INHIBITION OF DUST EXPLOSION

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by

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Just for you my only love ...

My mother.

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I would express my deepest thanks to all my friends especially Tareq al -Subaih , the three stars, Omar al-Ostah, Ma'moun Medraj.

Finally I appreciate the patience and solid support of my family.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Inhibition Of Dust Explosion

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This study aims to investigate the inhibition of oil shale and olive cake dust explosions when they are used as an alternative source of fuel. Special emphasis was given to the effect of particle size and mixtures of coarse and fine dusts of the same material on the maximum permissible oxygen concentration to prevent dust explosion for different concentrations using nitrogen as the diluent gas.

It was found that olive cake is ignited more easily than oil shale all over the range of particle sizes, dust concentration and mixtures of coarse and fine particles.

Tests on different particle sizes were carried out, and it was found that the maximum permissible oxygen concentration for a given dust concentration increases with increasing the particle size for both oil shale and olive cake.

Mixtures of coarse and fine particles were examined, and it was found that the mixture with 30% coarse particles is the most probable to explode among all other particle sizes for both oil shale and olive cake.

CHAPTER ONE

INTRODUCTION

1.1 General

Every year people are killed and equipment is destroyed by dust explosions. The present death rate from grain dust explosions alone averages between five and fifteen people a year. 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 could not be ignored. According to Alids (1990) and during 1977 and 1978, the destruction caused by grain dust explosions amounted to over 100 million dollars. In 1986, several people died in a coal dust explosion in Japan. In Britain dust explosions have caused some of the worst accidents. In the years between 1958 and 1978, 164 employees were killed and 605 injured in 250 accidents.

Here in Jordan, during the period 1977-1982 the only period for which information about industrial fires and explosions is available, there were many fires and explosions which occurred in the Jordan's industries, and according to the Public Fire Brigades records (1984), a total number of 36 Fires and explosions were recorded during that period; the chemical industries (i.e. cement, sponge and battery manufacturing) had the most incidents, while the food, textile, woodwork industries had the fewest incidents.

Generally an explosion occurs only when the dust is dispersed in air, or can be dispersed by some means whilst the source of ignition is present. The basic philosophy of protection is that safety precautions shall be designed to be adequate but as economical as possible, that any fire explosion which should occur will be safely dealt without causing loss or injury, and by that, catastrophic situations are prevented.

Many solid materials are combustible and are handled in various processes in some industries. In these processes extreme care must be taken for fine powders against dust explosions, which are phenomena of ignition and flame propagation between solid particles suspended in air. The ease of occurrence (ignitability) and severity of explosion (explosibility) are represented by ignition temperature, minimum ignition energy, explosible limit of dust concentrations, flame propagation velocity, pressure developments in closed vessels and so on. These explosion characteristics depend upon the kind of dust material, the state of dust clouds, the atmospheric conditions and also the type of explosion apparatus.

1.2 Objectives Of The Present Work

This work is an experimental investigation directed towards studying oil shale and olive cake dust explosion .

The parameter that will be investigated is the maximum permissible oxygen concentration to prevent the occurrence of an explosion. This will be carried out by taking into consideration the effect of both particle size and dust concentration on such parameter by using fine particles, coarse particles and mixtures of both for different dust concentrations. Finally, the effect of furnace apparatus temperature will be studied.

1.3 Layout Of The Thesis

This thesis is divided into six chapters, this introduction is the first. Literature review is presented in chapter two. Chapter three deals with the theory. Chapter four presents experimental setup and procedure. The results obtained together with their discussions are

CHAPTER TWO

LITERATURE REVIEW

This chapter contains a general review of some experimental and theoretical work that have been carried out in the field of dust explosins.

Long and Murray (1958) 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 that if the air surrounding the dust particles is at a higher temperature, then combustion starts by the ignition of the volatile matter and the inflammation of the solid particles occurs later. On the other hand they suggested that if the dust particles are at a higher temperature, 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 (1959) 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.

Rose (1970) in his work on the ignition of clouds of lycopodium 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. The first of these two processes is the initiation process; where a small volume of the dust cloud is ignited by electric spark. While the second one is the continuation process; where the combustion from the initially burning volume propagates to the remainder of the cloud. He concluded that if the process does not occur within the duration of the spark ($\cong 10^{-3}$ sec.), it will not occur at all, further he found that and by using a heated surface as the source of ignition, the probability of initiation (ignition) increases with the time of the exposure of the dust cloud to the hot surface. Finally, he suggested that the propagation of flame can occur if the initial volume of cloud, after combustion, releases enough energy to raise the temperature of that volume to a minimum temperature necessary for the combustion of a neighboring volume.

Sweis (1982) had measured the dust explosion parameters of Adipic acid and Fumaric. He developed a primarily model explaining the initiation and continuation of flame propagation, but he did not compare his data with experimental one.

Kjaldman (1987) have developed a numerical model for peat dust deflagrations based on experiments done in a 20 dm^3 closed spherical vessel. The model has been applied to explosions of dry peat dust in a vented vessel. The gas-particle mixture is described as a continuous two-phase flow with interphase mass, momentum and heat transfer. The model includes drying and pyrolysis of the particles, and combustion of devolatilized gasses and char.

Amyotte *et al.* (1988) investigated the effect of turbulence on dust explosion parameters. They found that turbulence tends to decrease the ignitability of dust.

Hertzberg *et al.* (1988) studied the lean limit of Pittsburg pulverized coal dust. They found that the value of lean limit depends on the particle size and on the degree of dispersion.

Aldis (1990) developed a two-dimensional two phase hydrodynamic computer model to predict pressure propagation in dust explosions. Two cases of detonation of dispersed powders were injected into a rectangular cavity and were analyzed. The ignition of an idealized, uniformly distributed powder in a box produced a pressure peak that propagated through the powder with an increasing amplitude from the ignition source at on corner.

Lesikar *et al.* (1991) studied minimum ignition temperature, maximum pressure, and maximum rate of pressure rise for three fractions of wheat and grain sorghum at five concentrations. They found that the accepted minimum explosive concentrations are lower than actual concentrations required for propagation of an explosion. They also studied primary and secondary explosions.

Nomura and Tanaka (1992) have developed a theoretical model for dust explosion parameters, the basis of their work are a simplified model of the dust cloud suspension, the flame propagation process and the combustion of solid particles. As a result, characteristics of the phenomena are expressed by combining reaction kinetics, heat transfer theory and thermodynamics. Further, theoretical information on some protection method is derived and shown to be safe. Thus, it appears that, although this treatment includes some severe assumptions, it could provide a basis for more rigorous theories for prediction of dust explosion and design of protection systems.

Amyotte et al. (1993) 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 that the ignitability of dust reduces with the presence of methane.

Mintz(1995) in his work examined the experimental method employed for measuring the parameters of dust explosions using air/methane as a model system. He found that the characteristics of the dust dispersal system and the ignition system must be studied in detail for any particular apparatus before it is possible to generate accurate data.

Al - Qubbaj (1996) studied two parameters namely, minimum ignition temperature and minimum explosive concentration of oil shale dust. Also the effect of particle size on such parameters was investigated. He found that particles with fine size in the range of 63 μm to 75 μm are the most probable to explode among all other particle sizes.

Cashdollar(1996) studied the explosibility of coal dusts to improve safety in mining and other industries that process or use coal. The tests were conducted in the USBM 20 liter laboratory explosibility chamber. The parameters measured included minimum explosible concentrations, maximum explosion pressure, maximum rates of pressure rise, minimum oxygen concentration and the amount of limestone rock dust required to inert the coals. The dust explosibilty data are compared to those of other hydrocarbons, such as polyethylene dust. He found that for various coals the higher volatile and finer sized coals are more hazardous.

CHAPTER THREE

THEORY

3.1 Introduction

Where combustible dusts are being handled or produced in industry, it is necessary to know whether these dusts are explosible or not. At present there is no reliable method of predicting the explosibility from the composition or heat of combustion of dusts. Until further information becomes available to enable this to be done, direct tests of explosibility have to be made .

Laboratory tests have been set up in various countries to enable investigations of dust explosion properties, whose explosion characteristics have been established in previous industrial experience. The tests may also be used to decide whether a new material shall be used in an industrial process, bearing in mind that if explosion precautions would be necessary, the cost of those explosion precautions should be taken into account.

3.2 Characteristics Of Dust Explosions

When a mass of flammable solid 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 dissipates 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 entire material will burn rapidity with the sudden release of energy and the evolution of large quantities of heat and, as a rule, a gaseous reaction products.

3.3 Explosive Concentration

Although an intimate mixture of a flammable dust and air may burn with explosive violence, not all mixtures will do so. There is a range of concentrations of the dust and air within which the mixture can explode, but mixtures above or below this range cannot. The lowest concentration of dust capable of exploding is refered to as the lower explosive limit and the concentration above which an explosion will not take place as the upper explosive limit.

The lower explosive limit of many materials have been measured. For most practical purposes it may be assumed that 0.02 (g/L) is the lower explosive limit for most flammable dusts. Though this may seem to be a very low concentration, in appearance a cloud of dust of such concentration would resemble a very dense fog. The upper explosive limits are not well defined and have been determined for only few dusts, but these data have limited importance in practice.

The most violent explosions are produced when the proportion of oxygen present is not far removed from that which will result in complete combustion.

The range of explosive concentration of a dust cloud, moreover, is not solely a function of the chemical composition of the dust; the limits vary with the size and shape of the particles in the dust cloud.

3.4 Factors Which Affect The Maximum Pressure And Rates Of Pressure Rise In Enclosed Explosions

The explosion can be characterized by two parameters: the maximum pressure attained and the rate of pressure rise. Either the maximum rate or the average rate of pressure rise can be used.

The severity of violence of the explosion can be characterized from the pressure time curve as the rate of pressure rise.

Explosion parameters may be affected by a number of factors, the most obvious being the combustible material itself and its concentration in a mixture with air.

3.4.1 The Combustible Material

The maximum pressure and rate of pressure rise which influence the severity of a dust explosion vary with the chemical constitution and certain physical properties of the dust. Health and Safety Executive in Britain (1976) reported that some metal powders, for example, aluminum, magnesium and alloys of aluminum and magnesium, can generate maximum pressure of 700 Kpa and maximum rate of pressure rise in excess of 70,000 Kpa/s. Many vegetable products produce similar maximum pressures but the rates of pressure rise are lower.

Combustible materials are expressible in air only when their concentration in air lies between the lower and the upper explosibility limits. Generally, the most explosive mixture lies on the fuel-rich side of the stoichiometric concentration, other concentrations between the explosibility limit having lower explosion pressure and lower rates of pressure rise. However, the maximum explosion pressure and maximum rate of pressure rise do not always occur at the same concentration of fuel in air.

3.4.2 Particle Size And Shape

The particle size of the material exerts a considerable influence on the explosibility of a dust cloud. The finer the dust the more readily its dispersed into a cloud and the longer it will remain in suspension. A reduction in the size of particles means an increase in surface area which is also determined by the shape of the particle. A thin flat particle is more readily ignited than a spherical particle of the same substance.

3.4.3 Ignition Source : Strength And Shape

Generally, an increase in the ignition energy causes an increase in the rate of pressure rise for dust explosions. The nature of ignition source is also important. Permanent spark gaps, for instance, give low values of the explosion parameters for some dusts even though the ignition energy is high compared to some other ignition sources. The position of the ignition source affects explosion parameters by changing the path of the flame and thus the amount of heat lost to the vessel walls.

3.4.4 Composition of the Atmosphere

The flammability of a dust cloud is reduced by decreasing the oxygen content of the medium in which it is dispersed.

As the oxygen content is reduced, the minimum hot-surface temperature necessary to ignite a dust cloud is progressively raised; and when a dust cloud is exposed to a source of ignition at a given temperature there is a critical percentage of oxygen below which the dust will not explode. This limit depends on the inerting properties of the other components of the atmosphere. Carbon dioxide and nitrogen are effective inerting agents for carbonaceous materials, but some metal powders may ignite and burn under certain circumstances.

CHAPTER FOUR

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.

4.1 Experimental Equipment

Laboratory equipment has been developed in various countries to assess the explosibility of dusts. Some differences may exist between countries, but the main idea of dispersing the dust sample in the vicinity of an ignition source is a common point amongst all the developed equipment. In this work the furnace apparatus will be used is the so called The Godbert-Greenwold Furnace Apparatus with slight modifications.

The general layout of the furnace apparatus is shown in Figure 4.1. It 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 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 0.94 cm inside diameter. The dust holder is connected to the air reservoir of 460 cm^3 capacity. The modifications are that the reservoir is supplied by two inlets, one for air and the other for Nitrogen.

The furnace space is filled with the air/Nitrogen mixture, also air/Nitrogen mixture is used to disperse the dust into the furnace. The temperature of the furnace is held constant. By varying the composition of the air/Nitrogen mixture, the maximum permissible oxygen concentration is obtained.

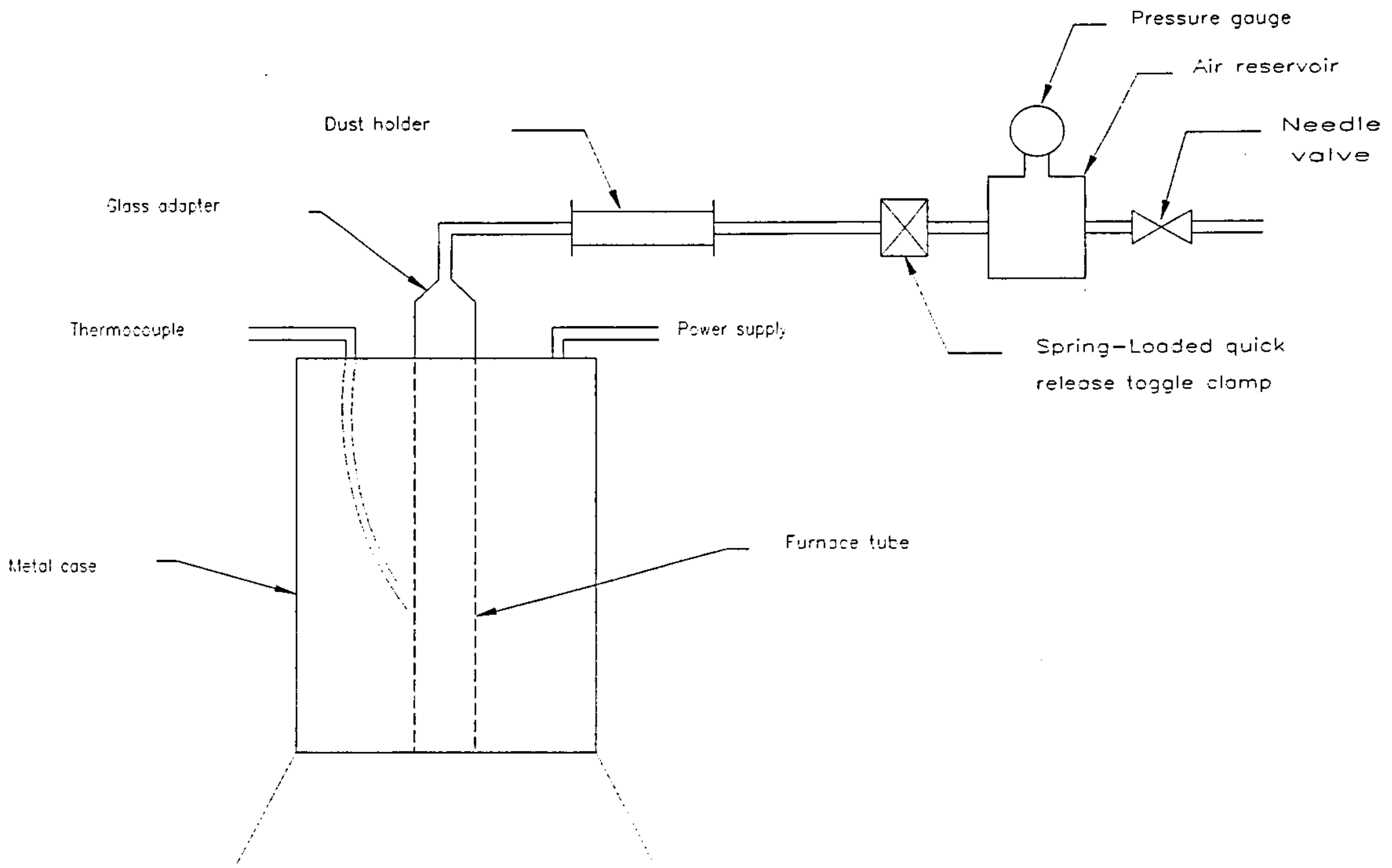

Figure 4.1 Furnace apparatus

4.2 Experimental procedure

The experimental procedure involves the measuring of the maximum permissible oxygen concentration of a dust cloud needed to prevent oil shale and olive cake explosion by using air/Nitrogen mixture 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. The air reservoir was charged to 70 kPa with the required air/Nitrogen ratio, then the mixture is released to fill the furnace space instead of air, and the bottom open mouth of the furnace is closed.
3. A known quantity of the dust was placed in the dust holder.
4. The air reservoir is charged again to 70 kPa with the same air/Nitrogen ratio.
5. The dust was dispersed through the furnace tube by air/Nitrogen blast (after opening the bottom open mouth of the furnace).

