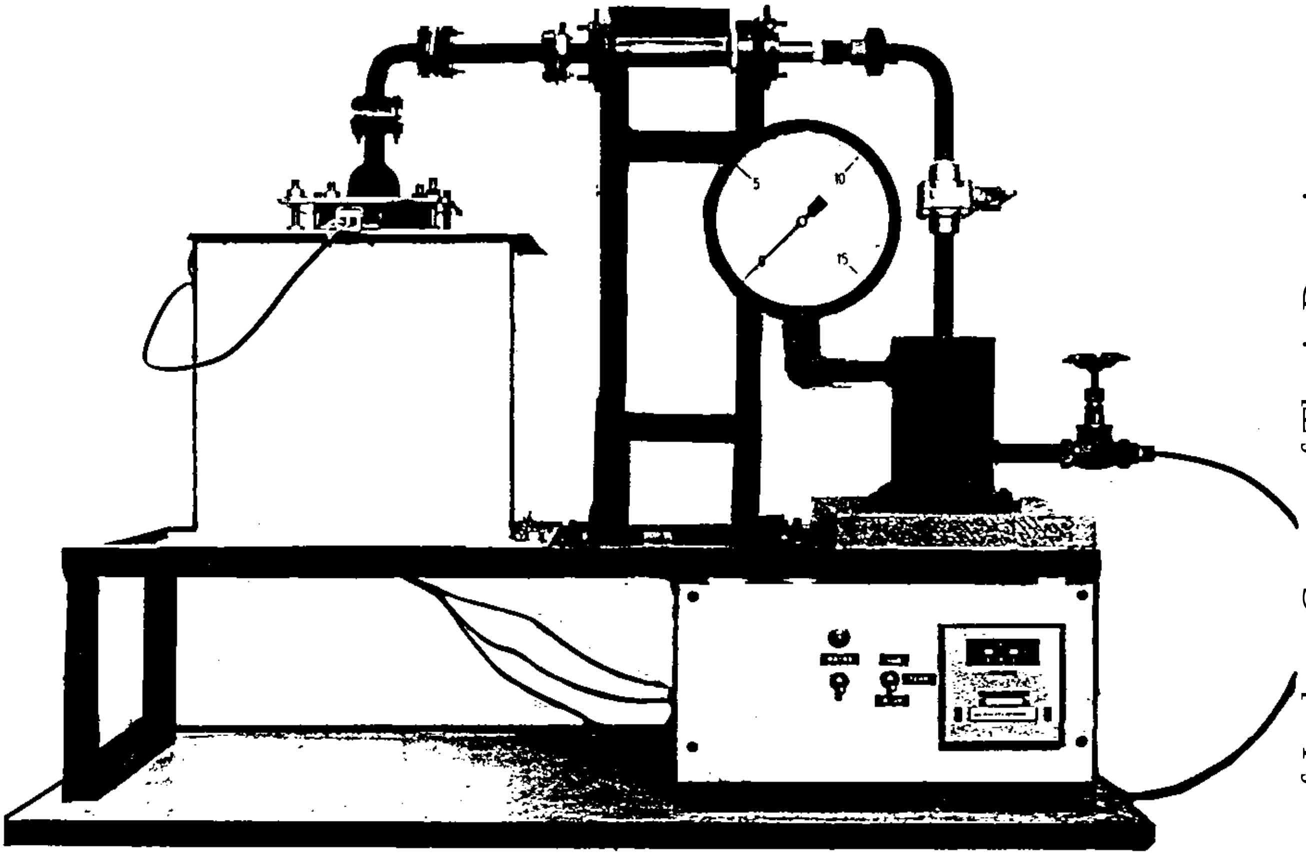


Figure (5.2): A photograph of the furnace apparatus[5]

is fitted to a Pyrex glass adapter with a right-angle bend, which in turn is connected to the dust holder. The dust holder is 10.2 cm long and contains a stainless steel barrel of 0.95 cm inside diameter. The dust holder is connected to the air reservoir of 460 cm^3 capacity with a gauge pressure ranges from 42 to 91 kN/m^2. The dispersing air is controlled by a spring-loaded quick release valve. The bottom end of the furnace tube is open to the atmosphere. Furnace temperature up to 1000°C are maintained by a temperature controller (Eurotherm) which is actuated by a chromel/alumel thermocouple of 19 SWG cemented into the wall of the furnace tube at its midpoint.

5.1.2 The Small Vertical Tube Apparatus:

It is used to measure the minimum explosible concentration. The general layout of the small vertical tube apparatus version are shown diagrammatically in figure (5.3). A photograph of the apparatus is shown in figure (5.4).

The combustion tube is made of perspex, it is a 30.5 cm long and 6.4 cm inside diameter and is fitted over a brass dispersion cup 6.4 cm in diameter and 1.6 cm deep in the center. To ensure perfect dispersion, a mushroom shaped deflector is fixed in the middle of the dispersion cup. The dispersing gas mixture is released from a reservoir of 460 cm^3 capacity at a gauge pressure of 280-350 kN/m^2. The gas flow into the combustion tube is controlled by a full port solenoid valve to ensure a momentary (single) blast (since all the work with this apparatus was carried out with single blasts). The gas reservoir is connected to the gas supply via a needle valve. The ignition source is a pair of brass electrodes mounted at a distance of 8.4 cm above the mushroom deflector, the spark gap can be varied between 0.64 cm and 1.5 cm. The continuous electric spark is obtained from an induction coil circuit with an energy of two joules.

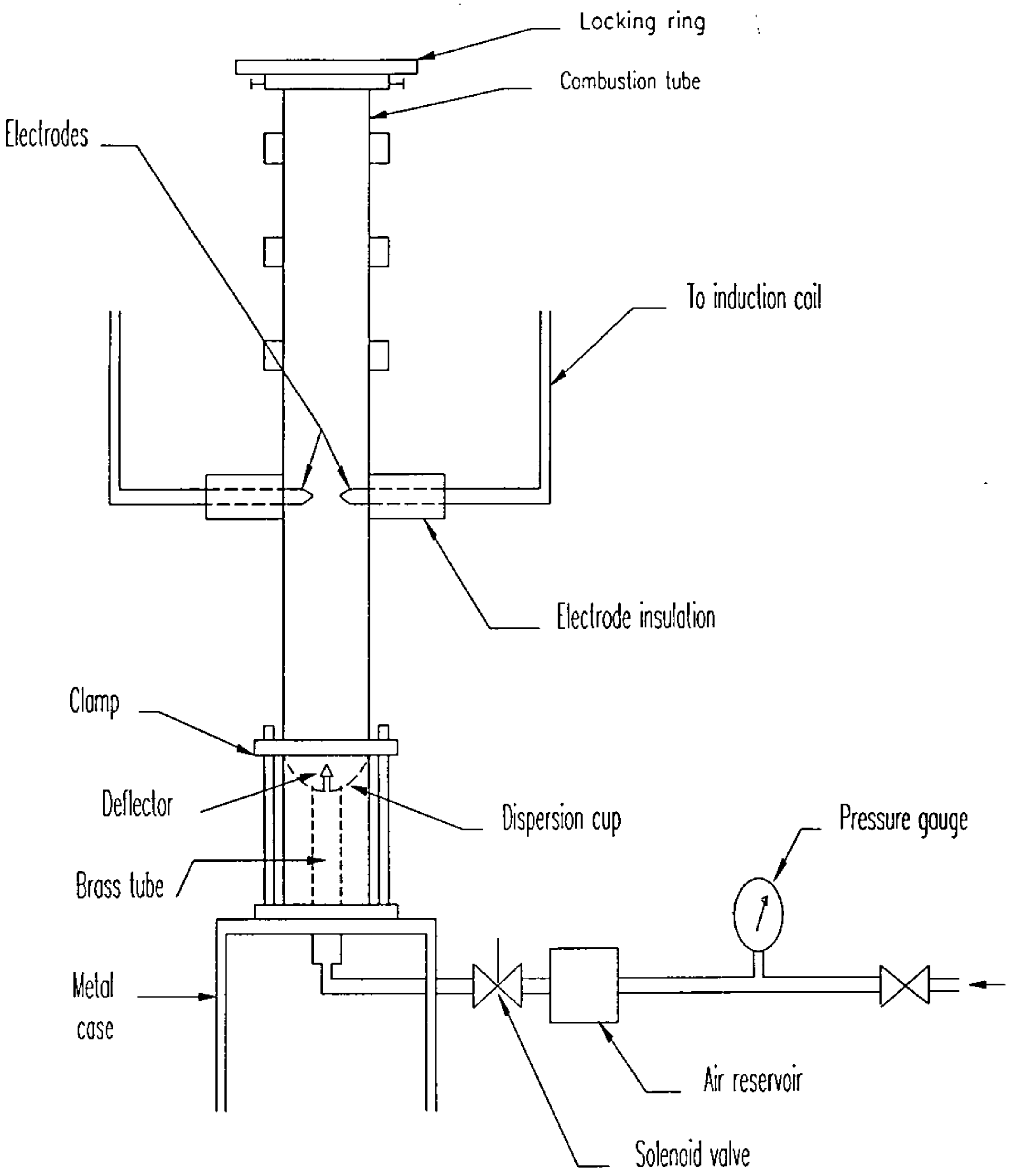


Figure 5.3 Small vertical tube apparatus

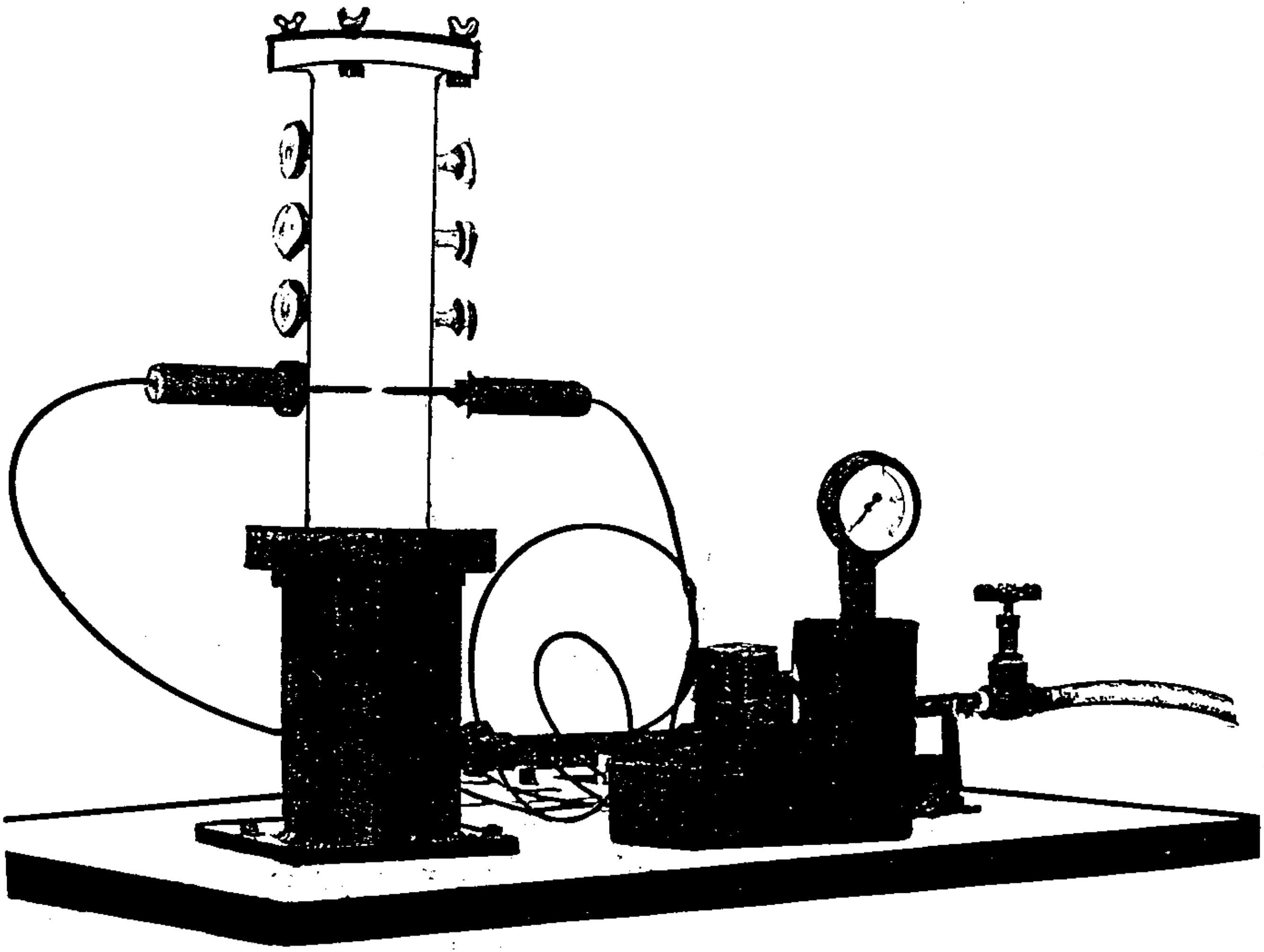


Figure (5.4): A photograph of the small vertical tube apparatus[5]

5.2 EXPERIMENTAL PROCEDURE.

The experimental procedure mainly involves measuring the two main parameters of oil shale dust explosion namely; the minimum ignition temperature and the minimum explosible concentration using the previously mentioned equipments. These parameters will be measured at different conditions.

5.2.1 Preparation of the dust samples :

The dust used is a Jordanian oil-shale from El-Lajjun deposit, which was supplied by the National Resources Authority.

Dust samples of different particle sizes were prepared by the method of sieving. This method is still the only reliable method of producing samples of different particle dimensions.

First of all, the material should be ground by a grinding machine, then, the powder was sieved, and the particle size was determined within two mesh sizes.

In this study, five particle sizes were used; the first with a particle size up to 63μm which referred to as very fine, the second with a particle size ranges between 63μm and 75μm which referred to as fine, the third with a particle size ranges between 90μm and 125μm, the fourth with a particle size ranges between 125μm and 180μm and the fifth with a particle size particle size ranges between 180μm and 250μm which referred to as coarse. Also mixtures of different weight percentage of coarse to fine particles were made.

In addition, samples of the inert additives (Stone, clay and Calcium carbonate) of fine particle size which ranges between 63μm and 75μm were prepared, and added with different weight percentages to the oil-shale samples.

5.2.2 Minimum Ignition Temperature:

The minimum ignition temperature of a dust cloud was measured using the Godbert-Greenwald Furnace apparatus, shown in figure (5.1), by using air as the dispersing gas. The following steps were followed for each sample:-

1- The furnace tube was heated and fixed at a desired temperature.

2- A known quantity of the dust was placed in the dust holder.

3- The air reservoir was charged up to the desired dispersion pressure (70 kN/m^2) and throughout all experiments the pressure was fixed at this value.

4- The dust was dispersed through the Furnace tube by an air blast.

The occurrence of an explosion was indicated by direct observation of a flame at the bottom open mouth of the furnace. If ignition occurs, the furnace temperature was lowered by 10°C, and the same procedure was carried out until a temperature set is reached at which no ignition occurs. The lowest Furnace temperature at which ignition occurred was taken as the minimum ignition temperature.

The quantity of the dust was varied between 0.3 - 1 g/L, and the furnace tube was cleaned after each test by blowing air through it.

5.2.3 Minimum Explosible concentration (lean limit):

The minimum explosible concentration is measured in the small vertical tube apparatus shown in figure (5.4), using a continuous electric spark as the source of ignition.

The following steps were followed out during each test:-

1- A filter paper diaphragm with a small hole in the center (0.5 cm in diameter) was attached across the top of the combustion tube by a locking ring, to impede, somewhat, the dispersion of the powder outside the combustion tube.

2- The air-reservoir was charged up to the desired dispersion pressure, which was set to be 315 kN/m^2 for all tests.

3- A known quantity of the dust was placed in the dispersion cup. This weight was divided by the volume of the combustion tube (1000 cm^3) give the concentration of the dust, assuming that uniform dispersion took place.

4- After placing the combustion tube over the dispersion cup, the ignition source was energized.

5- The full port solenoid valve was opened, and the dust was dispersed by a single blast of the air.

The criterion for the occurrence of an explosion was indicated by the propagation of flame away from the source of ignition; propagation is usually accompanied by bursting of the diaphragm. When explosion occurs the amount of dust is reduced and testing continued until no explosion is observed in at least ten tests at the same dust concentration. The mass of the minimum quantity of dust with which explosion occurs, divided by the total volume of the tube is taken as the minimum explosible concentration in air.

The tests were carried out at various dust concentrations within the range 0.1-10 g/L. The combustion tube was cleaned after each experiment, and the electrodes were frequently taken out to clean off any combustion products.

5.3 EXPERIMENTAL MATRIX:

The minimum ignition temperature was measured for samples of the following :

1) Very fine oil-shale particles of $d < 63 \mu m$
2) Fine oil-shale particles of $63 \mu m < d < 75 \mu m$
3) Coarse oil-shale particles of $180 \mu m < d < 250 \mu m$
4) Mixtures of coarse and fine particles, with different percentages of coarse to fine particles.

The minimum explosible concentration was measured for samples of the following

1) Very fine oil-shale particles of $d < 63\mu m$

2) Fine oil-shale particles of $63\mu m < d < 75\mu m$

3) Oil-shale particles of $90\mu m < d < 125\mu m$

4) Oil-shale particles of $125\mu m < d < 180\mu m$

5) Coarse oil-shale particles of $180\mu m < d < 250\mu m$

6) Mixtures of coarse and fine particles, with different percentages of coarse to fine particles.

In addition, an attempt was made to measure the maximum explosible concentration (rich limit) for the particle sizes mentioned above.

Having measured the minimum ignition temperature and the minimum explosible concentration for each sample. The effect of additives (clay, stone and calcium carbonate) on these two parameters was tested by adding known quantity of each one of these additives to the samples of fine particle sizes, and the same procedure was followed to find the new minimum ignition temperature and minimum explosible concentration.

6.2.1 Effect of concentration on minimum ignition temperature:

The variation of the minimum ignition temperature with dust concentration of oil shale is shown in figures (6.1-6.2), and in figures (6.5) through (6.11).

Each point on these curves, represents the lowest temperature at which ignition occurs for the corresponding concentration.

The range of concentrations under consideration was from 0.3 g/L to 1 g/L. The selection of this range of concentrations was based on the following:

1- It is well know that a very small quantity of solid fuel will be dispersed in air to form the dust cloud, so the expected concentrations of solid fuel are small.

2- The theoretical air-fuel ratio (stoichiometric) was calculated in chapter four to be 0.49385 g/L (≈0.5) , and since it is known from the theory of combustion that the ignition of a fuel is most probable and rapid at or around stoichiometric. Then, it is reasonable to study a range of concentrations around that of stoichiometric one.

Figures (6.1-6.2) and (6.5) through (6.11) show that the minimum ignition temperature, for all conditions, has a general behavior which decreases with increasing concentration in the range from 0.3 g/L to 1 g/L. The reason for this behavior is that an increase in concentration means an increase in the amount of solid fuel, which makes the ignition easier, and consequently lower temperatures are needed to ignite the mixture. This behavior was also predicted by Cassel and Liebman [4] in the literature.

One important point that should be taken into account, is that increasing the amount of fuel beyond a certain point, ignition difficulty will start to increase, and consequently the ignition temperature begins to increase. This behavior is due to the decrease of the oxidant (air) in the mixture. In this work, high concentrations will not be examined, because dust explosion concerns mainly with small concentrations. Further, the experimental facilities were not adequate enough to study the ignition possibility for concentrations of fuel above 10g/L.

It should be noted that each curve in the above mentioned figures represents a boundary, below which ignition is not possible, while above it ignition is possible as shown below:

6.2.2 Effect of particle size on minimum ignition temperature:

In reality , dusts exist in different particle sizes. Thus, it is important to know the effect of variable particle sizes on the minimum ignition temperature of oil shale dust.

Figure (6.1) shows the variation of the minimum ignition temperature with dust concentration of oil shale solid particles for three different particle sizes, namely; the very fine particles with diameter below 63μm, the fine particles with diameter ranges in between 63μm and 75μm, and the coarse ones with diameter between 180μm and 250μm.

It is clear from this figure that the fine particles have the lowest ignition temperatures, while the coarse particles have the highest ones. This is due to the fact that a reduction in the size of the particle means an increase in the surface area per unit weight exposed to the oxidant (air), and consequently ignition will be easier. In addition, the finer the dust the more uniform mixing will be with the oxidant which will also enhance the above result.

When using coarse particles instead of fine particles, the percent increase in the minimum ignition temperatures is shown in the following table:

Concentration (g/L)	Percent increase in min. ignition temp. (%)
0.3	30.645
0.5	33.898
0.7	34.483
1	29.825

Table (6.1): percent increase in minimum ignition temperature when coarse particles are used.

From the above table, it is clear that the percent increase in minimum ignition temperature, when coarse particles were used, ranges from 30% to 35% of that when fine particles were used.

However, decreasing the particle size more and more, ignition will not continue to occur easier, and if the particle size decreases below a certain limit the ignition will become more and more difficult to occur. This behavior is clear for the very fine dust as shown in figure (6.1), and although the particle size is smaller than the fine dust, it has higher ignition temperatures. The reason is that, when the particle size is reduced below the fine size, the dust becomes more cohesive and dispersion in air more difficult. This may cause the dust not to disperse as individual particles, but to agglomerate together and behave as if they were effectively of greater particle size.

From Figure (6.1), the minimum ignition temperatures for fine dust of oil shale was found to be between 570°C and 620°C for the range of concentrations measured. The minimum ignition temperature, whatever the concentration used, was found to be 570°C. This value of temperature should not be exceeded, in any way, to ensure no ignition and no explosion in a wide range of concentrations. In practical purposes, is recommended to take a lower value to account for the errors that may occur.

6.2.3 Effect of mixtures of coarse and fine particles on the minimum ignition temperature of oil shale dust:

In practical problems, in industry or mining, dusts are not usually of uniform particle sizes, on the other hand, it may contain both fine and coarse particles in a certain distribution.

Figure (6.2) shows the variation of the minimum ignition temperature with concentration for mixtures of coarse and fine particles, the percent indicated for each curve referred to the percent of coarse particles in the mixture, and the figure shows that as the percent of coarse particles increases the minimum ignition temperature will increase for the same reason mentioned in section (6.2.2).

The average percent increase in minimum ignition temperature for different percents of coarse particles is shown in the following table:

Percent of coarse particles (%)	Average percent increase in min. ignition temp. (%)
30	3.429
70	10.499
100	32.213

Table (6.2): Average percent increase in minimum ignition temperature for different percents of coarse particles.

From this table, it is clear that the effect of coarse particles becomes more dominant for a coarse particles percentage in the mixture higher than 70%.

Figure (6.3) gives the same results, it shows that the minimum ignition temperature increases slightly as the percentage of coarse particles increases up to 70%, with a further increase in the coarse particles beyond 70%, the minimum ignition temperature increases rapidly and sharply. The later behavior was not clear at very low concentrations as 0.3 g/L at which the relation seems to be linear.

6.2.4 Effect of inert additives on minimum ignition temperature of oil shale dust:

The effect of inert additives on the ignition of fine particles of oil shale was only examined because it was found that such dust is the most easy to ignite and to explode.

Figures (6.5) through (6.7) show the variation of minimum ignition temperature with mixture concentration for different added percents of three additives, namely; calcium carbonate, stone and clay respectively.

It is obvious from the general behavior of the above mentioned figures, that the addition of inert additives tends to increase the minimum ignition temperature of oil shale dust. This may be attributed to two facts; the first is that inert additives will behave as a thermal sink that will absorb the heat generated and vaporize. The second is that these additives act as a catalysts during the recombination reactions between radicals (very active intermediate molecules appear in the reaction zone) [13]. Ones these reactions are completed, the overall reaction will decrease. In addition, The inhibition effect was clearly dependent on the type of the additive and on the concentration by which it was added.

The average percent increase in minimum ignition temperature for different percents (20%, 30%, 50% and 70%) of calcium carbonate, stone, and clay different was calculated from tables (A.6), (A.7) and (A.8) respectively, and the results are presented in the following table:

Percent additive(%)	Avg. percent increase in min. ignition temp (%)		
	calcium carbonate	stone	clay
10	0	0	0
20	1.23	0	0
30	11.833	1.23	0
50	20.218	5.854	3.358
70	25.696	13.863	11.339

Table (6.3): Average percent increase in minimum ignition temperature for different percents and different additives.