The criterion for an explosion was the propagation of flame away from the furnace. A distinction is made between flames observed in the combustion tube.

1- Full flame propagation which means that the flame extends outside the tube.

2- Inside tube flame propagation (flame occurs but does not extend to the outside).

3- No explosion (no flame propagation).

If explosion occurs, i.e. observation of a flame at the bottom mouth of the furnace, the Nitrogen amount is increased and the same procedure was carried out until no explosion occurs. At this air/Nitrogen ratio the experiment was repeated three times to make sure that no explosion occurs at this mixture. The lowest Nitrogen amount at which no explosion occurs was taken as the maximum permissible oxygen concentration.

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 sizes. First, the material was ground by a grinding machine, then, the powder was sieved for at least 30 minutes, and the particle size was determined within two mesh sizes.

4.3 Experimental Matrix

The maximum permissible oxygen concentration is measured for oil shale and olive cake samples of the following particle size

1- $d < 63$ μm..

2- 75 μm < d < 90 μm.

3- 90 μm < d < 125 μm.

4- 180 μm < d < 250μm.

5- 250 μm < d < 355 μm.

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

Tests were carried out at 1000 °C.

Also the test was carried out for the particle size (90 μm < d < 125 μm) at different furnace temperatures.

The tests were carried out at various dust concentrations within the range 0.3 - 10 g/L.

CHAPTER FIVE

RESULTS AND DISCUSSION

5.1 Introduction

This chapter is mainly concerned with studying the variation of the maximum permissible oxygen concentration with the dust concentration for different particle sizes, and for several admixtures of fine and coarse dusts of the same material.

The effect of temperature on the maximum permissible oxygen concentration is also presented. Finally a comparison between two materials namely oil shale and olive cake is also presented.

5.2 Effect Of Particle Size And Dust Concentration On Maximum Permissible Oxygen Concentration

Tests were carried out to investigate the effect of particle size and dust concentration of oil shale and olive cake on the maximum permissible oxygen concentration. Figures (5.1) through (5.3) and Figure (5.7) through (5.9) show the variation of the maximum permissible oxygen concentration with dust concentration for different particle sizes for both oil shale and olive cake, respectively. From these figures it can be seen that in general the maximum permissible oxygen concentration decreases with dust concentration to a minimum value, beyond which it starts to increase. This is due to the fact that any increase in concentration (in the amount of solid fuel) makes the occurrence of the explosion easier, and consequently the maximum permissible oxygen concentration is reduced to prevent the explosion. Further increase in concentration leads to the decrease of the oxidant (air) in the mixture, this makes the occurrence of the explosion harder and consequently the maximum permissible oxygen concentration is increased.

It should be noted that each curve in the above mentioned figures represents a boundary, below which dust explosion is not possible, while above it explosion is possible.

In order to show the effect of particle size on the maximum permissible oxygen concentration Figures (5.4) through (5.5) and Figures (5.8) and (5.9) were plotted. As it may be seen and in general the maximum permissible oxygen concentration increases with increasing particle size for a fixed dust concentration. This is due to the fact that fine particles have larger surface area per volume of the mixture which means that the small particle sizes are easily ignited than larger ones.

From Figure (5.1) it can be seen that for large particle size with diameter range between 250 and 355 μm of oil shale, ignition in air was not obtained with a dust concentration up to 0.5 g/L, whereas for all smaller particle sizes of the same material ignition in air was successful with dust concentration as low as 0.3 g/L.

Figures (5.10) through (5.22) indicate that olive cake is more easily ignited than oil shale overall values range of both particle size and dust concentration. This is due that the percent by weight of the organic matter of olive cake is higher than that of oil shale.

Figures (5.23) and (5.24) show three dimensional representation for the maximum permissible oxygen concentration with both the particle size and dust concentration for both oil shale and olive cake respectively. These figures are considered as a summary for all the results obtained.

5.3 Effect of Temperature on Maximum Permissible Oxygen Concentration

Ignition temperature is an important parameter that affects dust explosion, so tests on different furnace temperatures settings were carried out for oil shale and olive cake.

Figures (5.25) and (5.25) compare all the results obtained for oil shale and olive cake, these figures show that, and as expected, all the oxygen values decreases with an increase of the furnace temperature for any dust concentration.

Figures (5.25) and (5.25) show that the effect of furnace temperature on maximum permissible oxygen concentration is the same on the two materials, but oxygen concentration for oil shale decreases at a higher rate than olive cake with an increase in the dust concentration to a minimum value beyond which it increases at higher rate. Further it can be seen that the minimum value of the maximum permissible oxygen concentration for oil shale is at higher dust concentration than that of olive cake for all temperatures.

5.4 Effect of Mixtures of Coarse and Fine Particles of The Same Material on The Maximum Permissible Oxygen Concentration

In practical problems, in industry or mining, dusts are not usually of uniform particle sizes and it may contain both fine and coarse particles in a certain distribution. It is important then to study the effect of mixtures of fine and coarse particles on the maximum permissible oxygen concentration.

Two particle sizes have been selected for each material to be mixed together, which are the smallest and largest particle sizes. Several percentages of the coarse and fine dusts were mixed together.

Figures (5.27) through (5.30) show the variation of the maximum permissible oxygen concentration for several mixtures of coarse and fine dusts for each of oil shale and olive cake. The figures show that the maximum permissible oxygen concentration decreases with dust concentration to a minimum value, beyond which it starts to increase for the same reasons mentioned previously which are the fact that any increase in concentration (in the amount of solid fuel) makes the occurrence of the explosion easier, and consequently the maximum permissible oxygen concentration is reduced to prevent the explosion. Further increase in concentration leads to the decrease of the oxidant (air) in the mixture, this makes the occurrence of the explosion harder and consequently the maximum permissible oxygen concentration is increased. These figures also show that the mixture with 30% coarse particles is the most easily ignited one, and hence the maximum permissible oxygen concentration for this mixture is of minimum value.

In order to show the effect of the fraction of coarse particles in the mixture on the maximum permissible oxygen concentration, Figures (5.31) through (5.34) were plotted. Values of maximum permissible oxygen concentration of 0% and 100% coarse particles for both oil shale and olive cake are also plotted. As it may be seen the maximum permissible oxygen concentration increases by increasing the percent of coarse particles for both oil shale and olive cake with low dust concentrations, whereas the maximum permissible oxygen concentration decreases to a minimum value, beyond which it starts to increase for both oil shale and olive cake with dust concentration above 0.7 g/L.

Figures (5.35) and (5.35) show three dimensional representation for the maximum permissible oxygen concentration with both the percent of coarse particles and dust concentration for both oil shale and olive cake respectively. These figures are considered as a summary for all the results obtained.

Figures (5.37) through (5.47) show that olive cake is easily ignited compared with oil shale over all the specified mixtures and dust concentration. This is due that the percent by weight of the organic matter of olive cake is higher than that of oil shale.

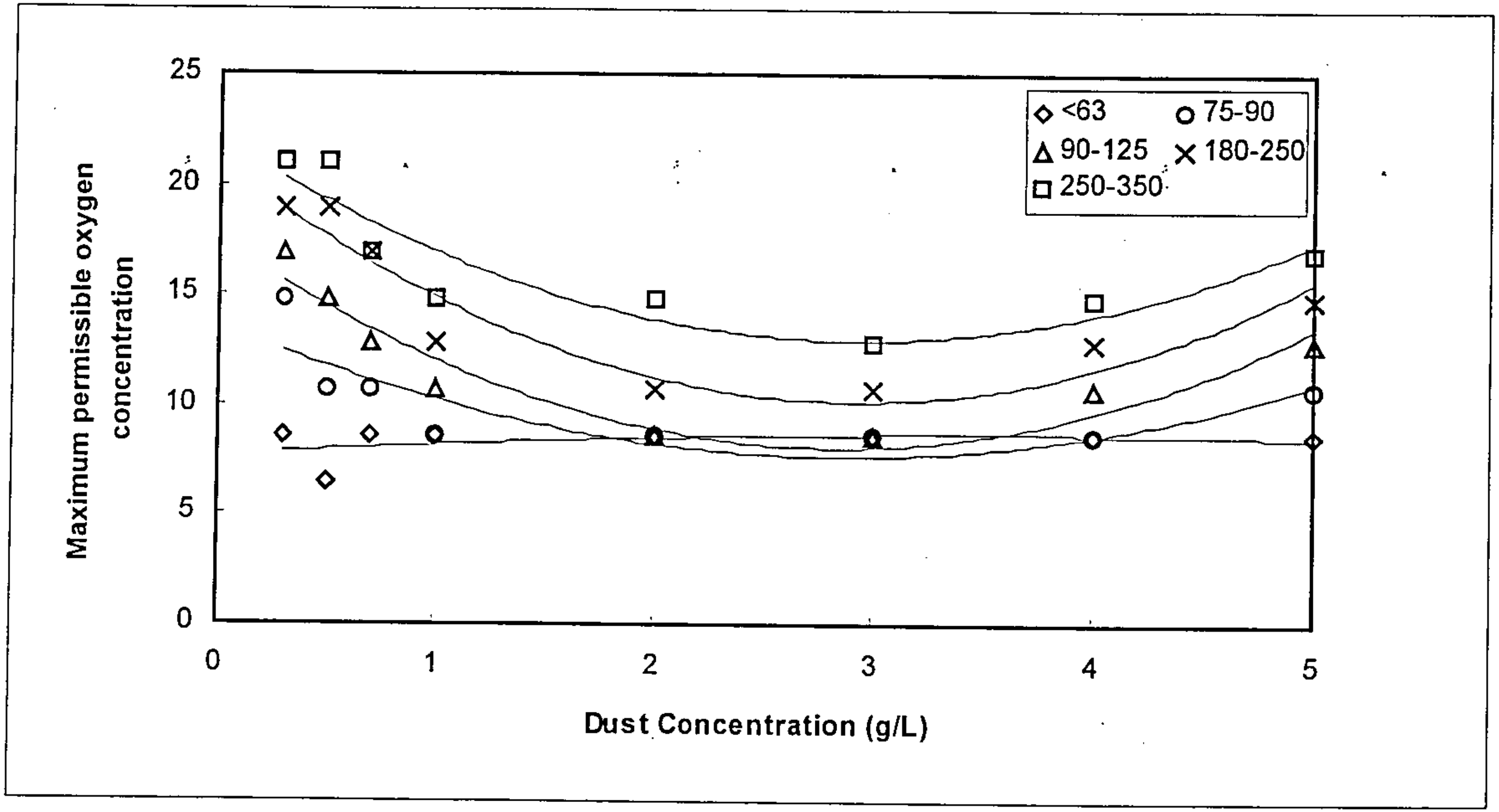

Figure (5.1): variation of maximum permissible oxygen concentration with dust concentration of oil shale with different particle sizes.

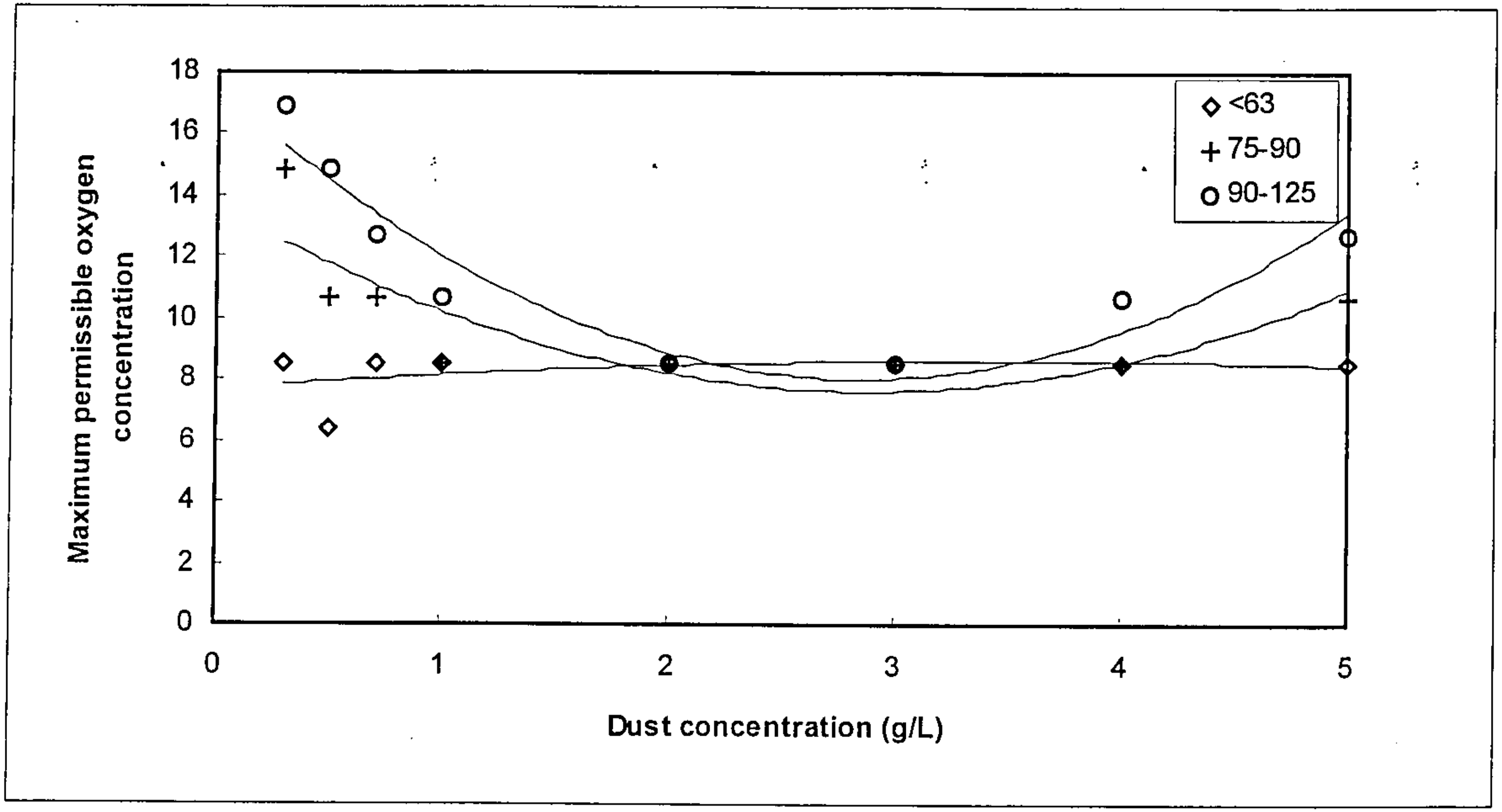

Figure (5.2): variation of maximum permissible oxygen concentration with dust concentration of oil shale with different particle sizes.

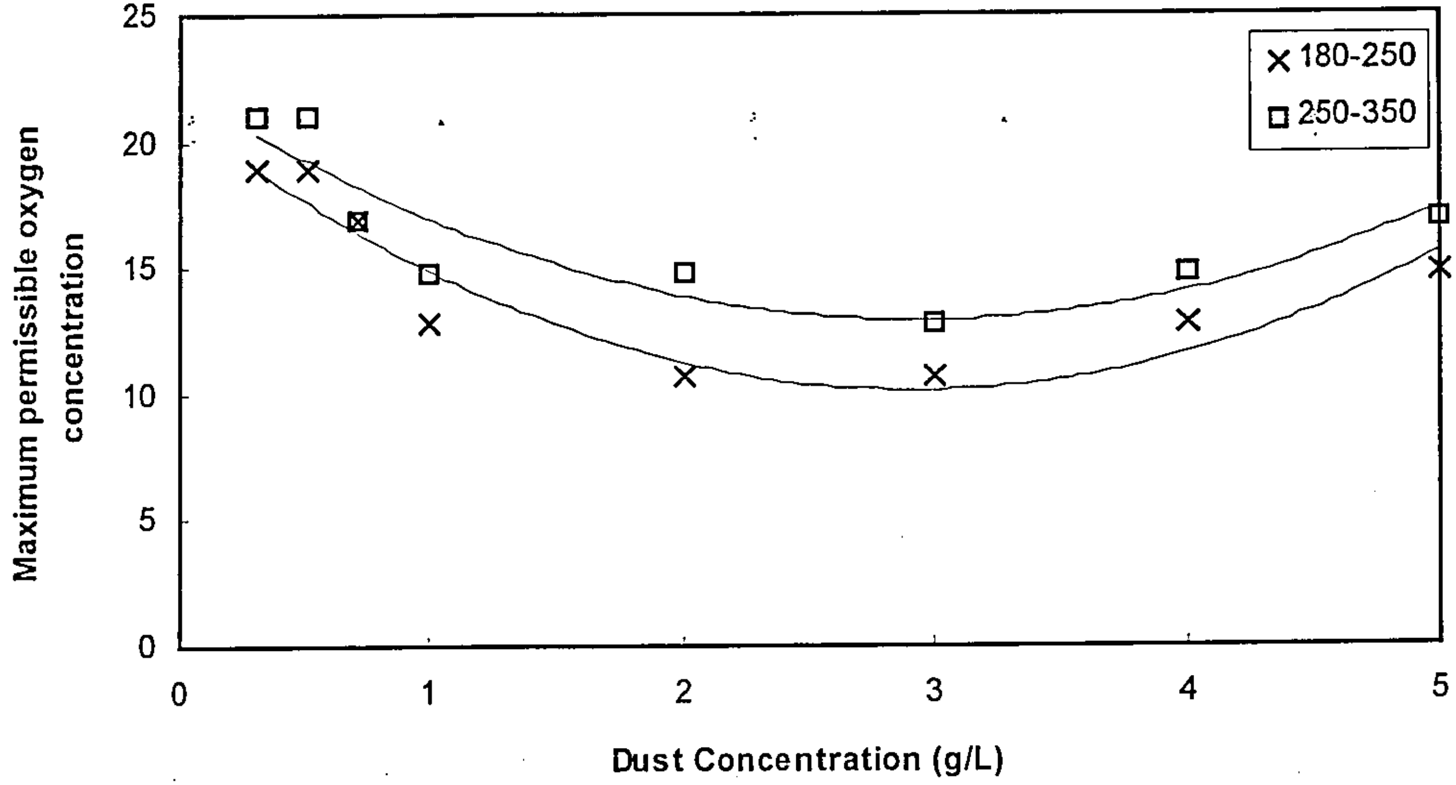

Figure (5.3): variation of maximum permissible oxygen concentration with dust concentration of oil shale with different particle sizes.

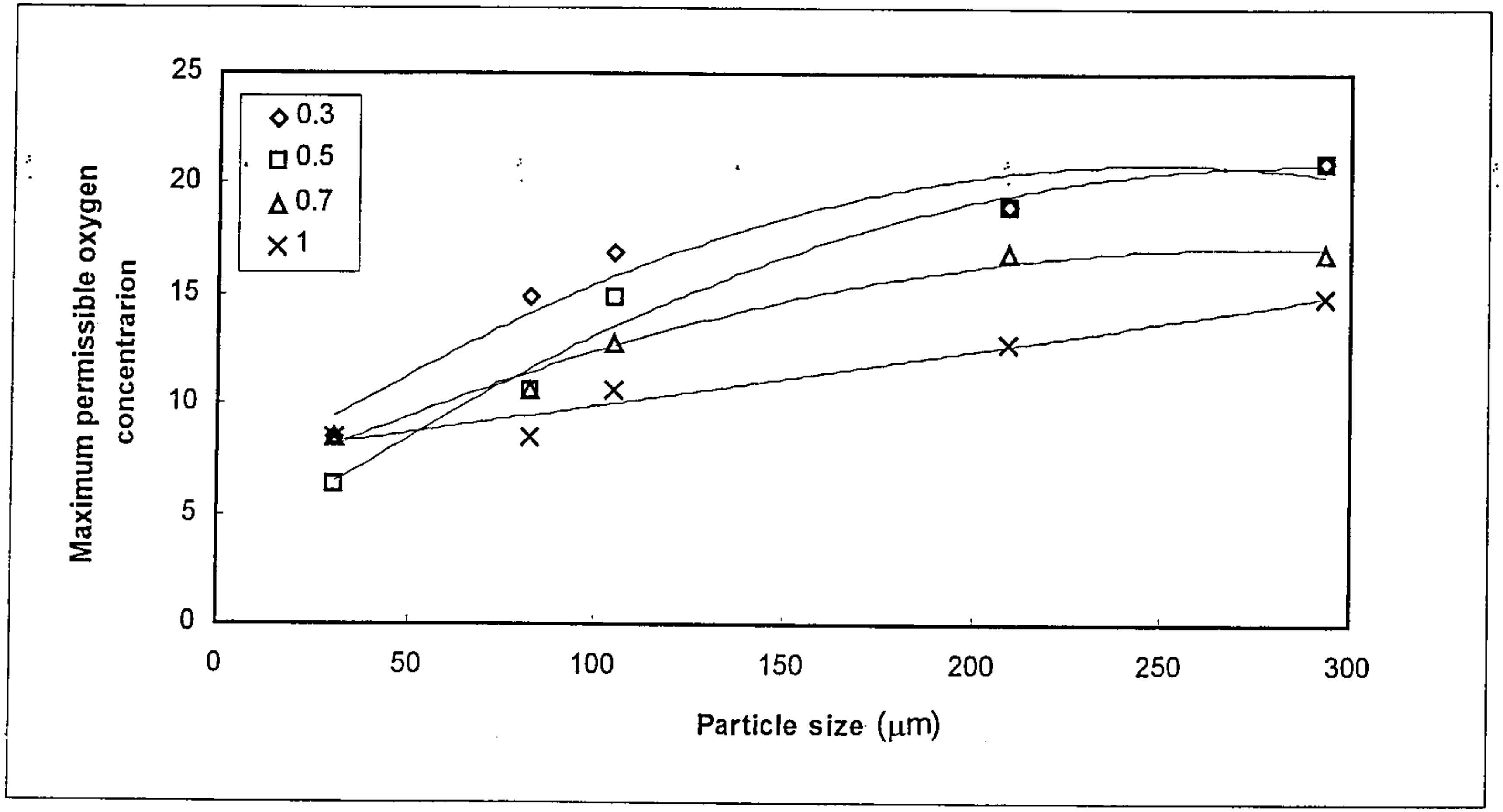

Figure (5.4): variation of maximum permissible oxygen concentration with particle size of oil shale under different concentrations

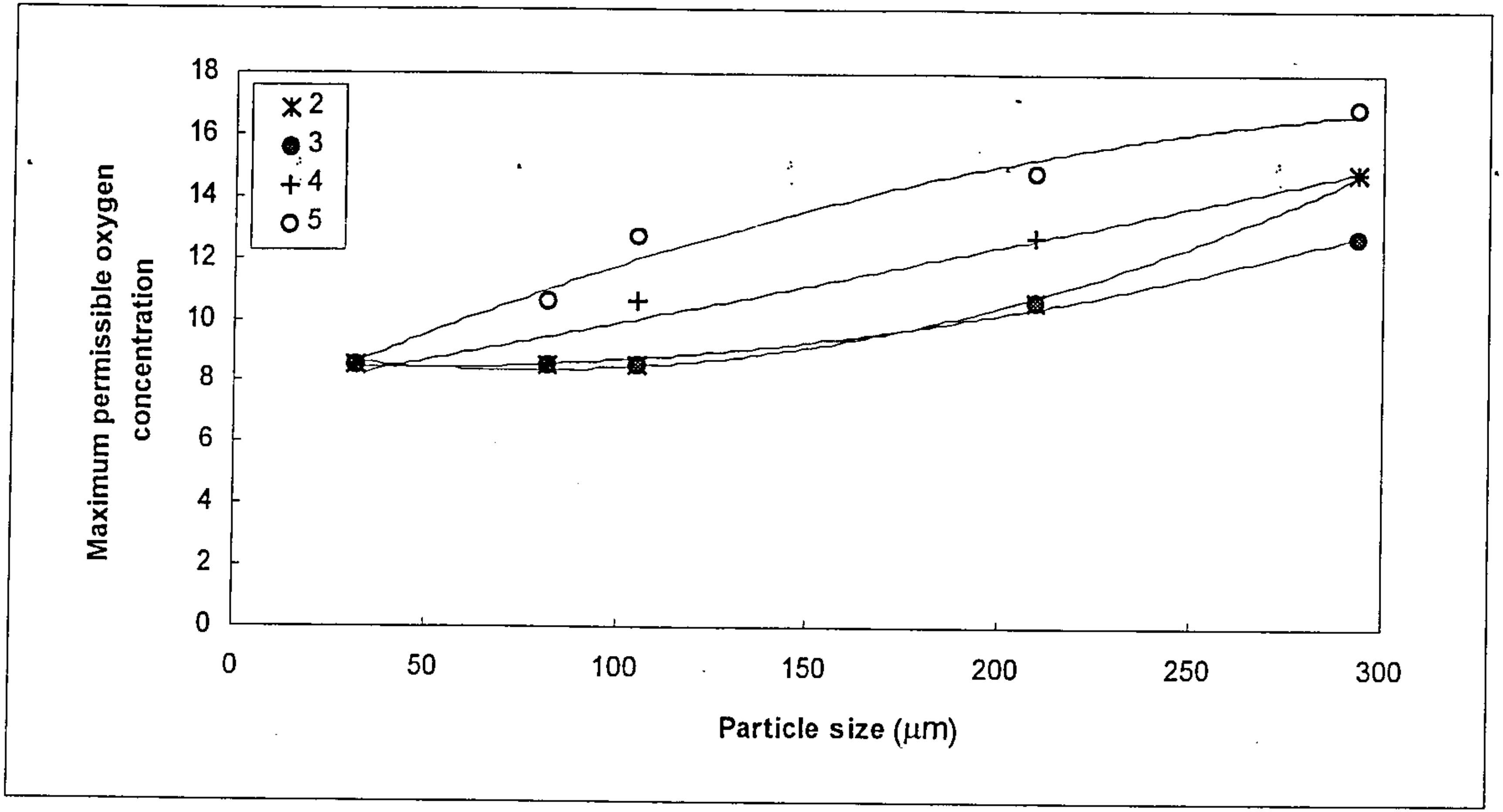

Figure (5.5): variation of maximum permissible oxygen concentration with particle size of oil shale under different concentrations.

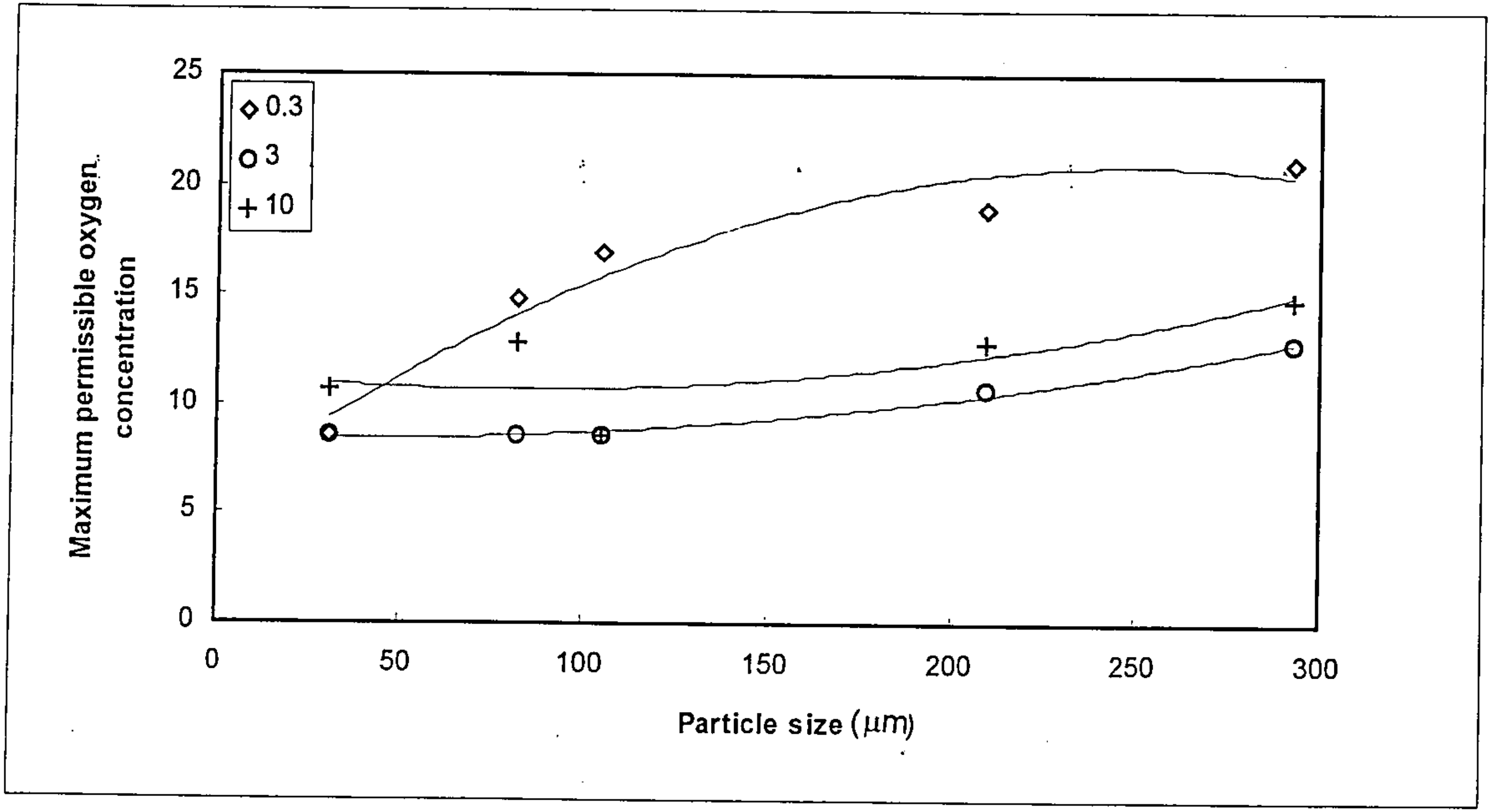

Figure (5.6): variation of maximum permissible oxygen concentration with particle size of oil shale under different concentrations.

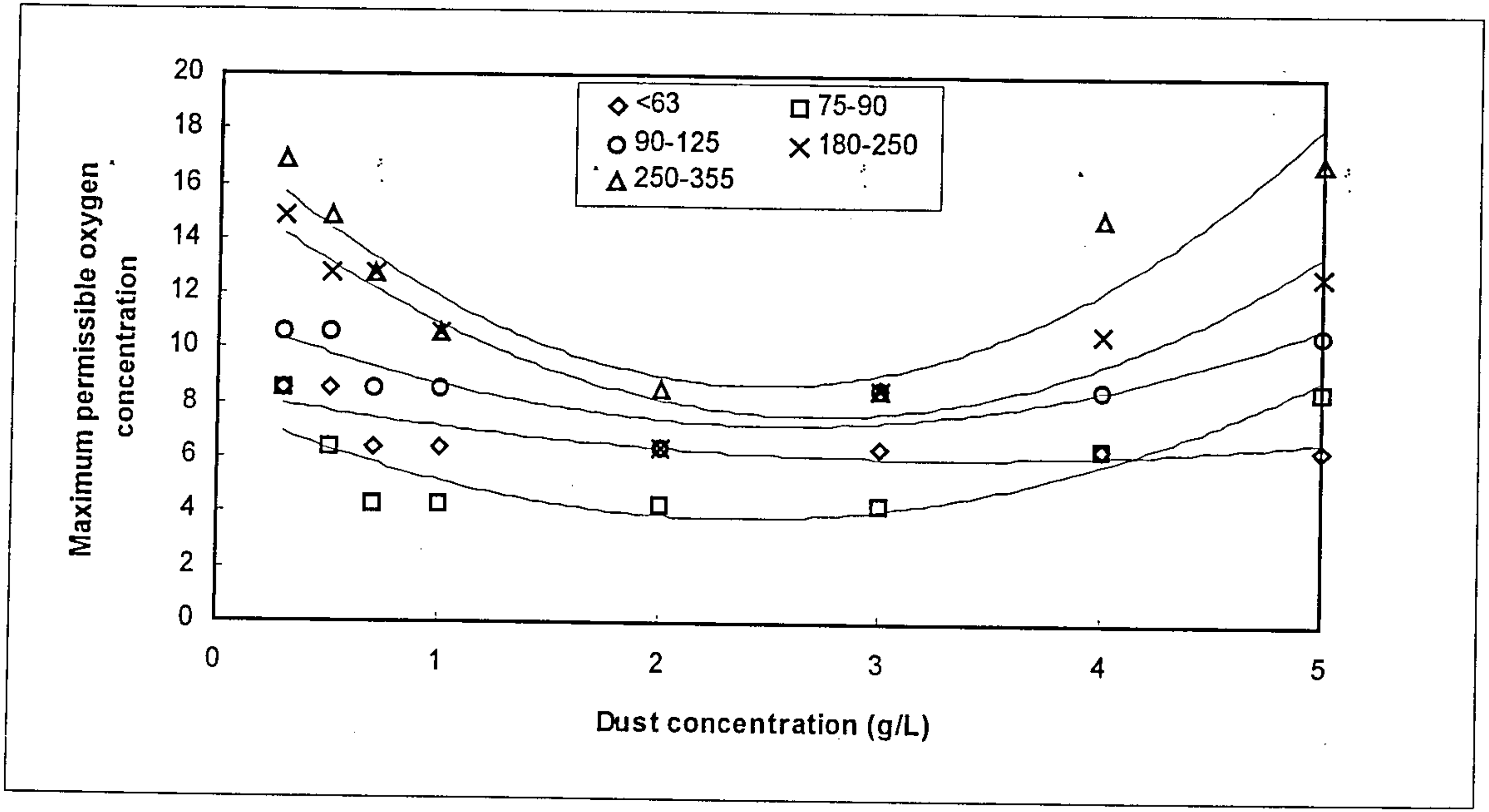

Figure (5.7): variation of maximum permissible oxygen concentration with dust concentration of olive cake with different particle sizes.