From the above table, it may be seen that the effect of calcium carbonate as an inhibitor on ignition starts to take an effect with a concentration of 20%, while that of stone and clay were 30% and 50% respectively. Also, the above table shows that calcium carbonate has the highest inhibition, followed by stone and clay has the least effect.

Figures (6.8) through (6.11) show the inhibition effect of the three additives, once each one is added with same concentration to the samples to be tested.

In the figures (6.8) through (6.11), calcium carbonate showed a high effect on the minimum ignition temperature compared to stone and clay ; the highest minimum ignition temperature was for calcium carbonate-oil shale mixtures, followed by stone-oil shale mixtures, then clay-oil shale mixtures, and the lowest ignition temperatures was for oil shale without any additives.

Figures (6.12) through (6.15) show the variation of the minimum ignition temperature with the amount of additives used for a certain dust cloud concentration. The general behavior of these figures is that increasing the amount of each additive leads to an increase in the minimum ignition temperature of the dust cloud. However, the rate of this increase differs from one additive to another. The highest increase was for calcium carbonate and lowest was for clay. Also it can be noted from these figures that the inhibition effect starts to be more effective when 20% of each additive is used.

6.3 EXPLOSIBILITY LIMITS:

Two explosibility limits exist, namely; the minimum explosible concentration which is called the lean limit, and the maximum explosible concentration which is called the rich limit.

This work, concentrates on the lean limit, with no investigation was carried concerning the rich limit, this is due to the fact that dust explosions involve small quantities of dust dispersed in air, i.e. on the lean limit side.

6.3.1 Effect of particle size on minimum explosible concentration of oil shale dust:

The minimum explosible concentration was measured for different particle sizes , the results are presented in table (A.3), and in figure (6.4). It may be calculated from table (A.3) that when using coarse particles instead of fine particles an increase of more than 645% will be observed in the minimum explosible concentration.

Figure (6.4) shows that the minimum explosible concentration varies very slightly up to 100μm, further increase in the particle size will cause a rapid increase in the minimum explosible concentration. This behavior is due to the decrease in the surface area of oil shale particles in contact with the oxidant (air) as the particles become larger, so ignition is expected to become more difficult, and consequently the minimum explosible concentration will increase to compensate for the loss in surface area exposed to the oxidant.

Figure (6.17) shows the variation of the minimum explosible concentration with the amount of coarse particles in the mixture. It is clear from the figure that the minimum explosible concentration increases with increasing the amount of coarse particles due to the same reason mentioned previously. This increase is small up to 50% of coarse particles in the dust cloud, but beyond this amount of coarse particles in the mixture, the increase becomes rapid and sharp.

The minimum explosible concentration for oil shale dust will be taken as that of the fine particles, because it has the lowest value necessary for ignition and consequently the most probable to explode. thus , then as shown in figure (6.4) the minimum explosible concentration of oil shale dust will be taken as 1.55 g/L,

6.3.2 Effect of inert additives on the minimum explosible concentration:

The effect of adding various amounts of the three inhibitors to the dust clouds on the minimum explosible concentration is shown in figure (6.16). Three different percentages of each inhibitor were added, namely; 5 %, 10 % and 15 %

The general behavior of figure (6.16), is that as the amount of additive increases the minimum explosible concentration will increase, This is due to the same reasons mentioned in explaining the effect of inert additives on minimum ignition temperature (section 6.2.4).

The percentage increase in minimum explosible concentration with the amount of additive is shown in the following table:

percent additive(%)	Percent increase in min. explosible conc. (%)		
	calcium carbonate	stone	clay
5	190.323	93.548	61.29
10	480.645	287.097	222.581
15	>545.163	480.645	416.129

Table (6.4): percent increase in minimum explosible concentration for different percents and different additives.

From this table, it is obvious that calcium carbonate has the highest inhibition effect on the dust cloud for a given minimum explosible concentration, followed by stone, and finally clay has the lowest effect. This result may be noticed also from figure (6.16).

It is important to be noted that effect of adding inert additives on the minimum explosible concentration is more pronounced than that on the minimum ignition temperature, where this effect becomes pronounced when the amount of additives exceeds 70%.

6.4 COMPARISON OF OIL SHALE DUST TO COAL DUST:

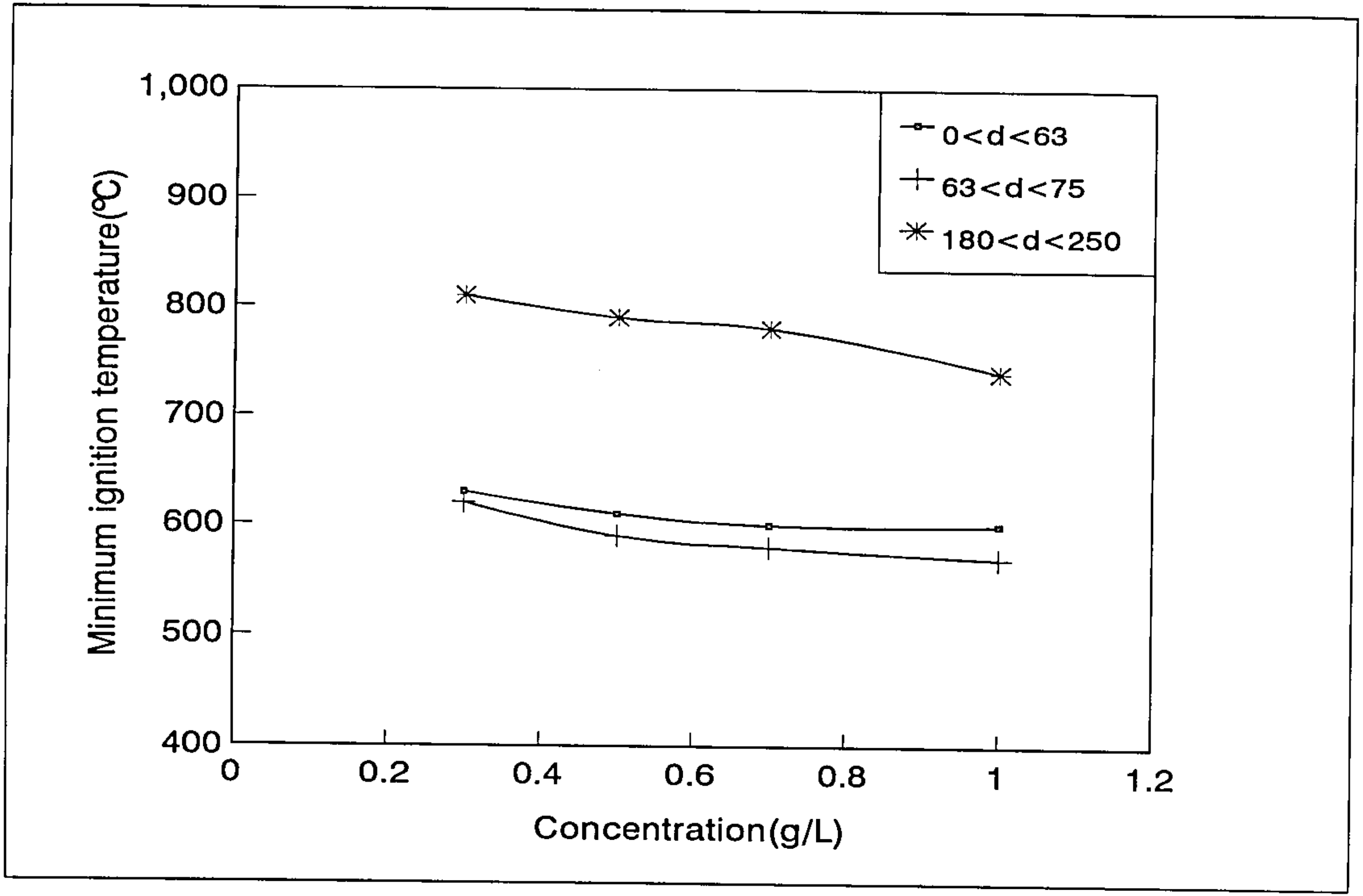
Coal is well known for the problem of dust explosions, which were and still occurring in different coal mines all over the world.

For better understanding and estimation of the hazards that will be in oil shale mines, it is of value to compare oil shale dust to another well known one as coal.

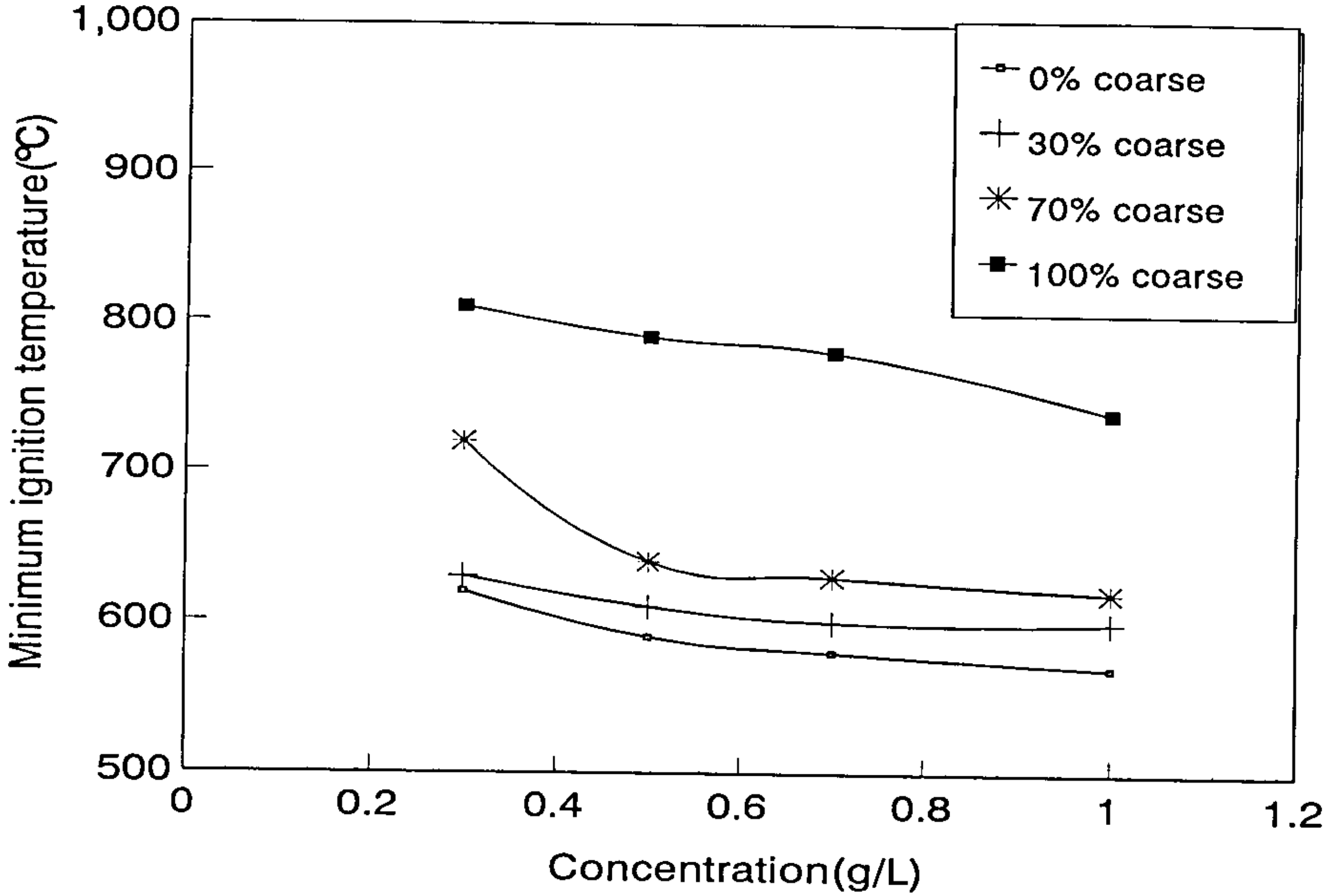
In literature, many studies were done on coal dust [10] to define the minimum ignition temperature and the minimum explosible concentration of it, these two parameters were dependent on the type of coal used and on its composition, but in general, the minimum ignition temperature of coal was found to be in a range between 485°C and 730°C, while the minimum explosible concentration was given between 0.055 g/L and 0,12 g/L.

Comparing these values to what has been found for oil shale dust in the present work, to have a minimum ignition temperature of 570 °C and a minimum explosible concentration of 1.55 g/L. So, the minimum ignition temperature of oil shale dust approaches, in average, that of coal, while the minimum explosible concentration is much higher than that of coal.

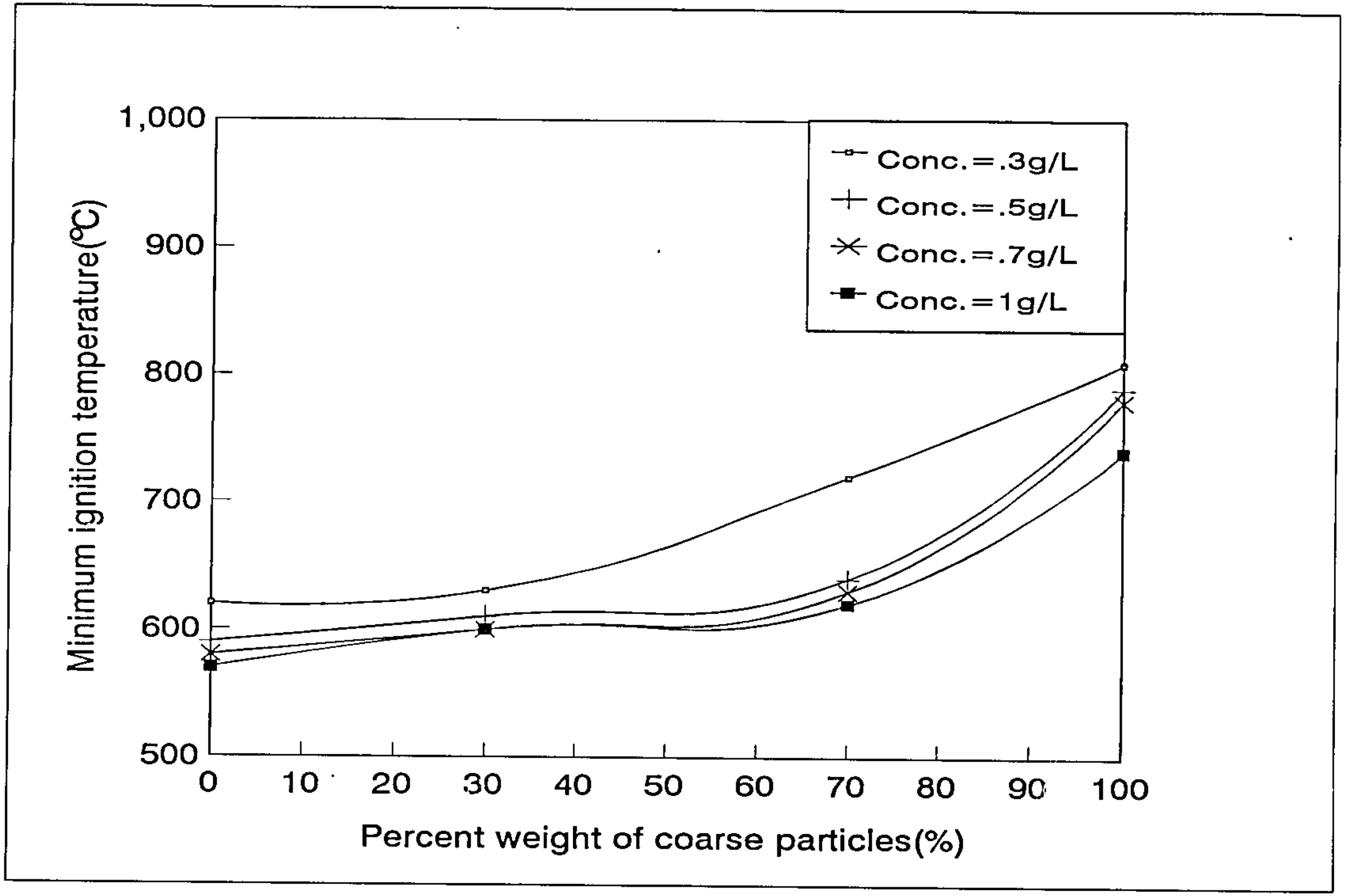
And since the hazard of an explosion to occur depends on the above two parameters together, it may be concluded that oil shale dust has less hazard or possibility of explosion than coal, due to the very high minimum explosible concentration that it has. This may be referred to the high percent of ash that oil shale contains.



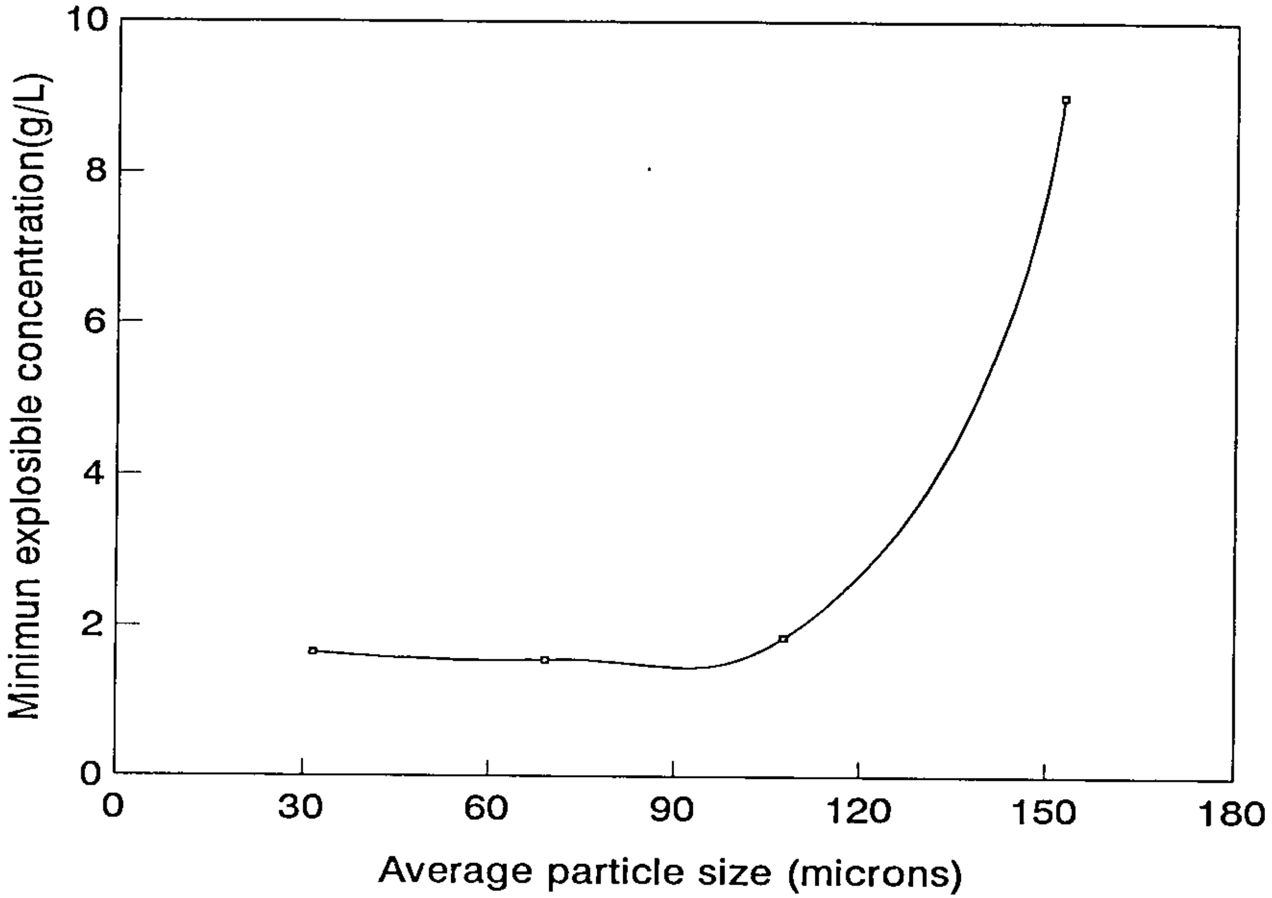
Figure(6.1):variation of minimum ignition temperature with dust concentration of oil shale for different particle sizes



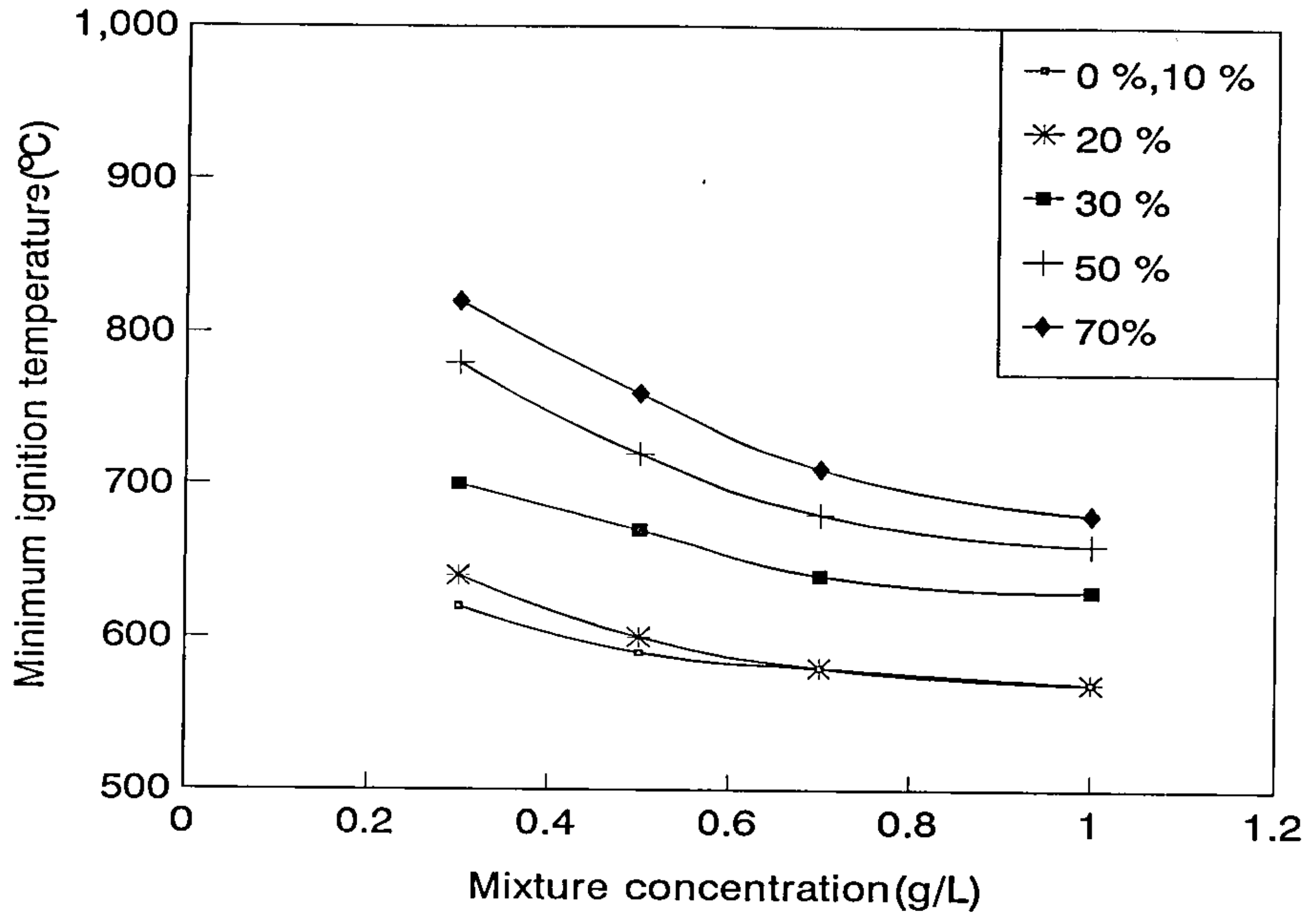
Figure(6.2): variation of minimum ignition temperature with dust concentration of oil shale for defferent weight percents of coarse particle in the mixture.