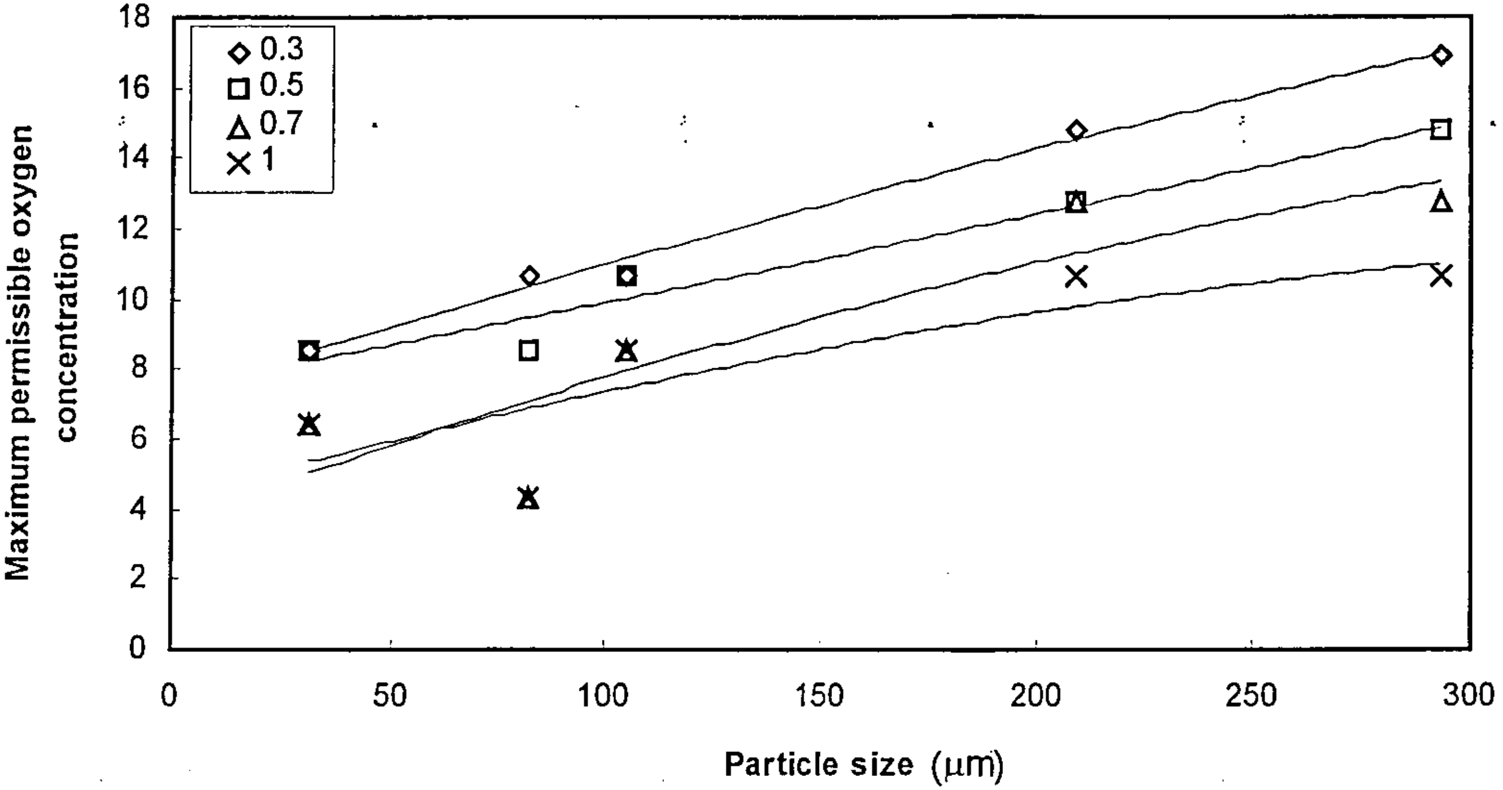

Figure (5.8): variation of maximum permissible oxygen concentration with particle size of olive cake under different concentrations.

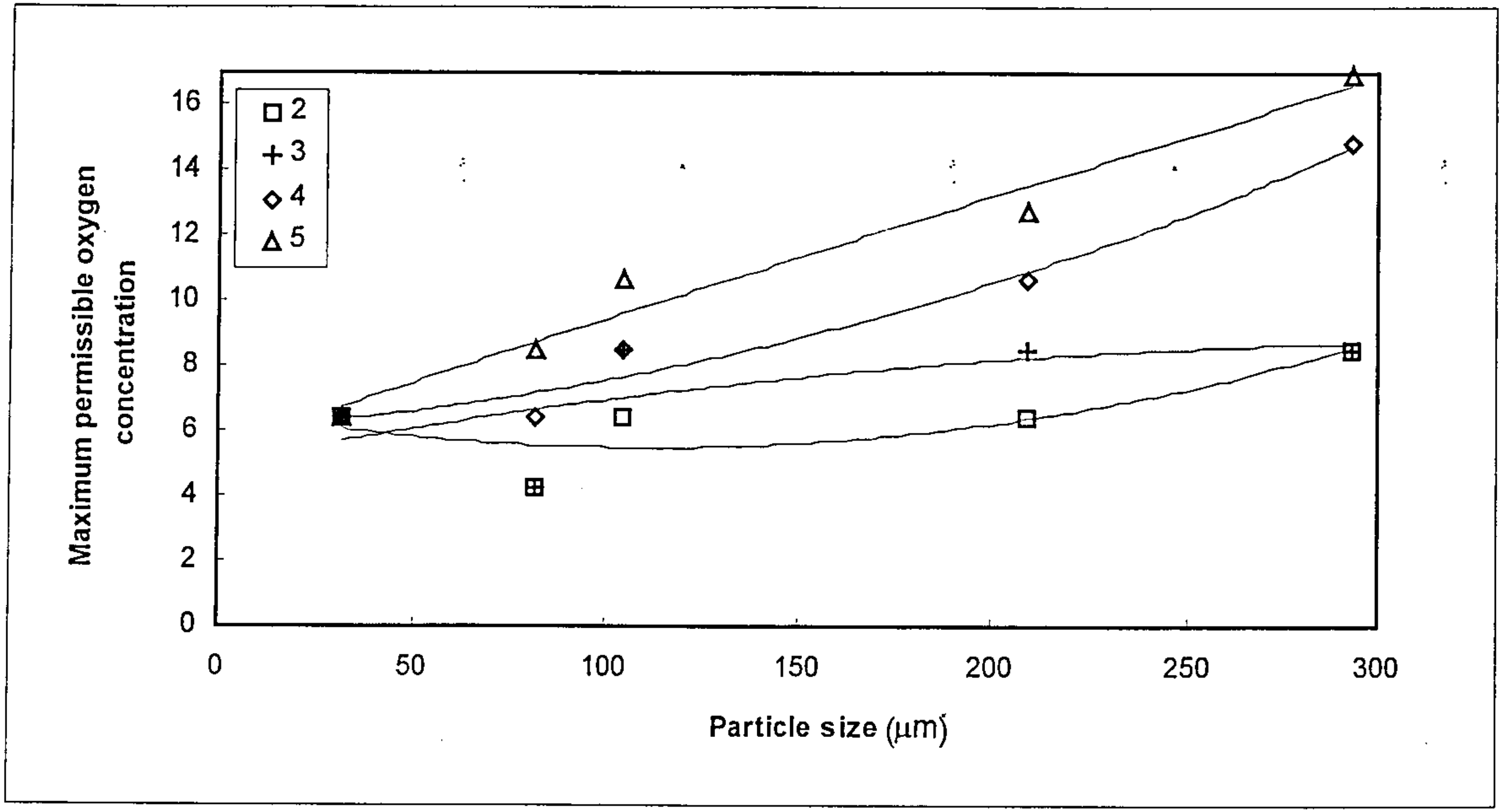

Figure (5.9): variation of maximum permissible oxygen concentration with particle size of olive cake under different concentrations.

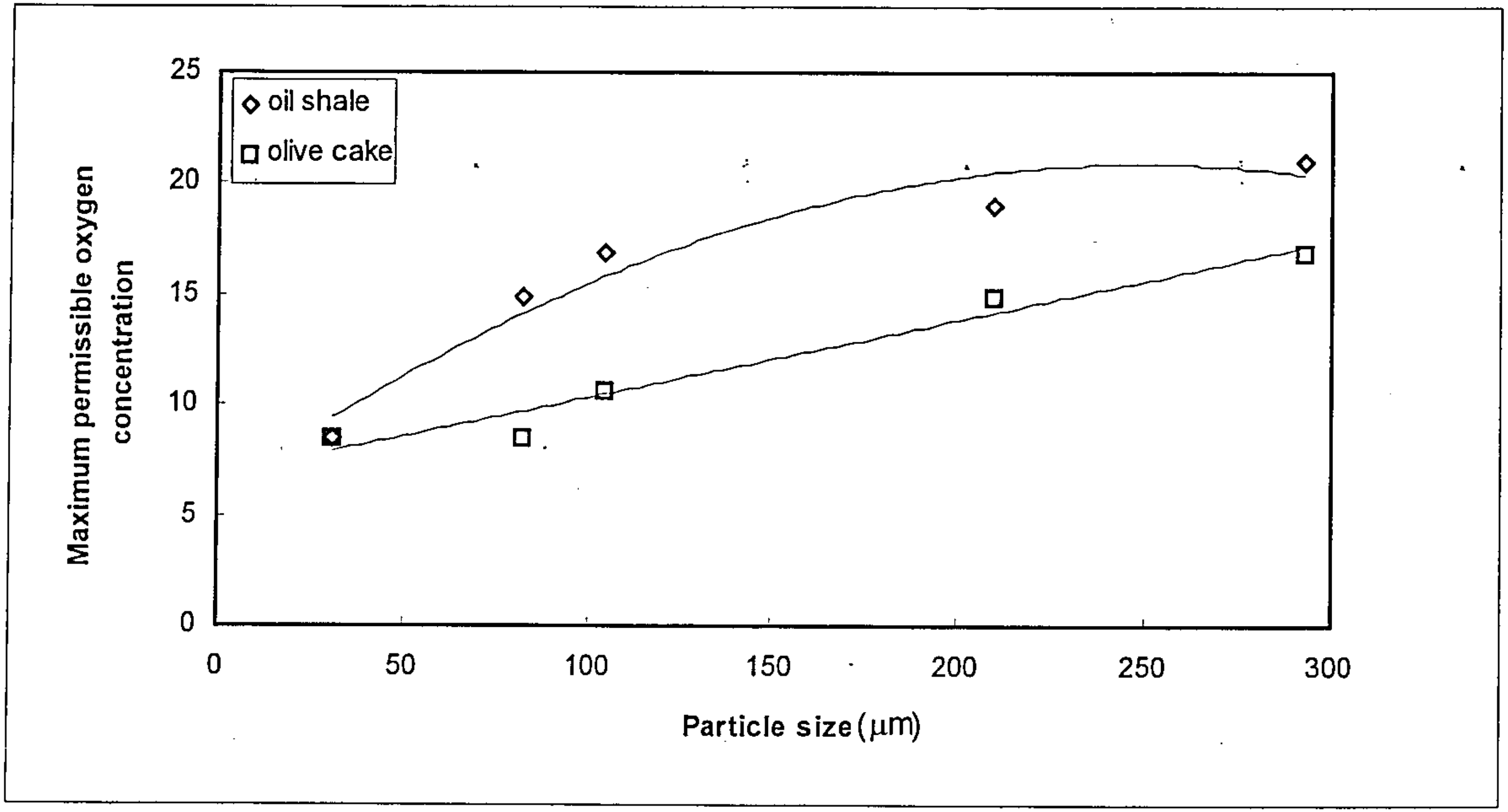

Figure (5.10):variation of maximumpermissible oxygen concentration with particle size of oil shale and olive cake at concentration of (0.3g/L)

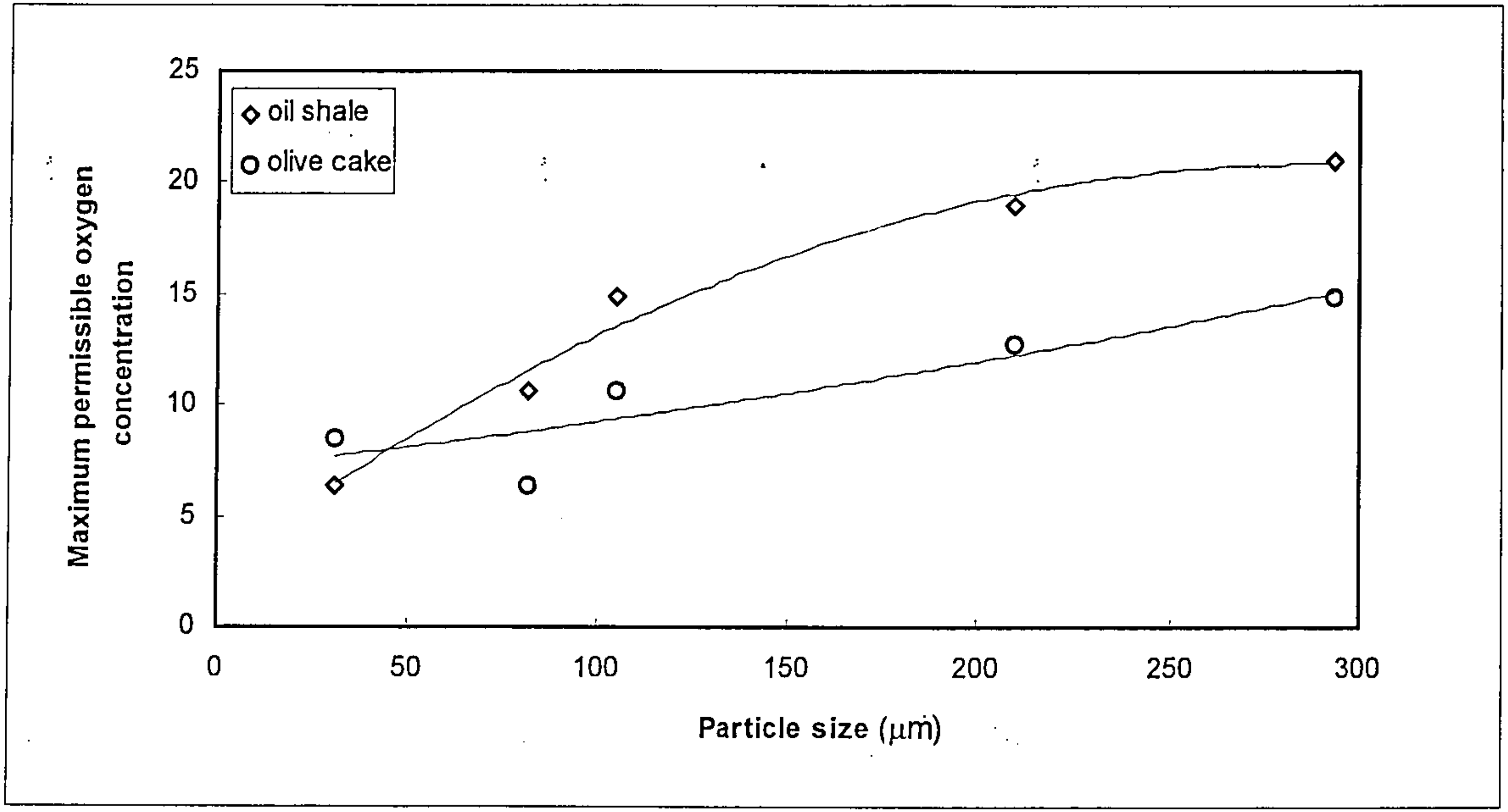

Figure (5.11):variation of maximumpermissible oxygen concentration with particle size of oil shale and olive cake at concentration of (0.5g/L)

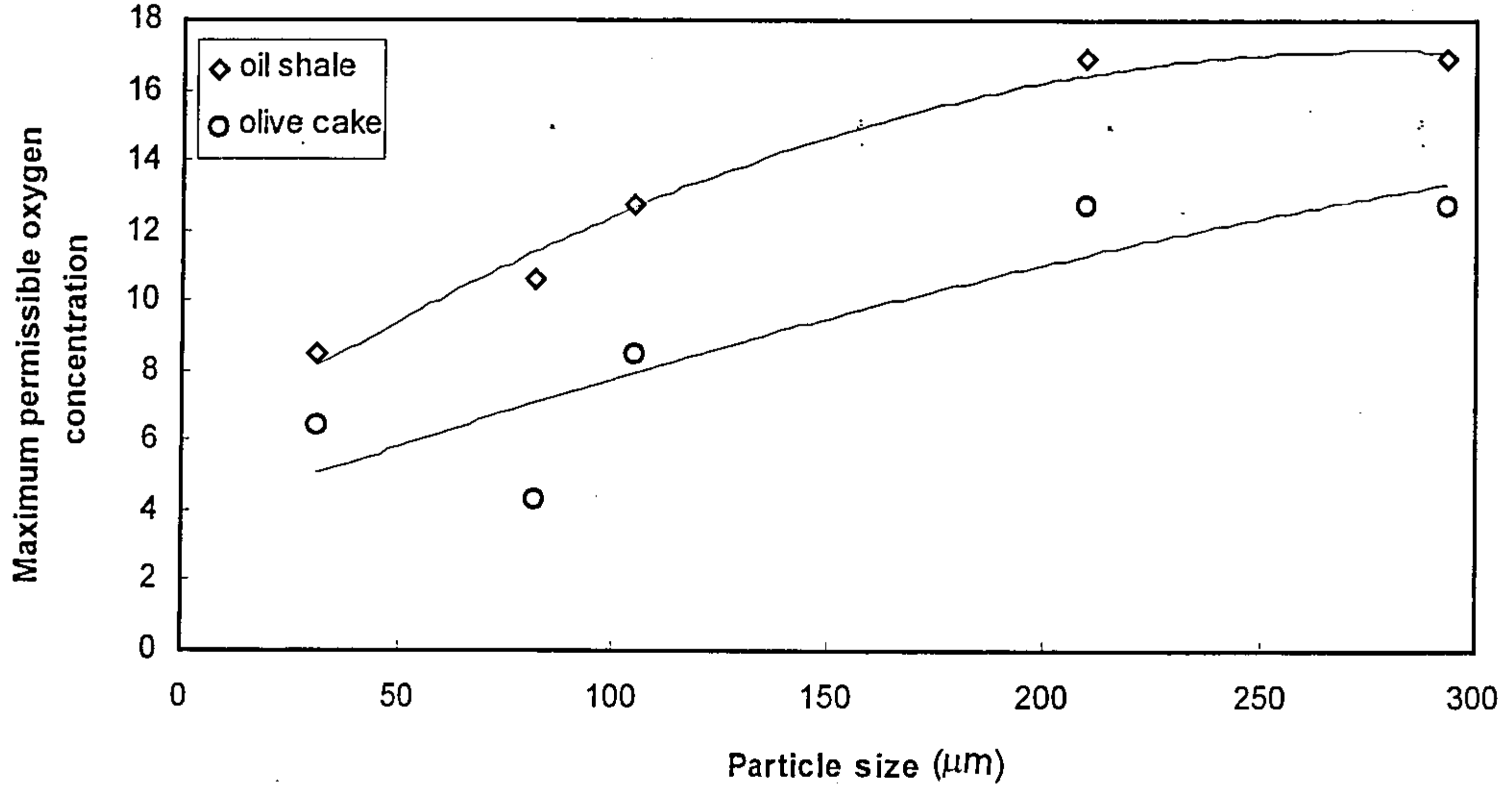

Figure (5.12):variation of maximumpermissible oxygen concentration with particle size of oil shale and olive cake at concentration of (0.7g/L)