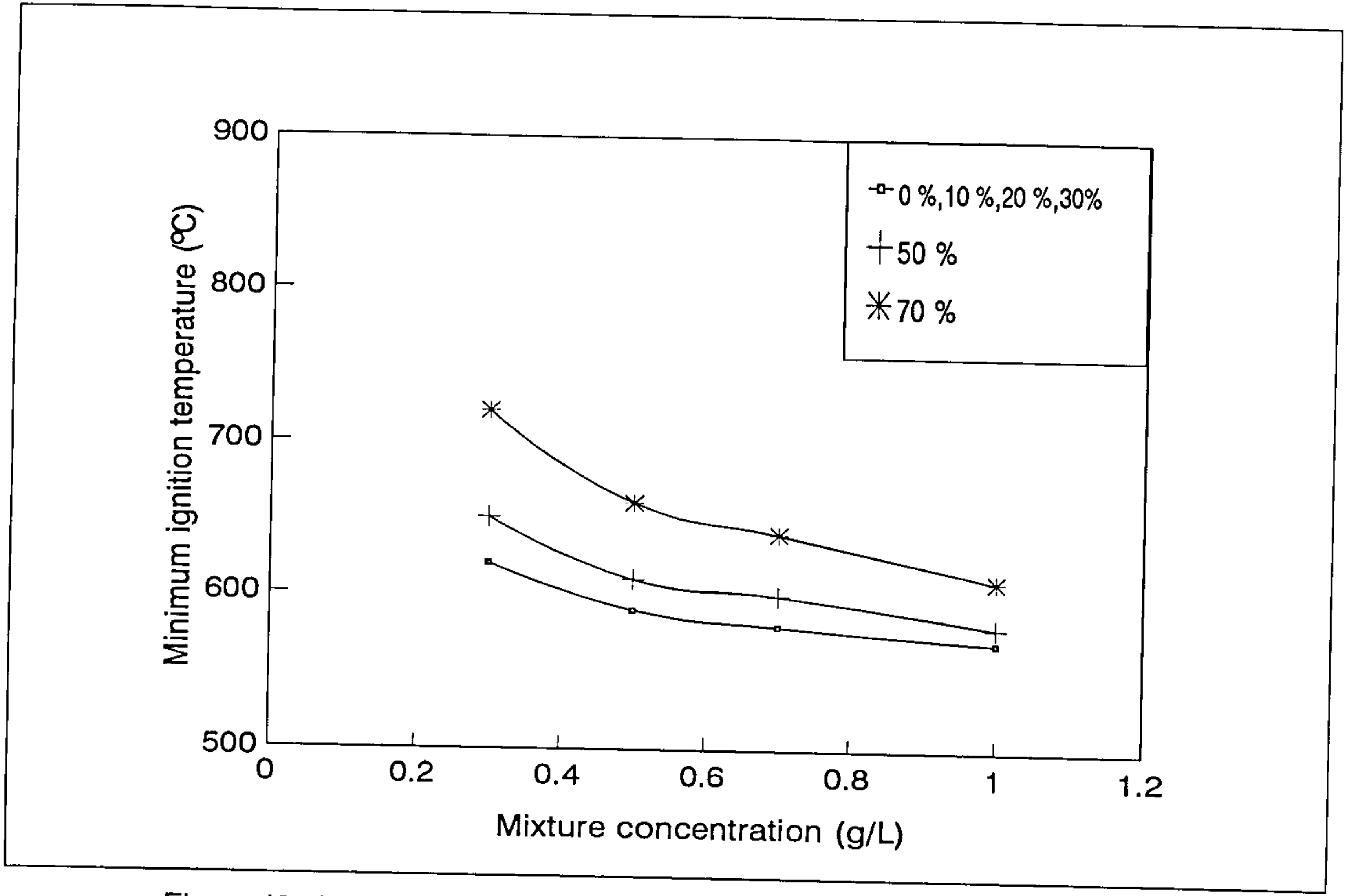
Figure(6.3):variation of minimum ignition temperature with percent weight of coarse dust in the mixture for different concentrations of the mixture



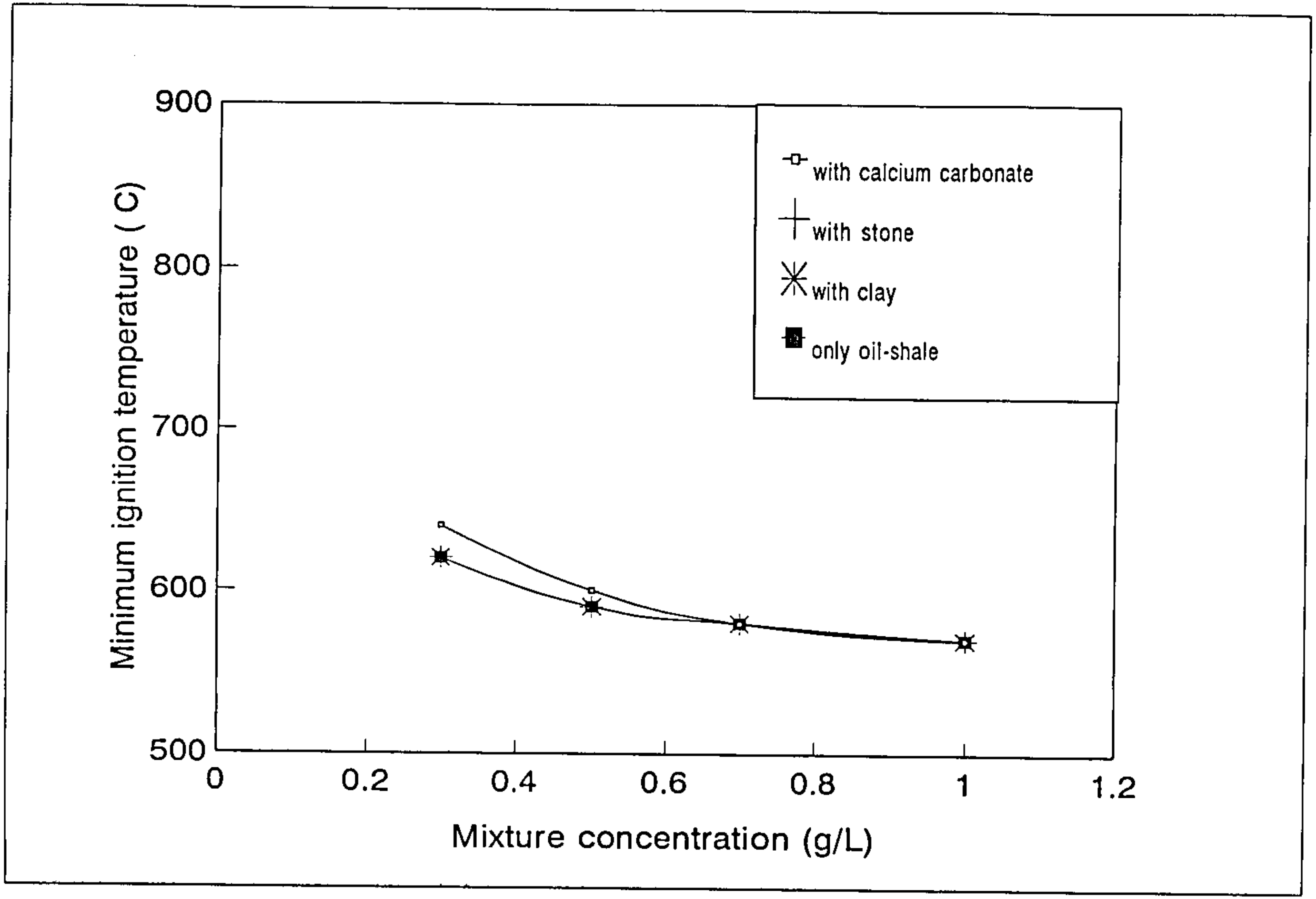
Figure(6.4):variation of minimum explosible concentration with particle size of oil shale dust



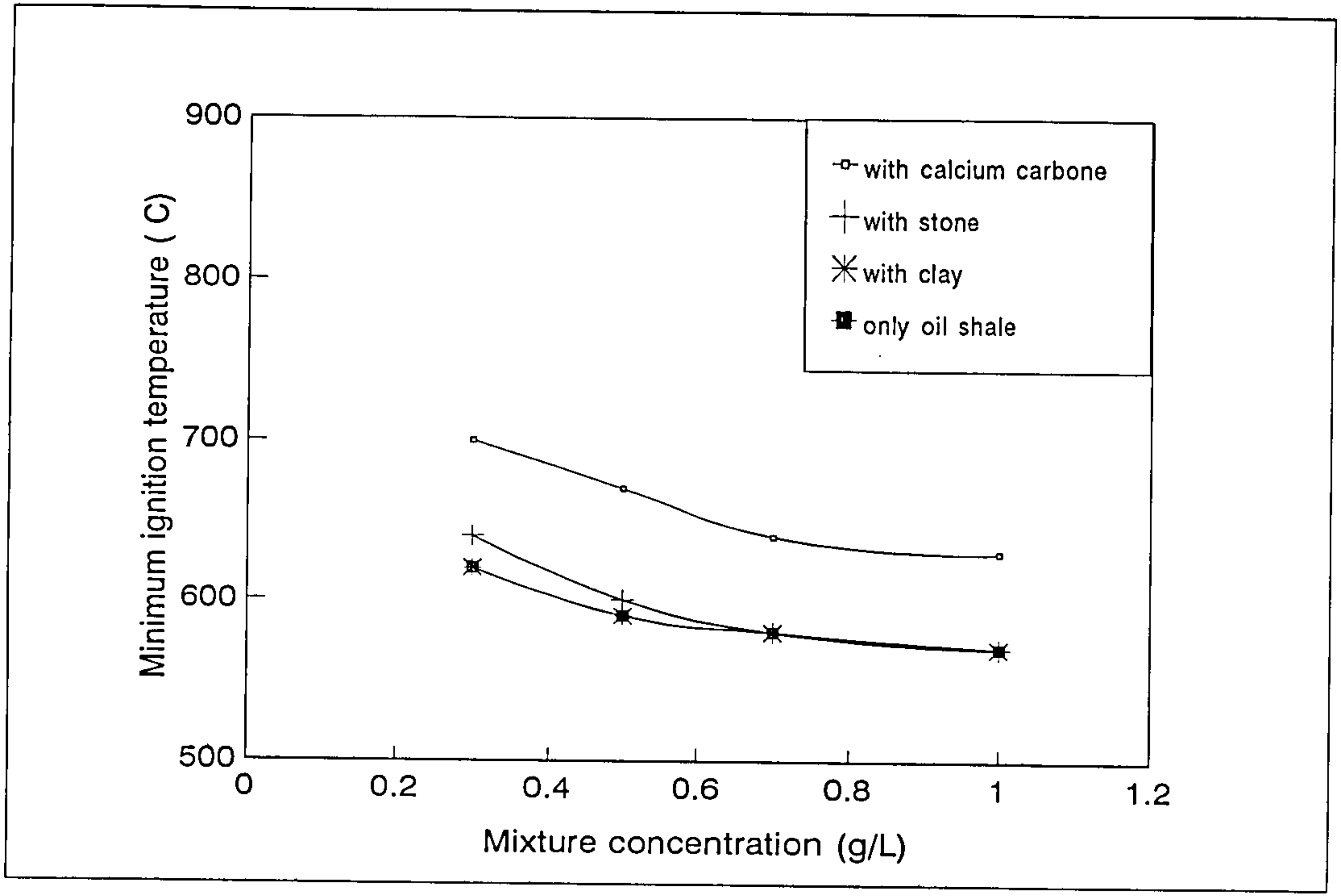
Figure(6.5): variation of minimum ignition temperature with mixture concentration for different percents of calcium carbonate.