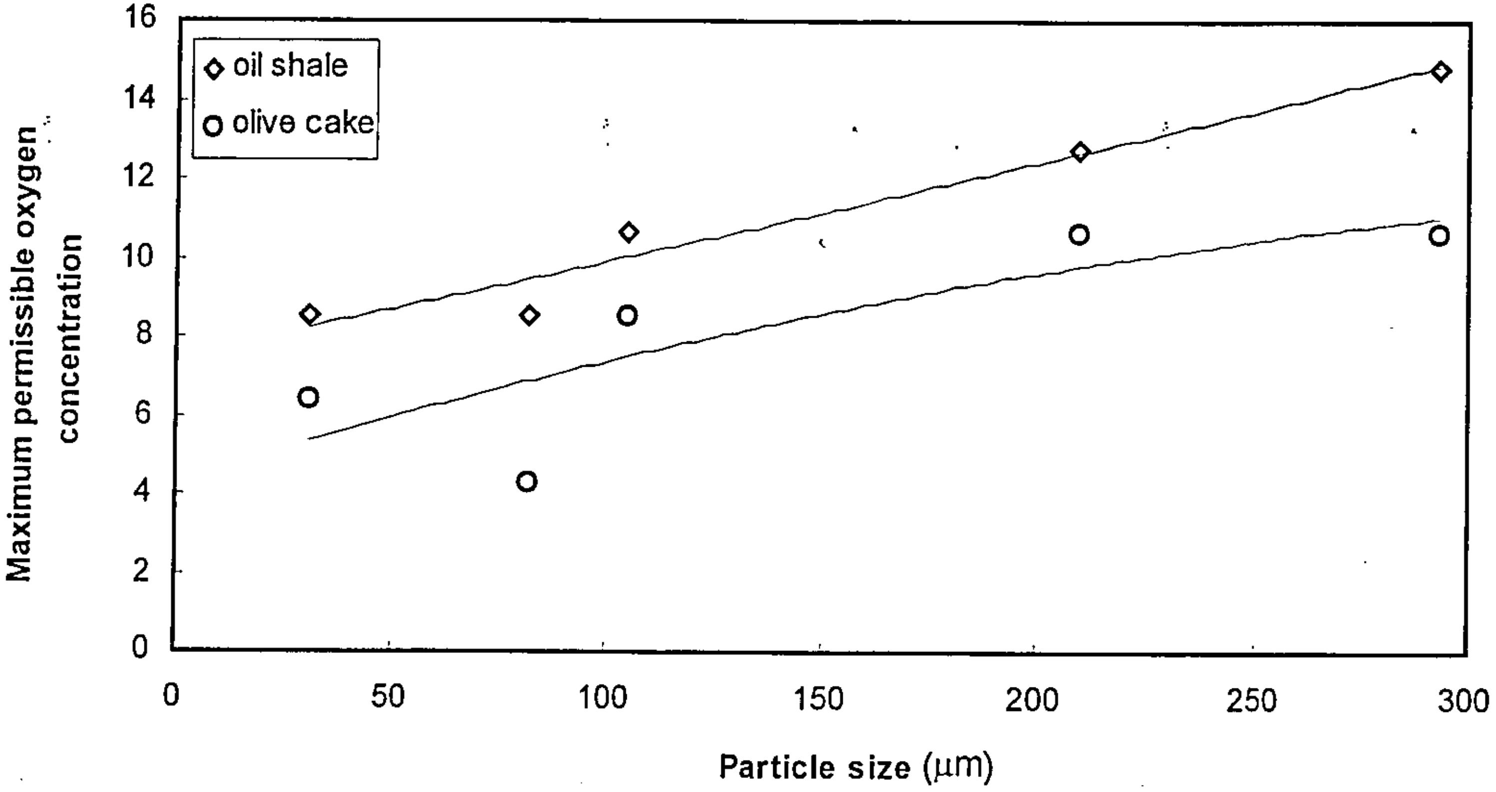

Figure (5.13):variation of maximumpermissible oxygen concentration with particle size of oil shale and olive cake at concentration of (1.0g/L)

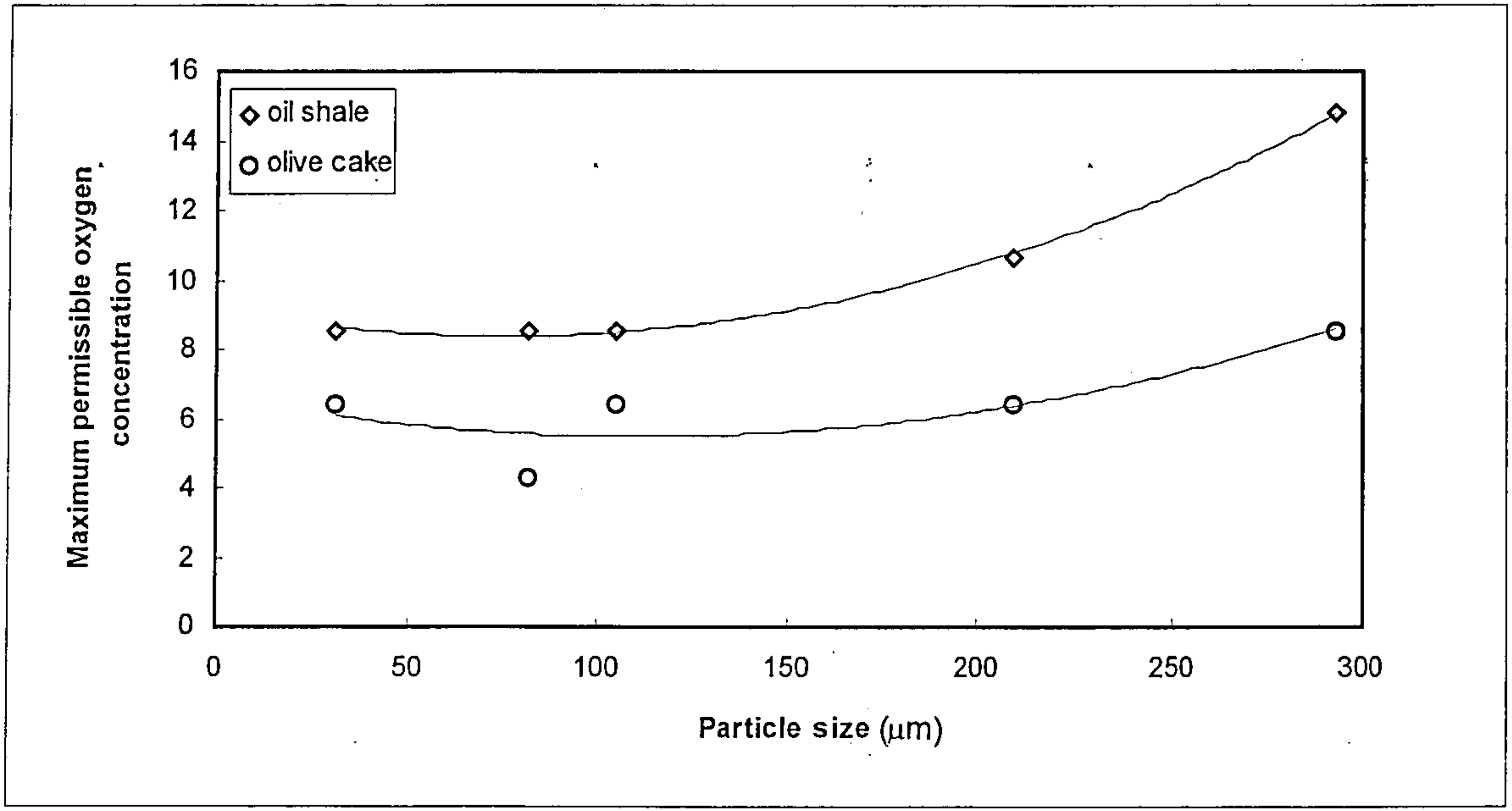

Figure (5.14):variation of maximumpermissible oxygen concentration with particle size of oil shale and olive cake at concentration of (2.0g/L)

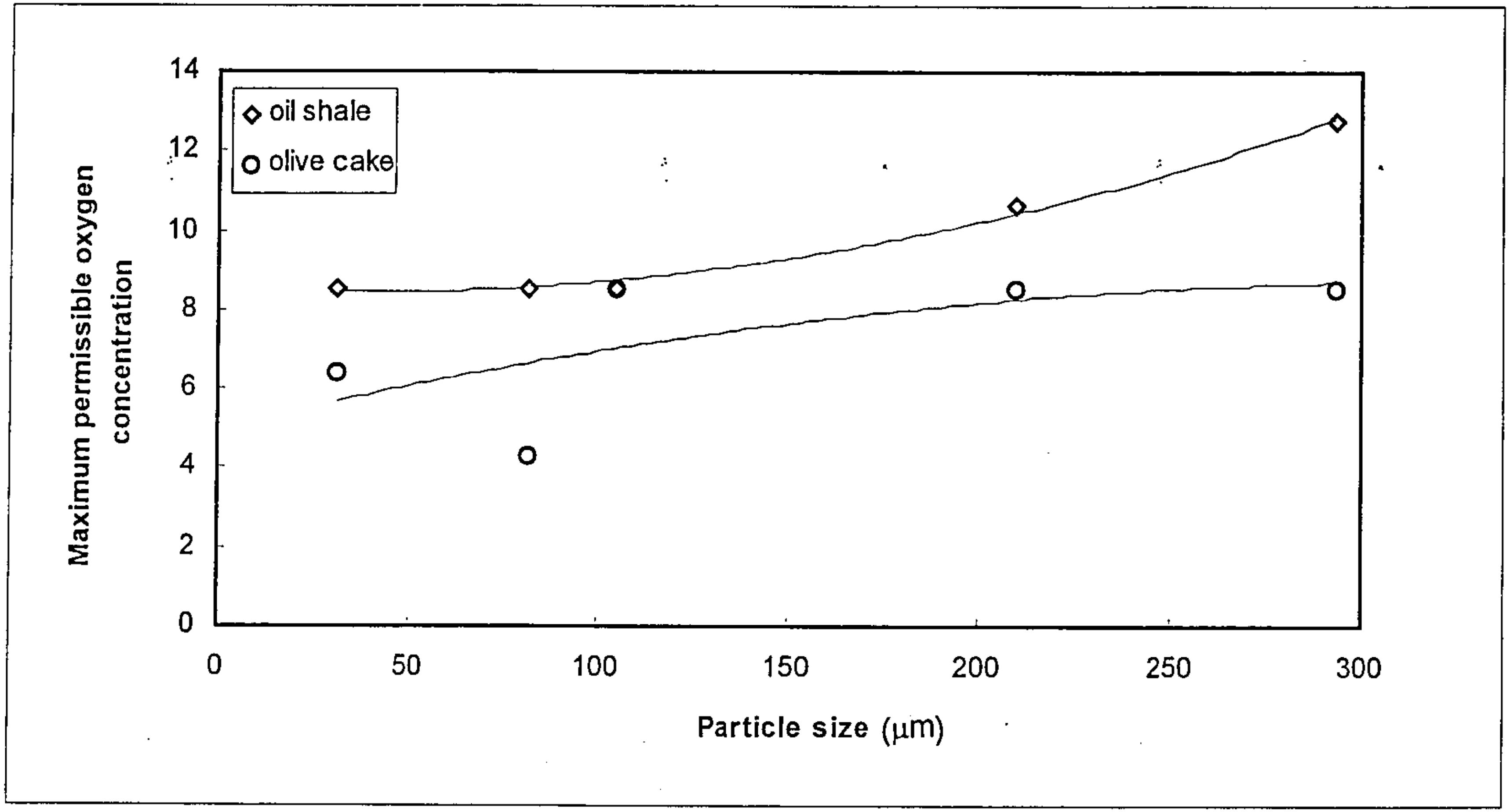

Figure (5.15):variation of maximumpermissible oxygen concentration with particle size of oil shale and olive cake at concentration of (3.0g/L)

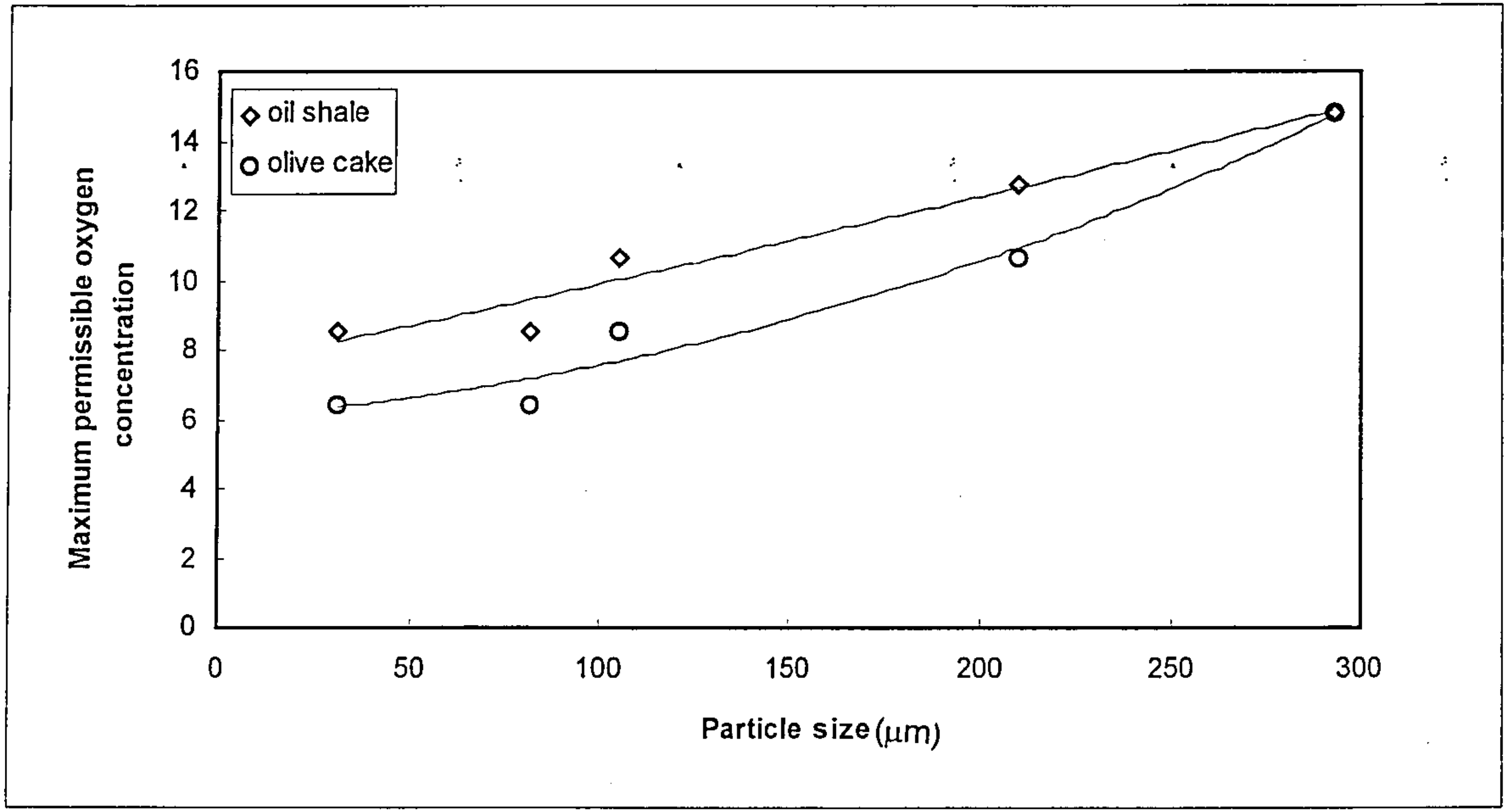

Figure (5.16):variation of maximumpermissible oxygen concentration with particle size of oil shale and olive cake at concentration of (4.0g/L)