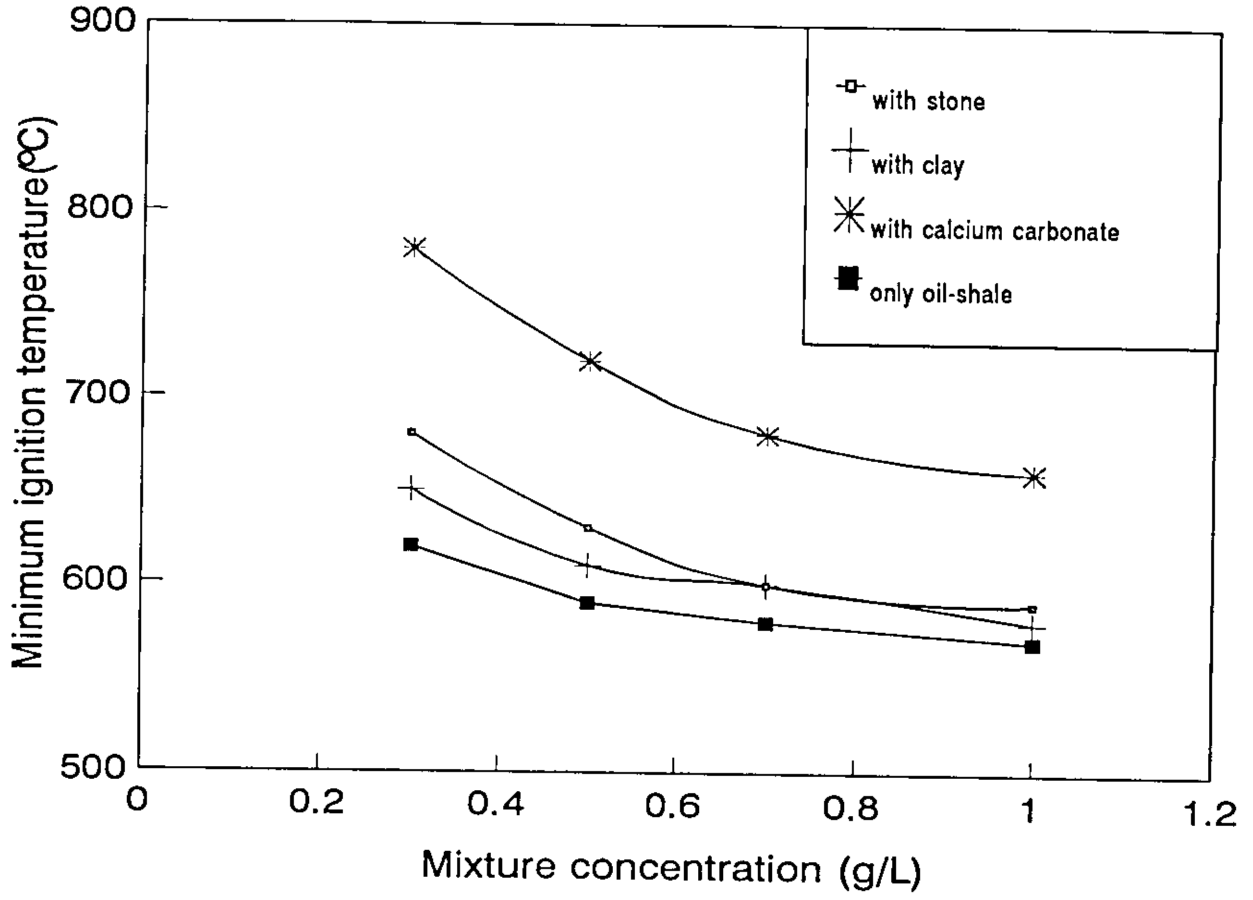
Figure(6.7): variation of minimum ignition temperature with mixture concentration for different weight percents of clay.



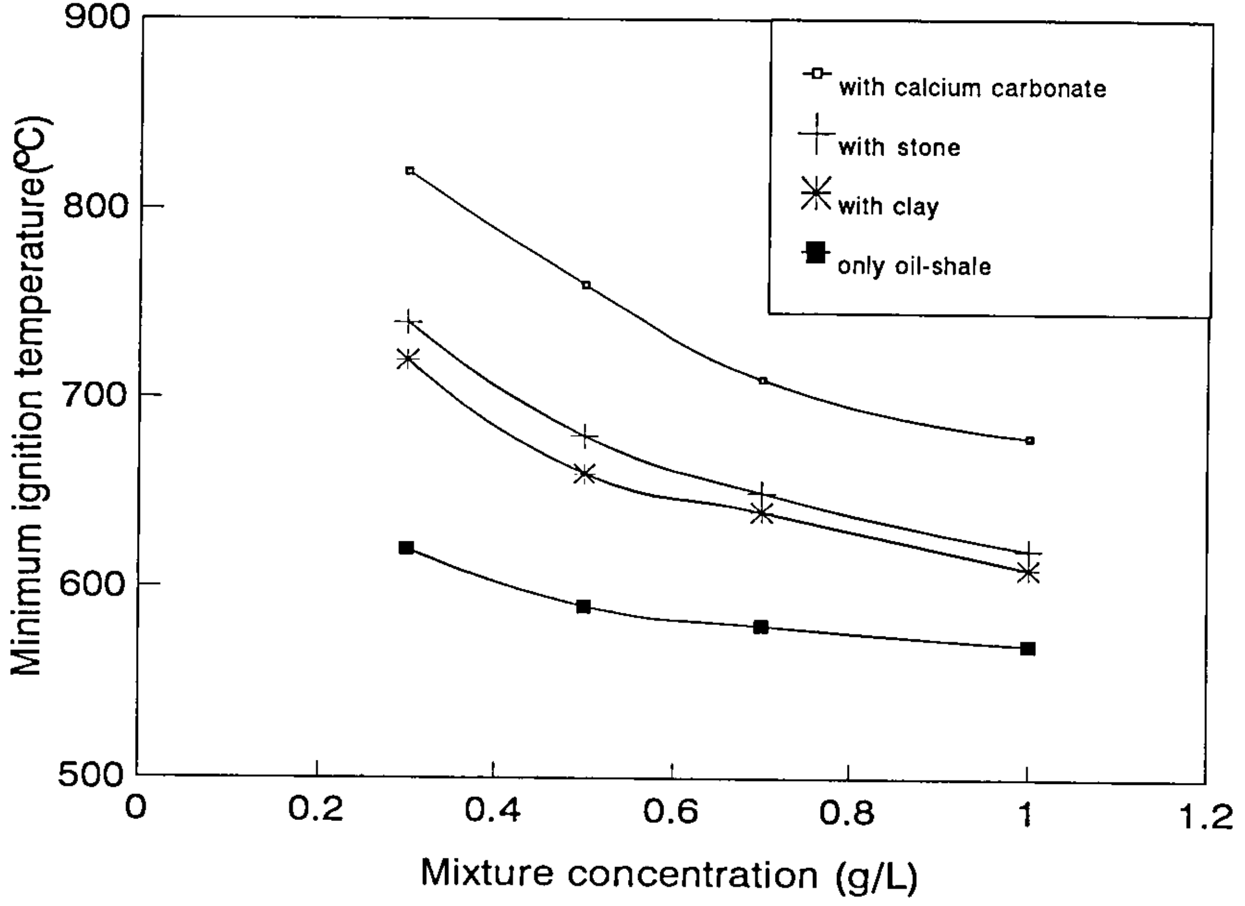
Figure(6.8): variation of minimum ignition temperature with mixture concentration for 20% additive (calcium carbonate,stone,clay).



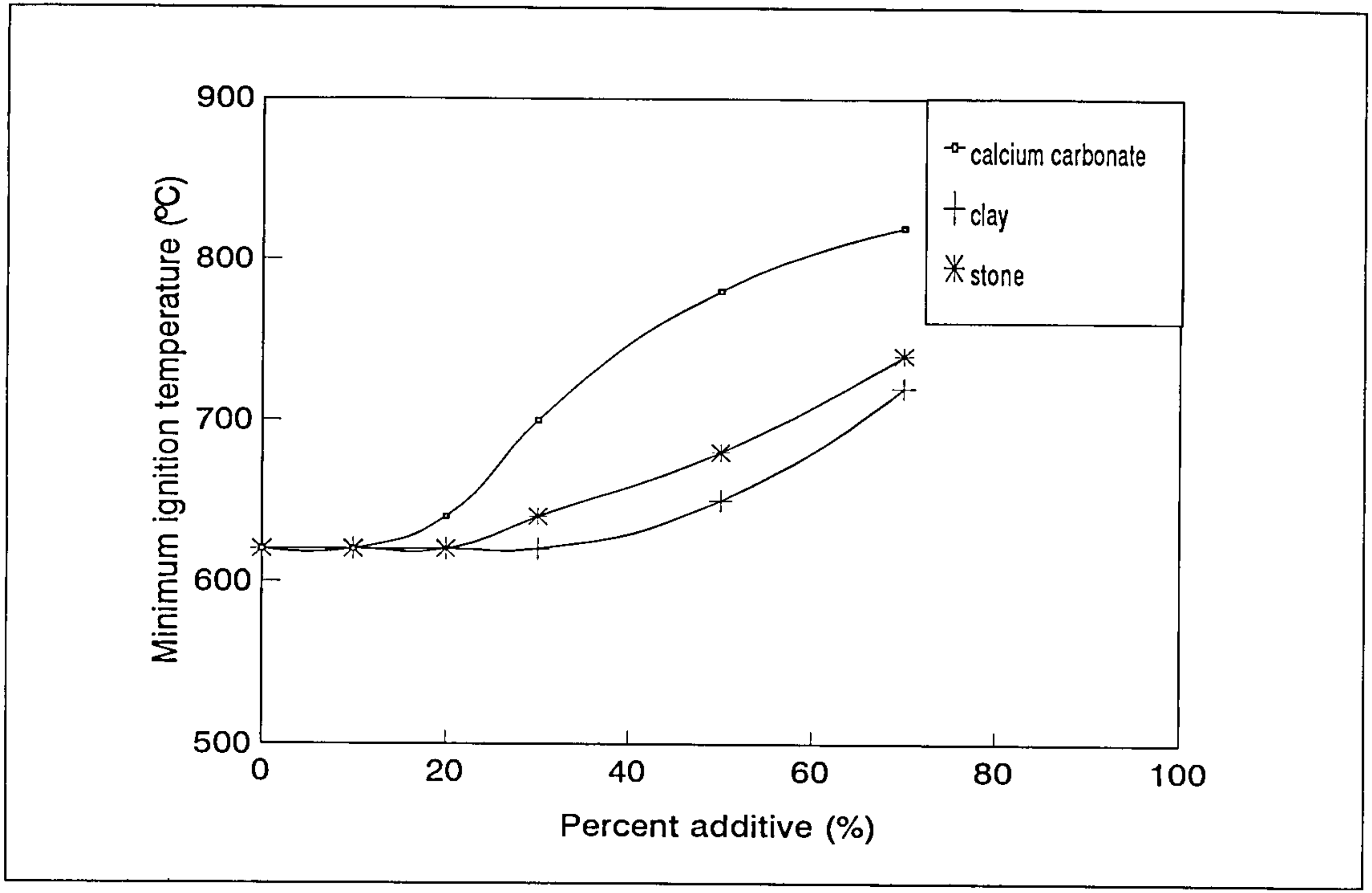
Figure(6.9): variation of minimum ignition temperature with mixture concentration for 30% additive (calcium carbonate,stone and clay).



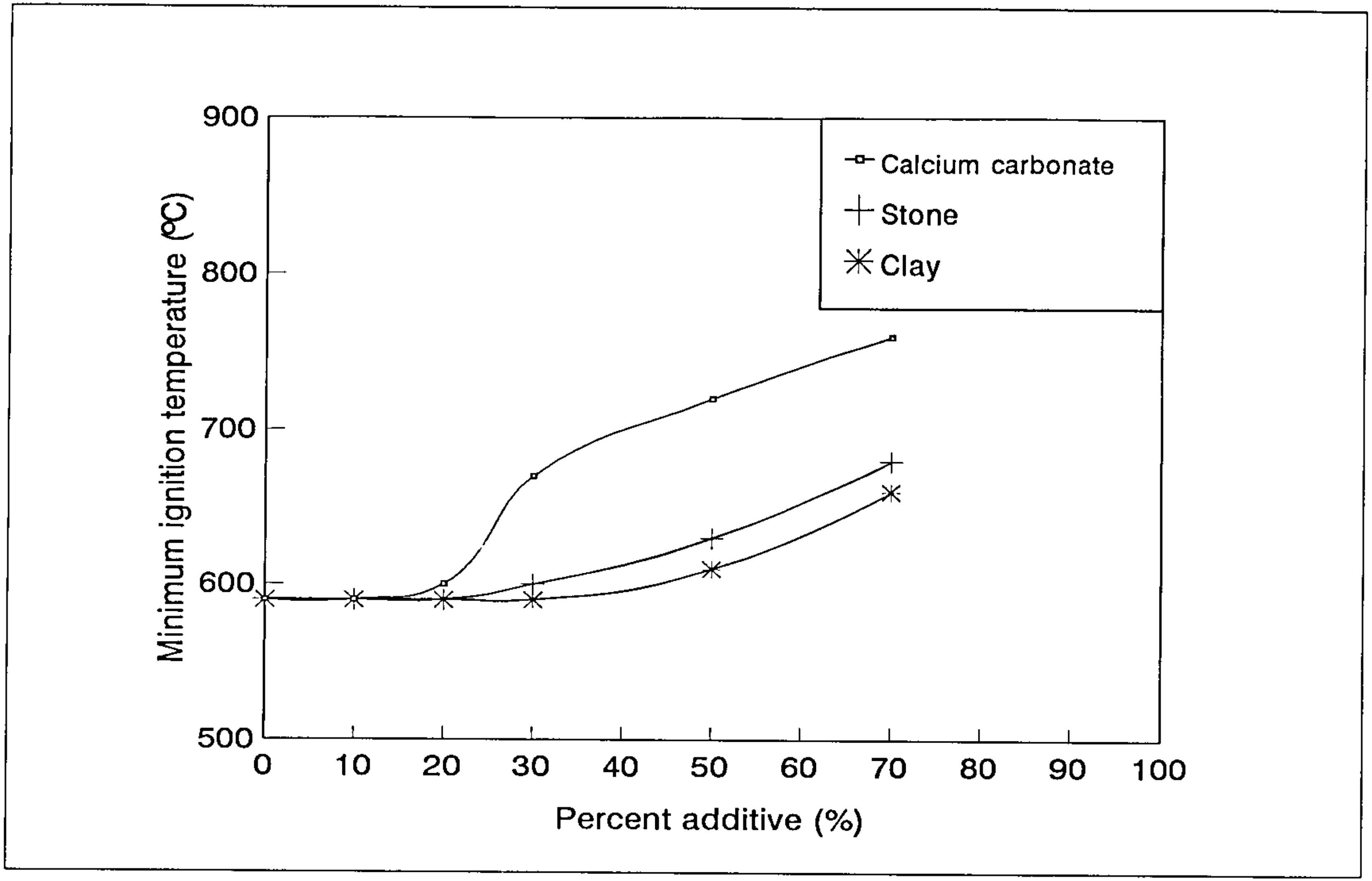
Figure(6.10): variation of minimum ignition temperature with mixture concentration for 50% additive (calcium carbonate,stone,clay).



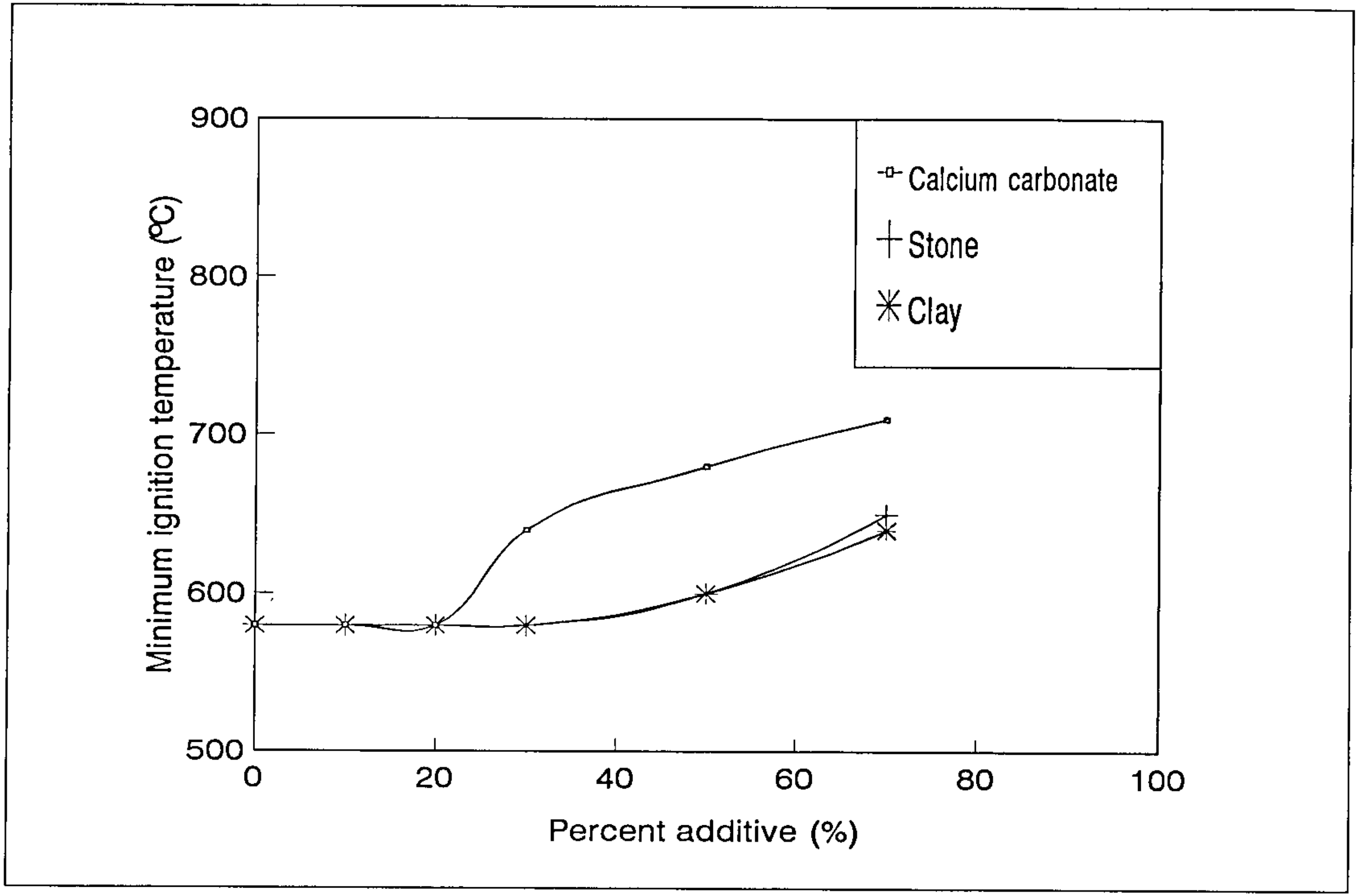
Figure(6.11): variation of minimum ignition temperature with mixture concentration for 70% additive (calcium carbonate,stone and clay).



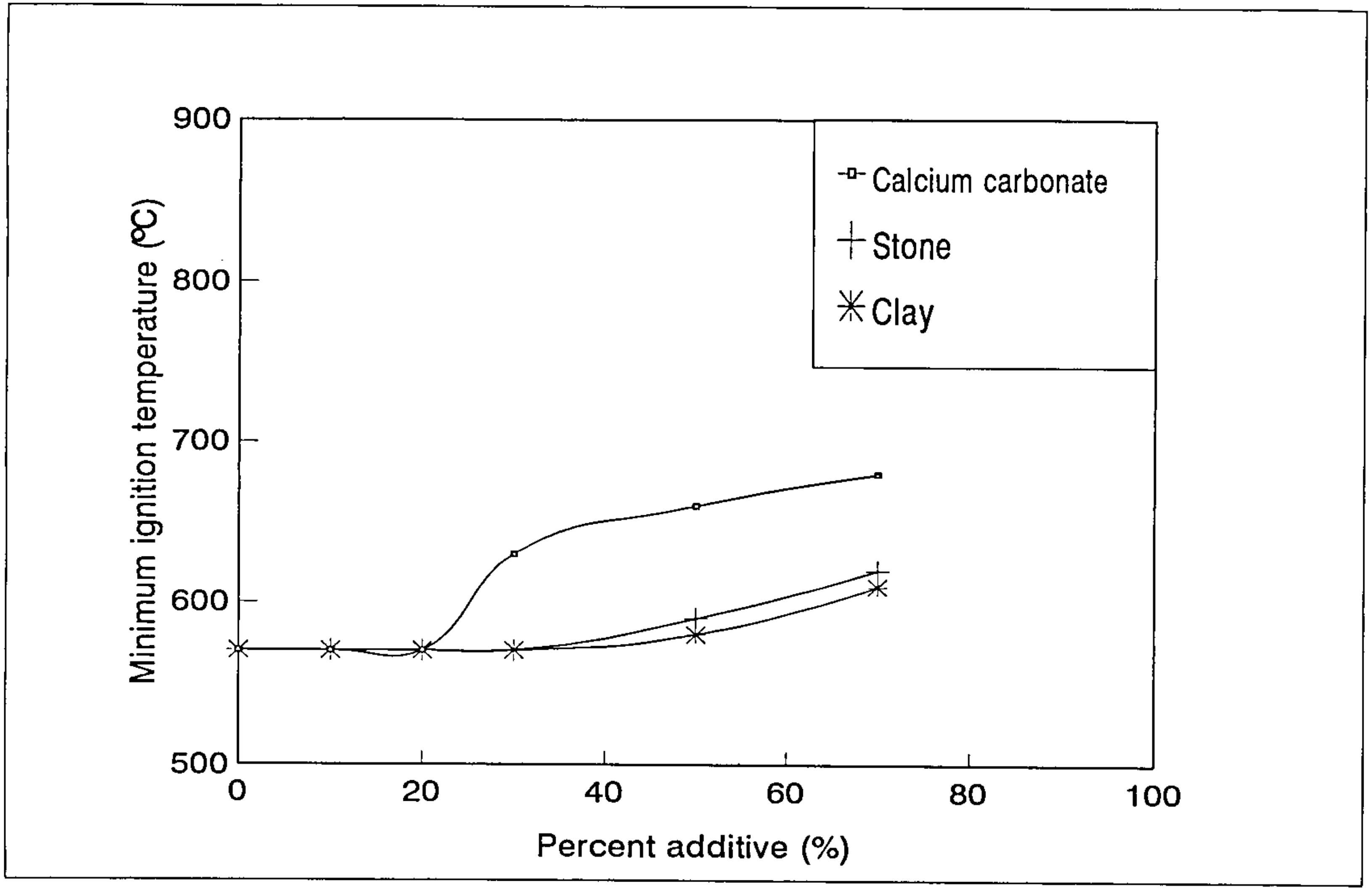
Figure(6.12): variation of minimum ignition temperature with percent weight of additive (calcium carbonate,stone,clay)in a mixture of concentration 0.3g/L