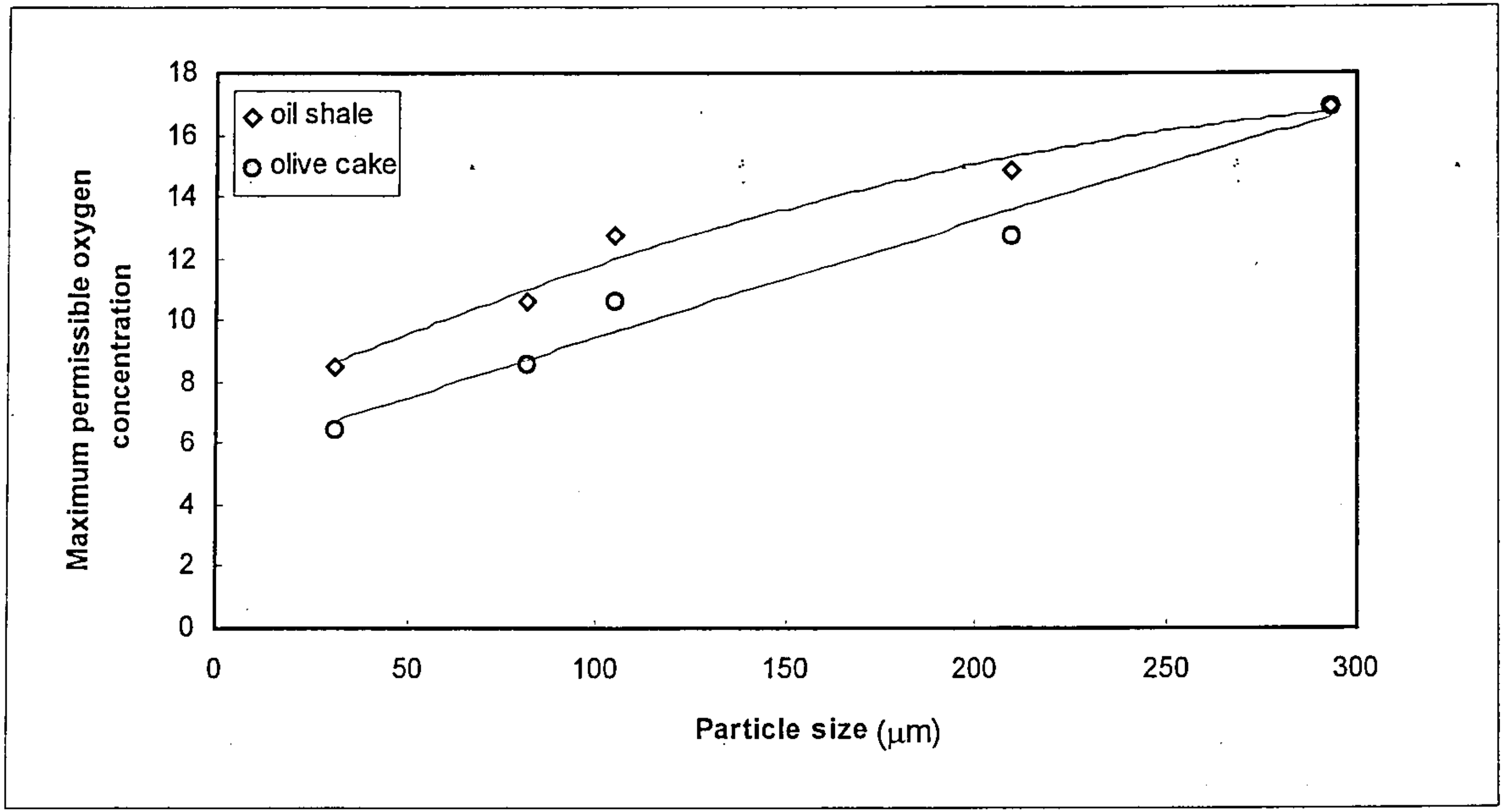

Figure (5.17):variation of maximumpermissible oxygen concentration with particle size of oil shale and olive cake at concentration of (5.0g/L)

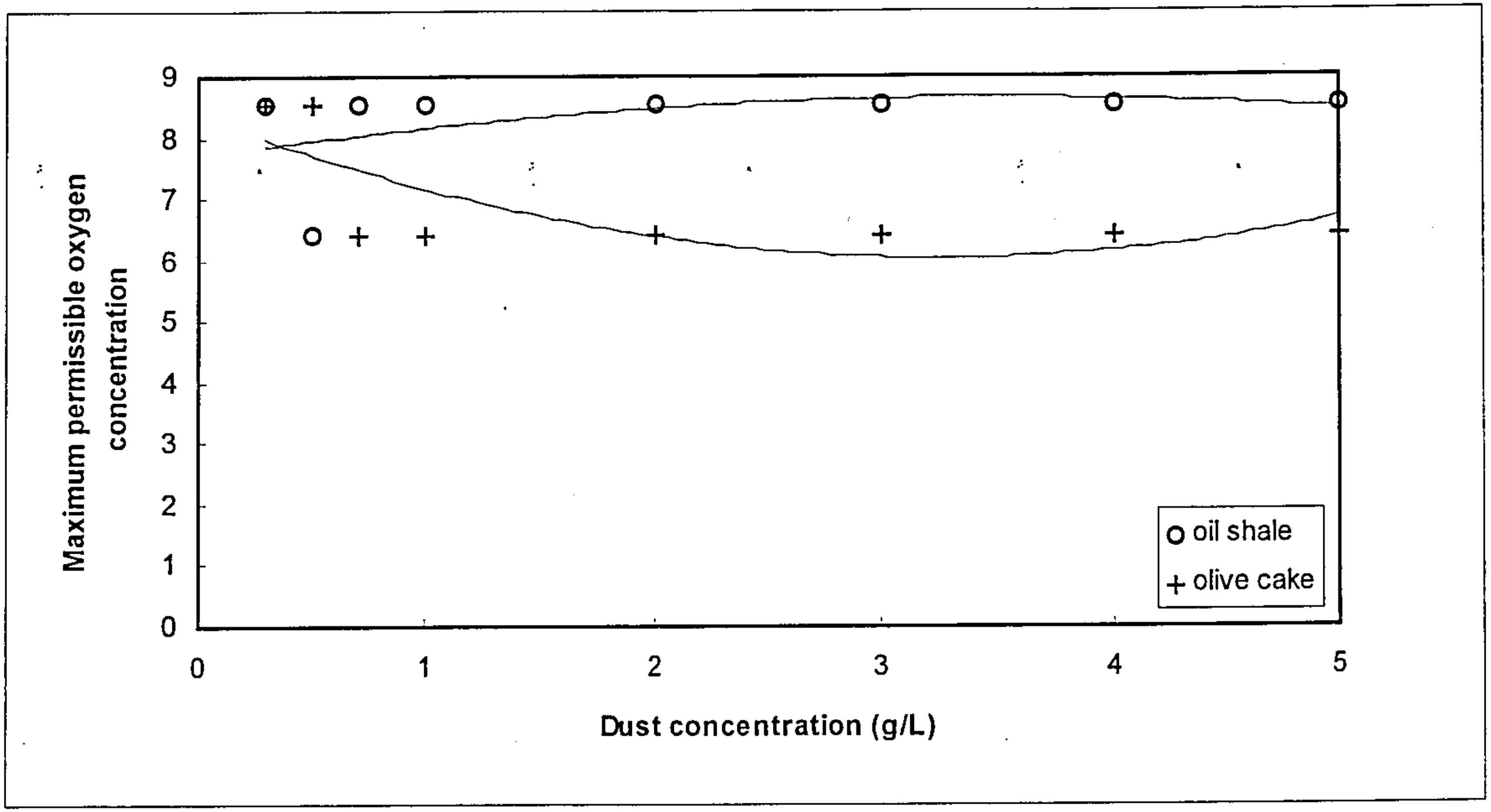

Figure (5.18):variation of maximum permissible oxygen concentration with dust concentration for oil shale and olive cake for particle size (<63μm)

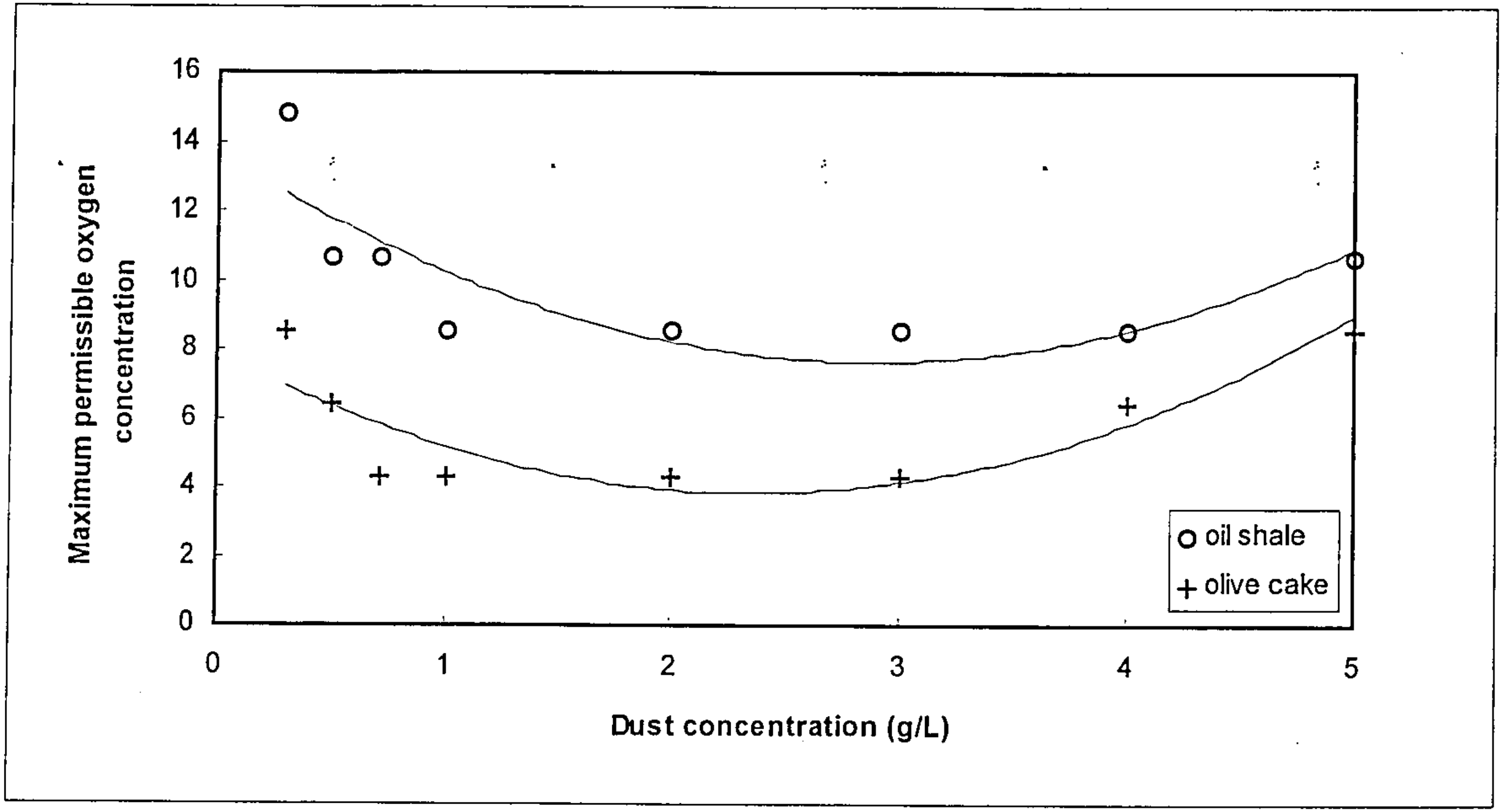

Figure (5.19):variation of maximum permissible oxygen concentration with dust concentration for oil shale and olive cake for particle size (75-90 μm)

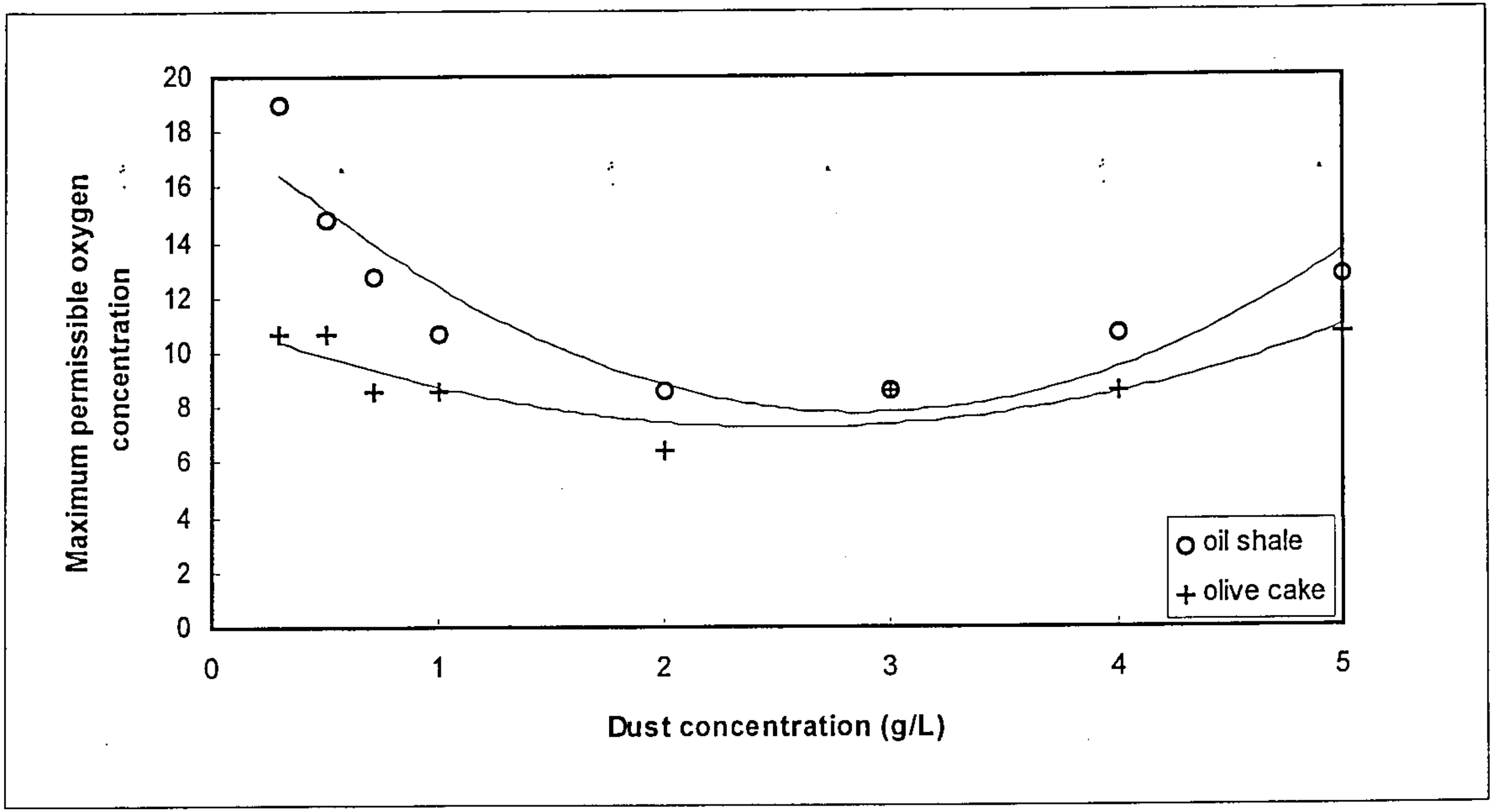

Figure (5.20):variation of maximum permissible oxygen concentration with dust concentration for oil shale and olive cake for particle size (90-125 μm)