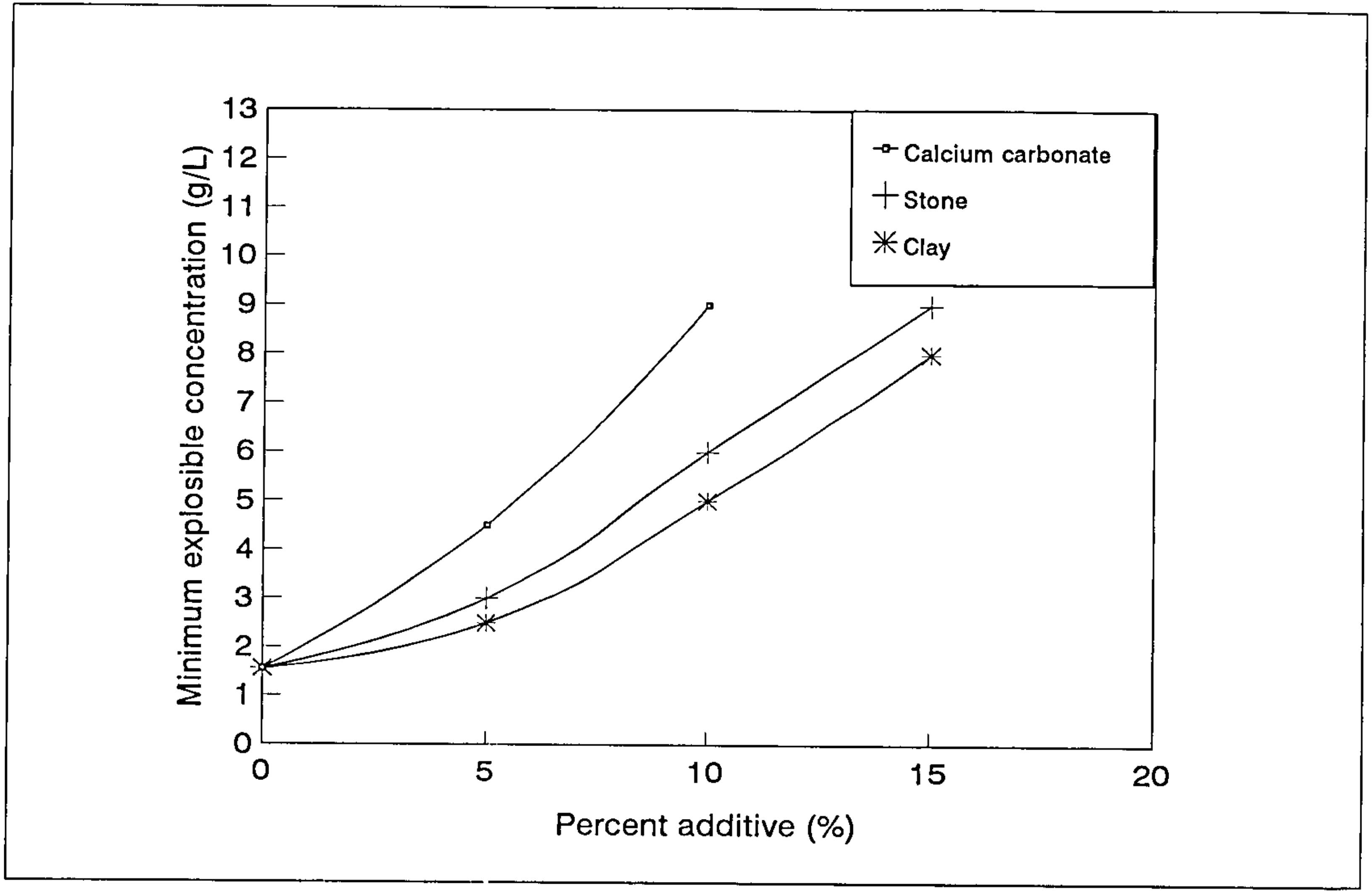
Figure(6.13): variation of minimum ignition temperature with percent weight of additive (calcium carbonate,stone,clay) for a mixture concentratiion of 0.5g/L



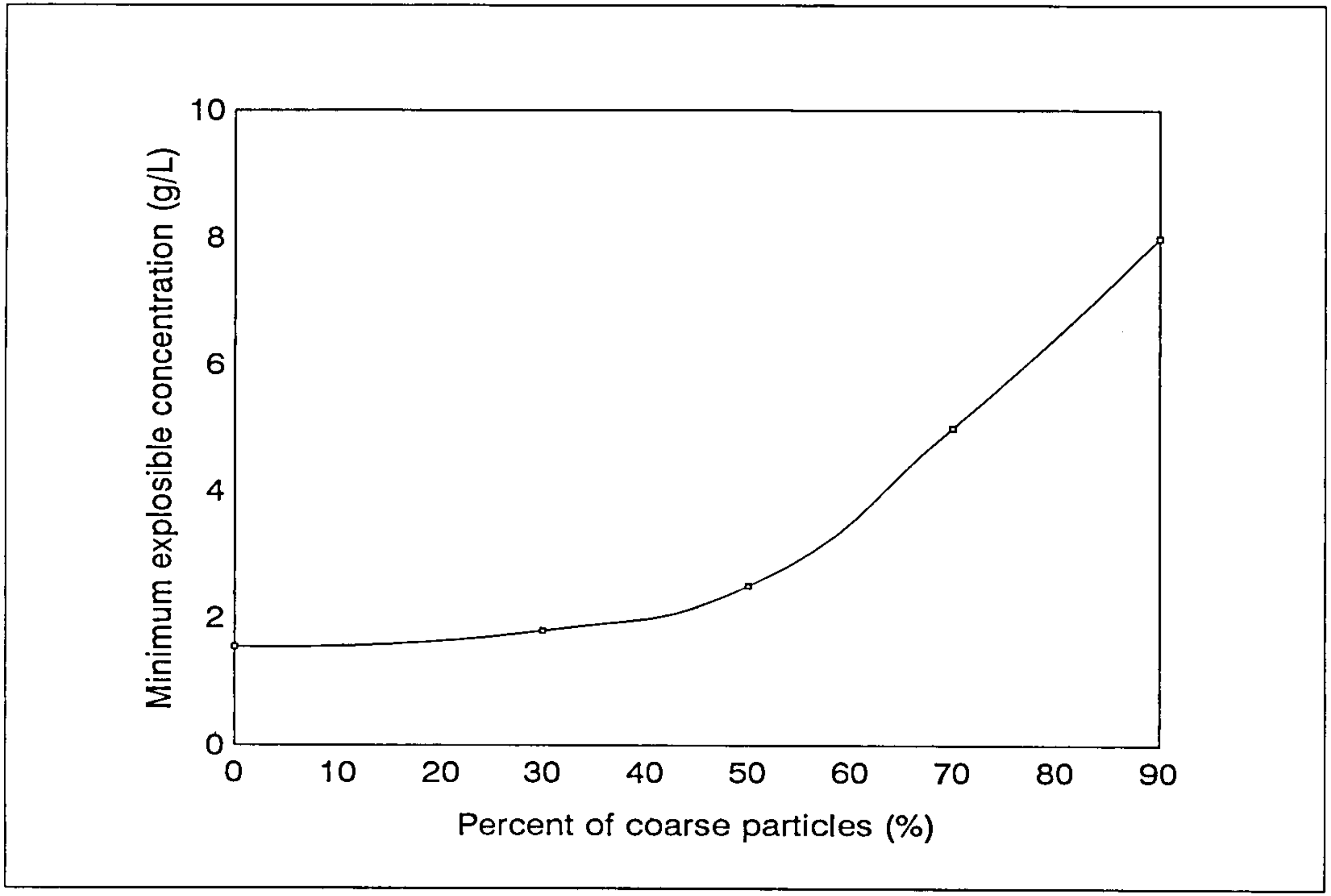
Figure(6.14): variation of minimum ignition temperature with percent weight of addiitive (calcium carbonate,stone,clay) for mixture concentration of 0.7g/L



Figure(6.15): variation of minimum ignition tempewrature with percent weight of additive (calcium carbonate,sone and clay) for mixture concentration of 1g/L



Figure(6.16): variation of minimum explosile concentration (lean limit) with percent weight of additives (calcium carbonate,stone,clay).



Figure(6.17): variation of minimum explosible concentration with wight pecent of coasrse particles in a mixture of coarse and fine particles.

7.2 RECOMMENDATIONS:

The present work suggests that the following points need to be investigated.

1- Other oil shale explosion parameters such as: maximum explosion pressure and maximum permissible oxygen concentration should be studied and determined.

2- Other inert additives such as: lime stone fuller's earth and phosphate, may be used to investigate the inhibition effect of these materials.

3- It would be of value to study a mathematical model to predict the minimum ignition temperature of oil shale dust as a function of different parameters such as: concentration, particle size and others.

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Table (A.1): Minimum Ignition temperatures at different concentrations and for different particle sizes.

Concentration (g/L)	Minimum ignition temperature (°C)		
	0μm< d <63μm	63μm< d <75μm	180μm< d <250μm
0.3	630 °C	620 °C	810 °C
0.5	610 °C	590 °C	790 °C
0.7	600 °C	580 °C	780 °C
1	600 °C	570 °C	740 °C

Table (A.2): Minimum Ignition Temperatures at different Concentrations and for different percents of coarse particles in a mixture of fine and coarse particles.

Concentration (g/L)	Minimum Ignition temperature (°C)			
	0%	30%	70%	100%
0.3	620	630	720	810
0.5	590	610	640	790
0.7	580	600	630	780
1	570	600	620	740

Table (A.3): Minimum explosible Concentration (lean limit) for different particle sizes.

Range of particle size (μm)	Min. explosible Concentration (g/L)
0< d <63	1.65
63< d <75	1.55
90< d <125	1.85
125< d <180	9
180< d <250	>10

Table (A.7): Minimum Ignition temperatures at different concentrations and for different weight percents of stone in the mixture.

Concentration (g/L)	Minimum Ignition temperature (°C)					
	0%	10%	20%	30%	50%	70%
0.3	620	620	620	640	680	740
0.5	590	590	590	600	630	680
0.7	580	580	580	580	600	650
1.0	570	570	570	570	590	620

Table (A.8): Minimum Ignition temperatures at different Concentrations and for different weight percents of clay in the mixture.

Concentration (g/L)	Ignition temperature (°C)					
	0%	10%	20%	30%	50%	70%
0.3	620	620	620	620	650	720
0.5	590	590	590	590	610	660
0.7	580	580	580	580	600	640
1.0	570	570	570	570	580	610

Table (A.9): Minimum explosible concentration of fine oil-shale particles for different weight percents of calcium carbonate stone and clay.

Weight percent (Wt%)	Minimum explosible concentration (g/L)		
	calcium carbonate	stone	clay
0%	1.55	1.55	1.55
5%	4.5	3	2.5
10%	9	6	5
15%	>10	9	8

APPENDIX B

UNCERTAINTY ANALYSIS

B.1 Introduction:

The uncertainties associated with the experimental work in measuring the minimum ignition temperature may be summarized as follow:

1- weighing the samples (±1°C)

2- measuring the temperature (±5°C)

3- Visual observation of the flame (±0.5°C)

B.2 Evaluation of the Uncertainty:

Each error will contribute in some manner with other errors to increase the uncertainty of the data obtained. These effects can be combined by using the root sum squares method (**RSS**):

$$u = \pm\sqrt{\sum_{j=1}^{k} e_j^2} \qquad \text{(B.1)}$$

where, k is the number of errors taken into account.

Using equation (B.1), the uncertainty in measuring the minimum ignition temperature was calculated to be ± 5.12°C or 0.86 %.

B.3 Repeatability of Results:

Measuring the minimum ignition temperature was repeated for the same sample several times and the repeatability was calculated to be about ± 2 %

ملخص

انفجار غبار الصخر الزيتي

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تهدف هذه الدراسة إلى دراسة مشكلة انفجار غبار الصخر الزيتي ، المتوقع حدوثها هنا في الأردن، في مناجم الصخر الزيتي عندما يبدأ استغلالها في السنوات القادمة. وقد تم قياس عاملين هما: درجة الاشتعال الدنيا والتركيز الأدنى للانفجار لغبار الصخر الزيتي، كذلك تم دراسة تأثير حجم حبيبات الصخر الزيتي على هذين العاملين.

وقد وُجد أن الدقائق الناعمة هي الأكثر احتمالية للاشتعال والانفجار ولذلك يجب إجراء الفحوصات عليها ، كذلك تم تحديد درجة الاشتعال الدنيا والتركيز الأدنى لانفجار هذا الحجم من الدقائق بـ ٥٧٠ درجة مئوية و١,٥٥ غرام/لتر.

كذلك تم فحص مزيج من الدقائق الناعمة والخشنة ، وقد وجد أن استبدال الدقائق الناعمة بدقائق خشنة أدى إلى ارتفاع درجة الاشتعال الدنيا بنسبة ٣٢,٢٪ والتركيز الأدنى للانفجار بنسبة ٦٤٥٪.

في هذه الدراسة ، وبهدف التقليل من المخاطر في مناجم الصخر الزيتي ، فقد تم دراسة مدى تأثر درجة الاشتعال الدنيا والتركيز الأدنى لحدوث الانفجار عند إضافة مواد خاملة مثل كربونات الكالسيوم ، الحجر الصخري والحجر الجيري.

لقد وجد أن كربونات الكالسيوم قد كان لها التأثير الأعظم في كبح الانفجار نظراً لأنها تسببت في زيادة درجة الاشتعال الدنيا والتركيز الأدنى للانفجار بشكل ملحوظ ، بينما أبدى الحجر الصخري تأثيراً متوسطاً ، والحجر الجيري هو الأقل تأثيراً.