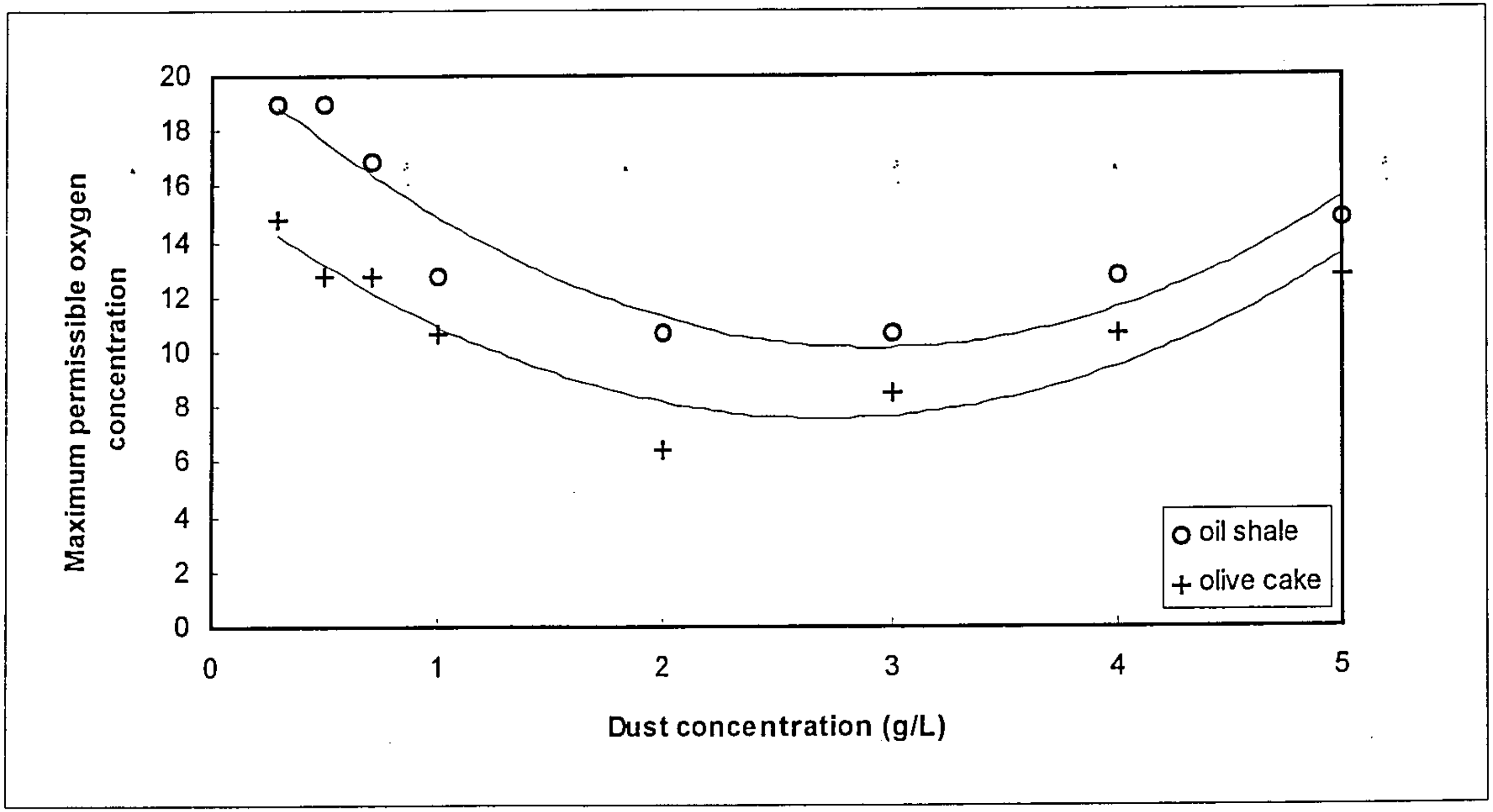

Figure (5.21):variation of maximum permissible oxygen concentration with dust concentration for oil shale and olive cake for particle size (180-250 μm)

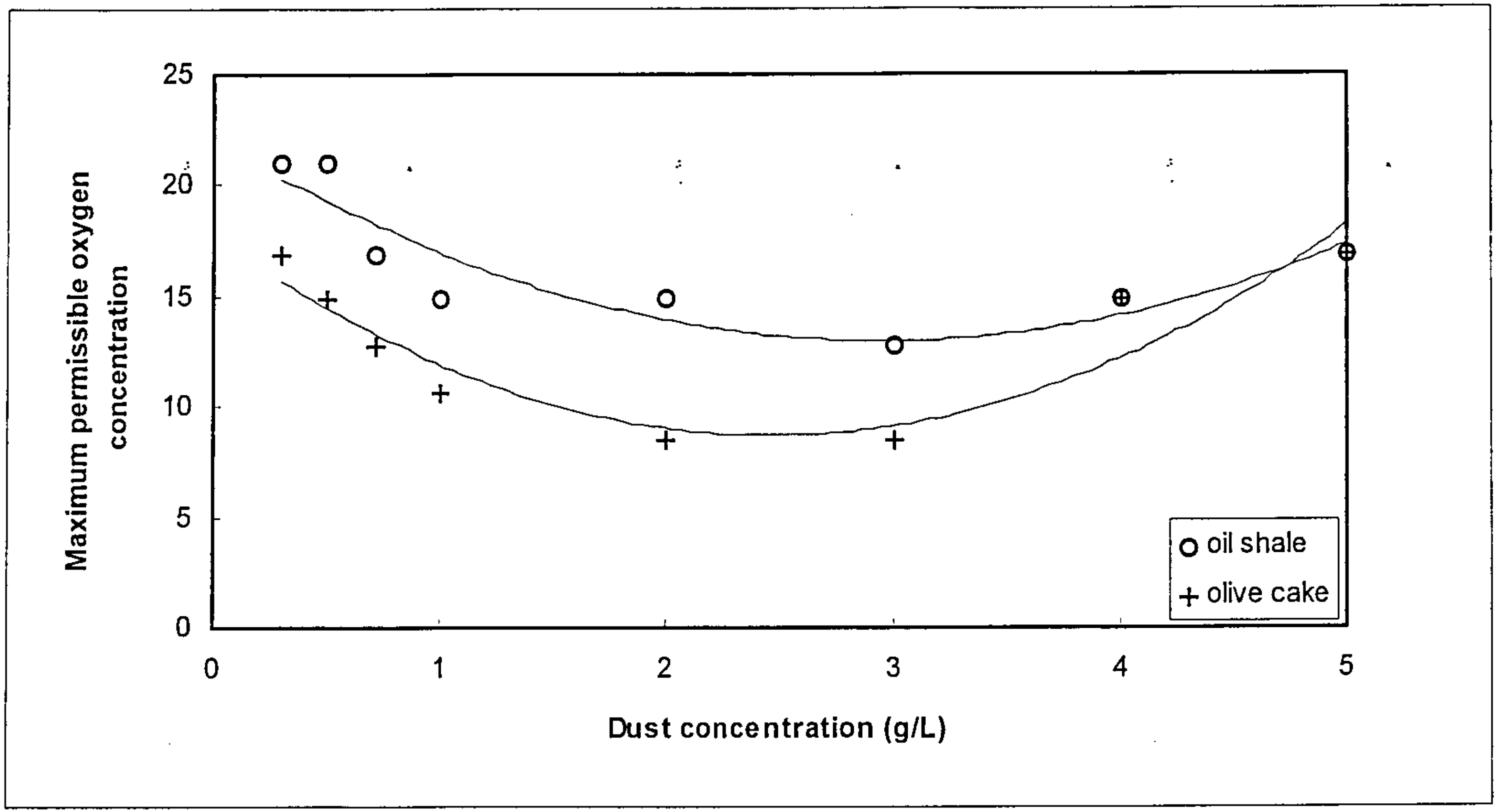

Figure (5.22):variation of maximum permissible oxygen concentration with dust concentration for oil shale and olive cake for particle size (250-355 μm)

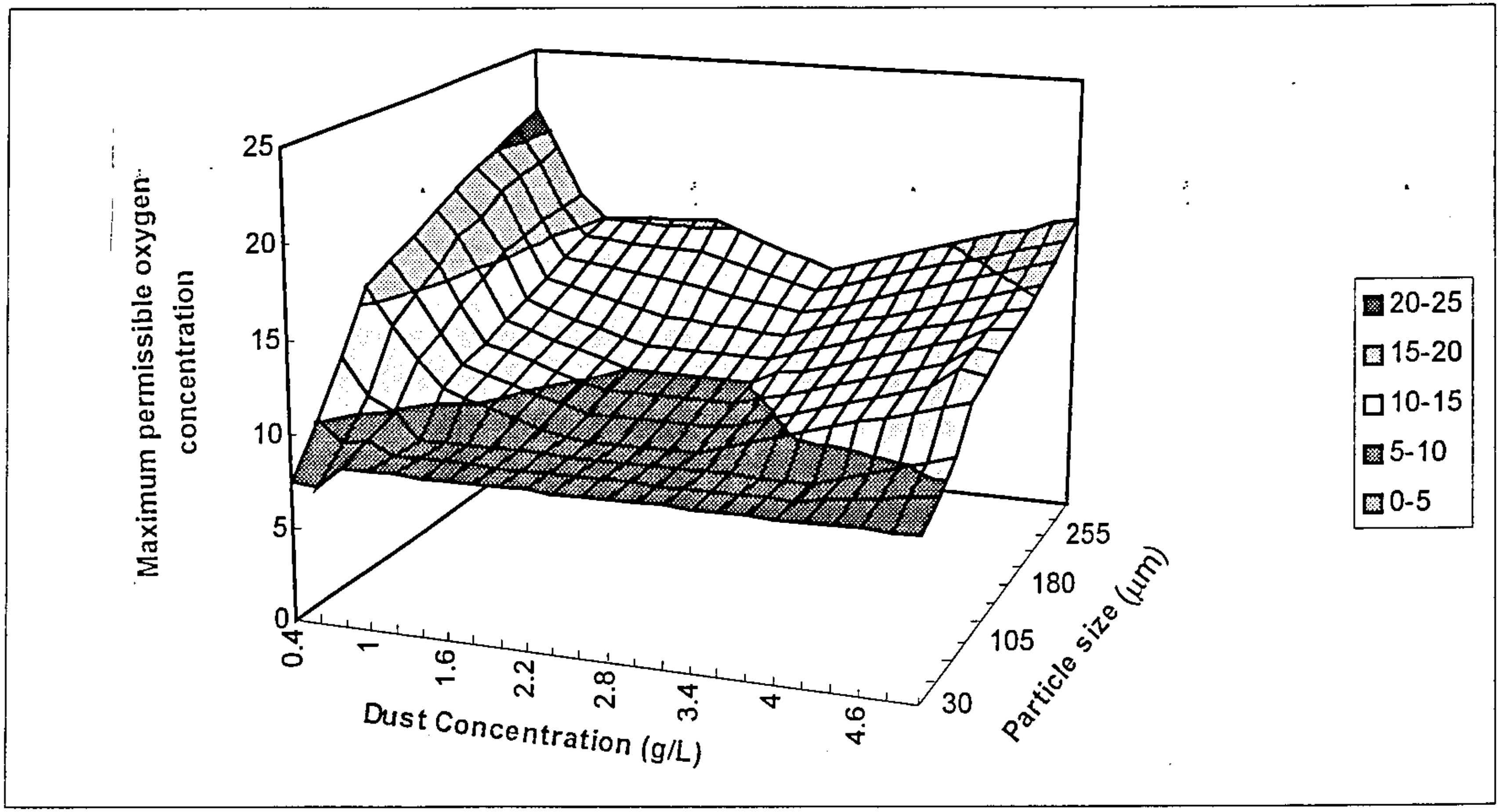

Figure (5.23):variation of maximum permissible oxygen concentration with both particle size and dust concentration for oil shale (3-dimensional representation)

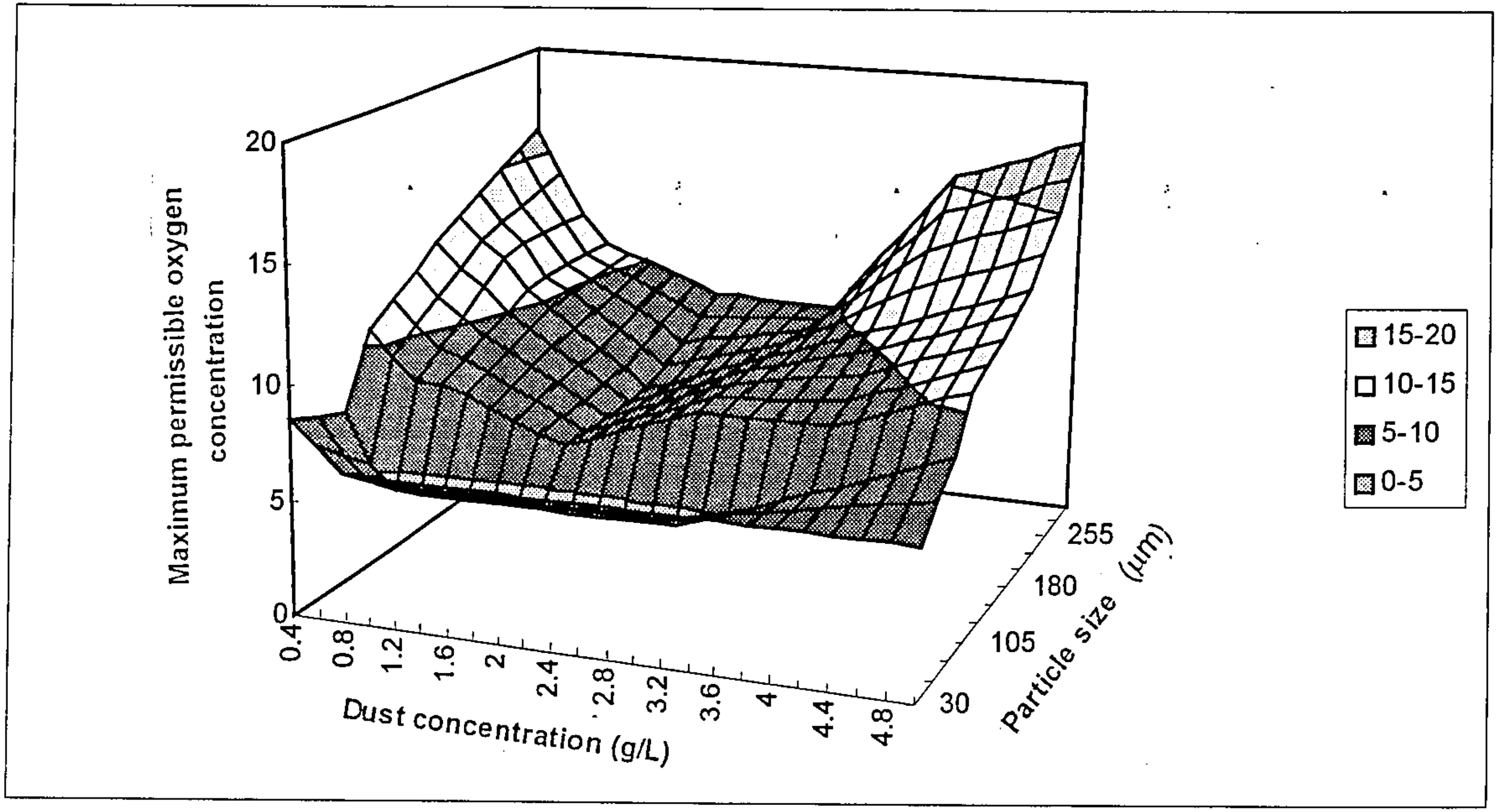

Figure (5.24):variation of maximum permissible oxygen concentration with both particle size and dust concentration for olive cake (3-dimensional representation)

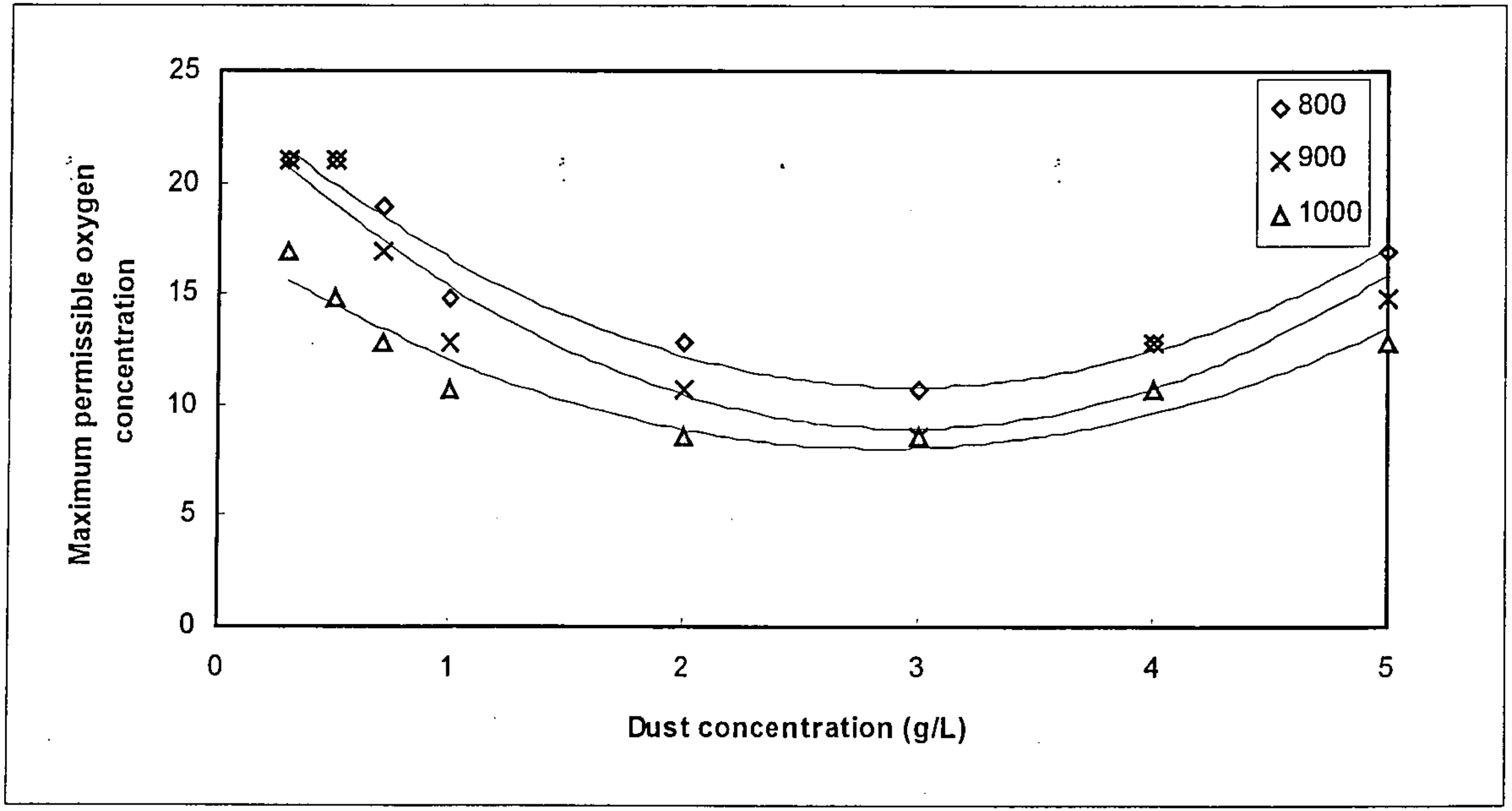

Figure (5.25):variation of maximum permissible oxygen concentration with dust concentration of oil shale for different temperatures

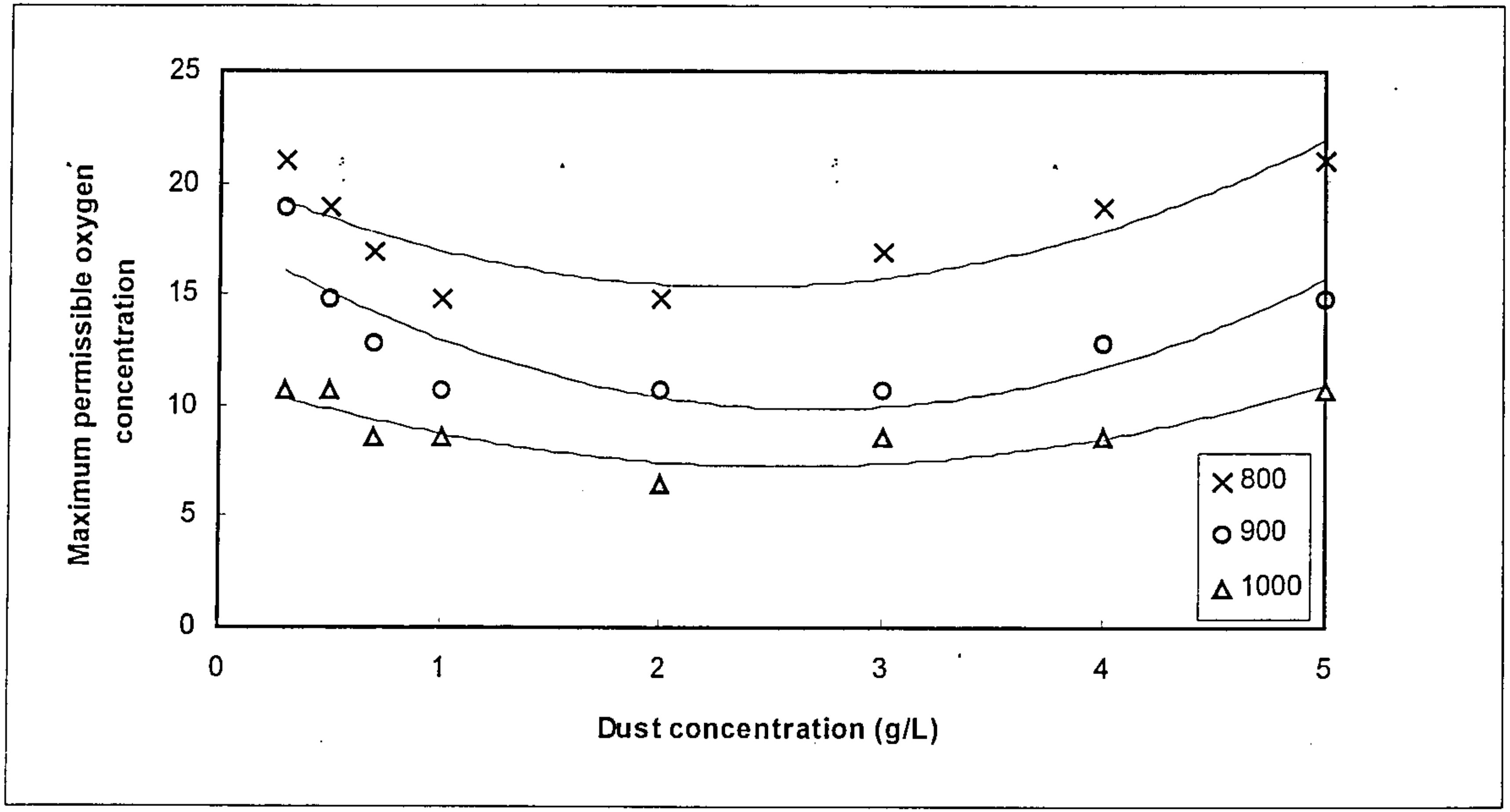

Figure (5.26):variation of maximum permissible oxygen concentration with dust concentration for olive cake different temperatures

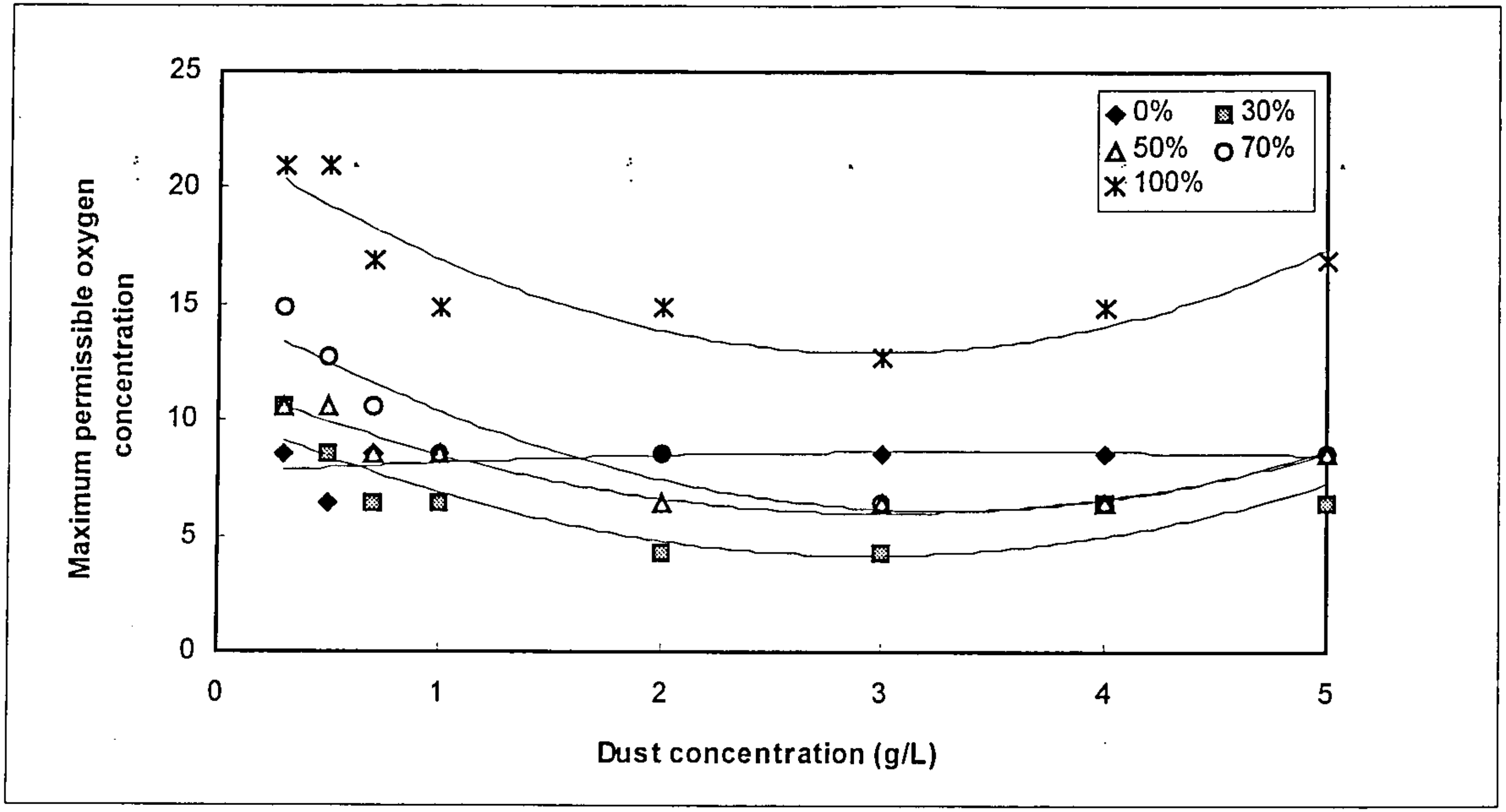

Figure (5.27): variation of maximum permissible oxygen concentration with dust concentration of oil shale for different weight percents of coarse particles in the mixtures

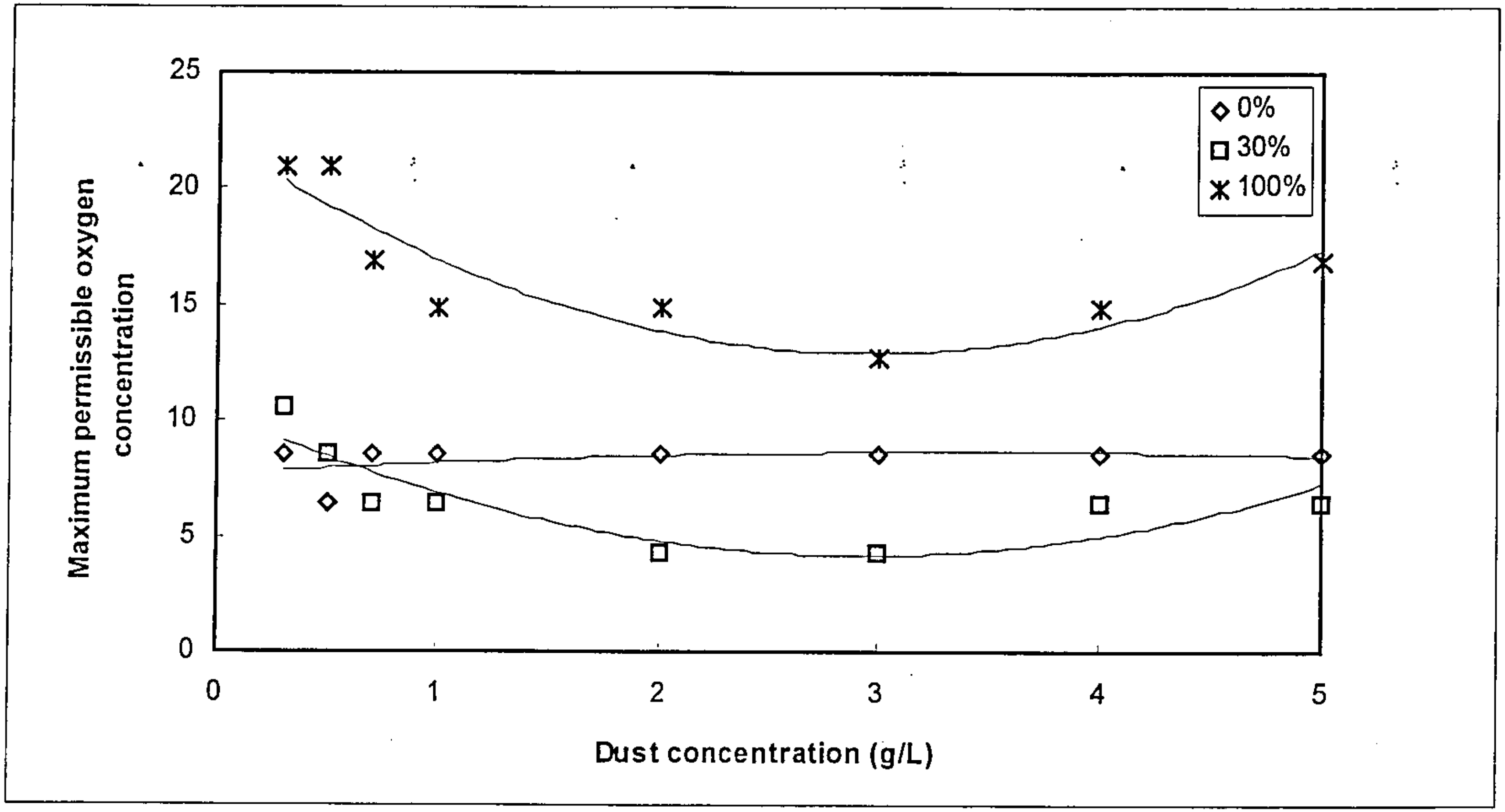

Figure (5.28): variation of maximum permissible oxygen concentration with dust concentration of oil shale for different weight percents of coarse particles in the mixtures

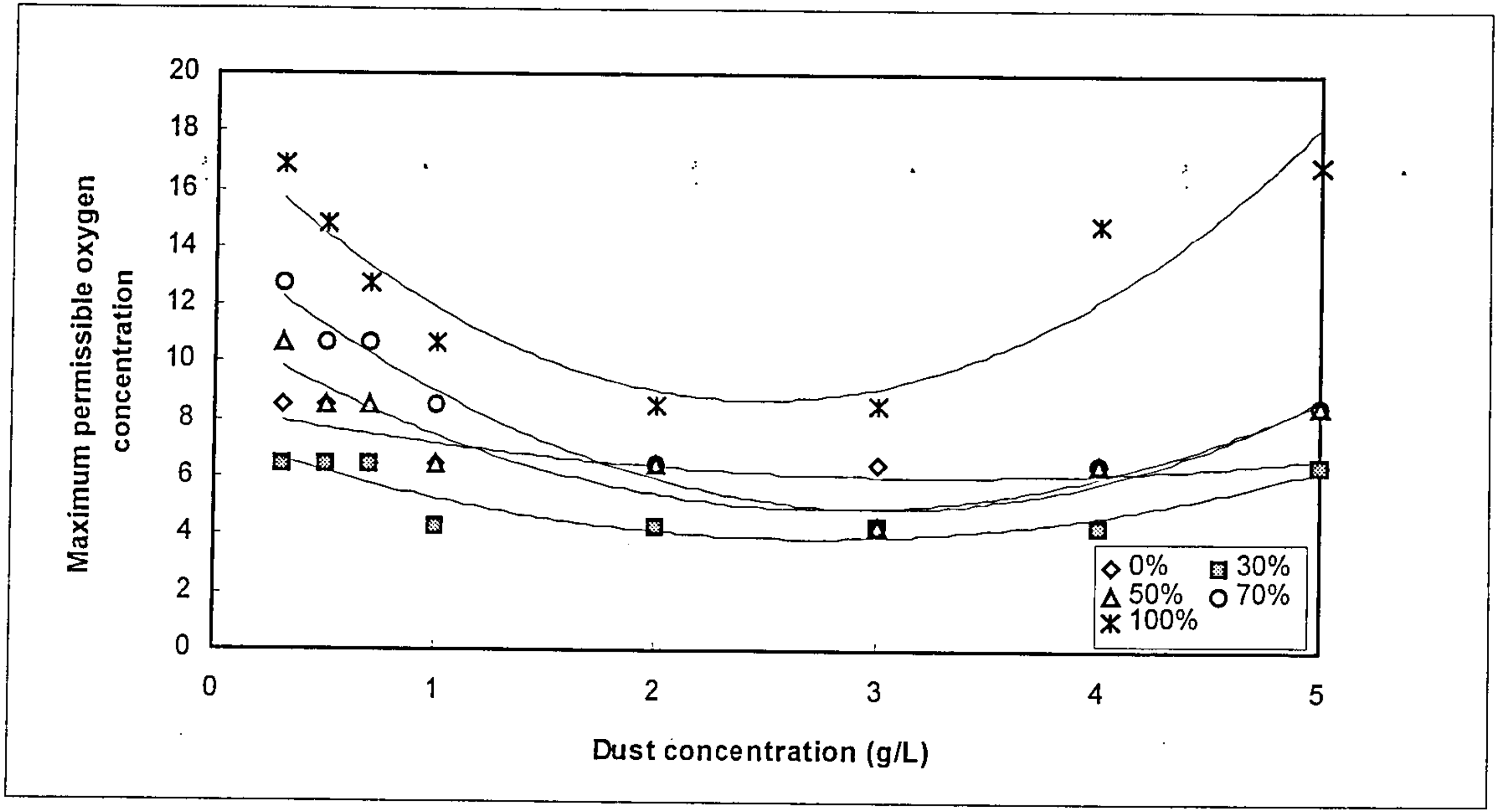

Figure (5.29): variation of maximum permissible oxygen concentration with dust concentration of olive cake for different weight percents of coarse particles in the mixtures

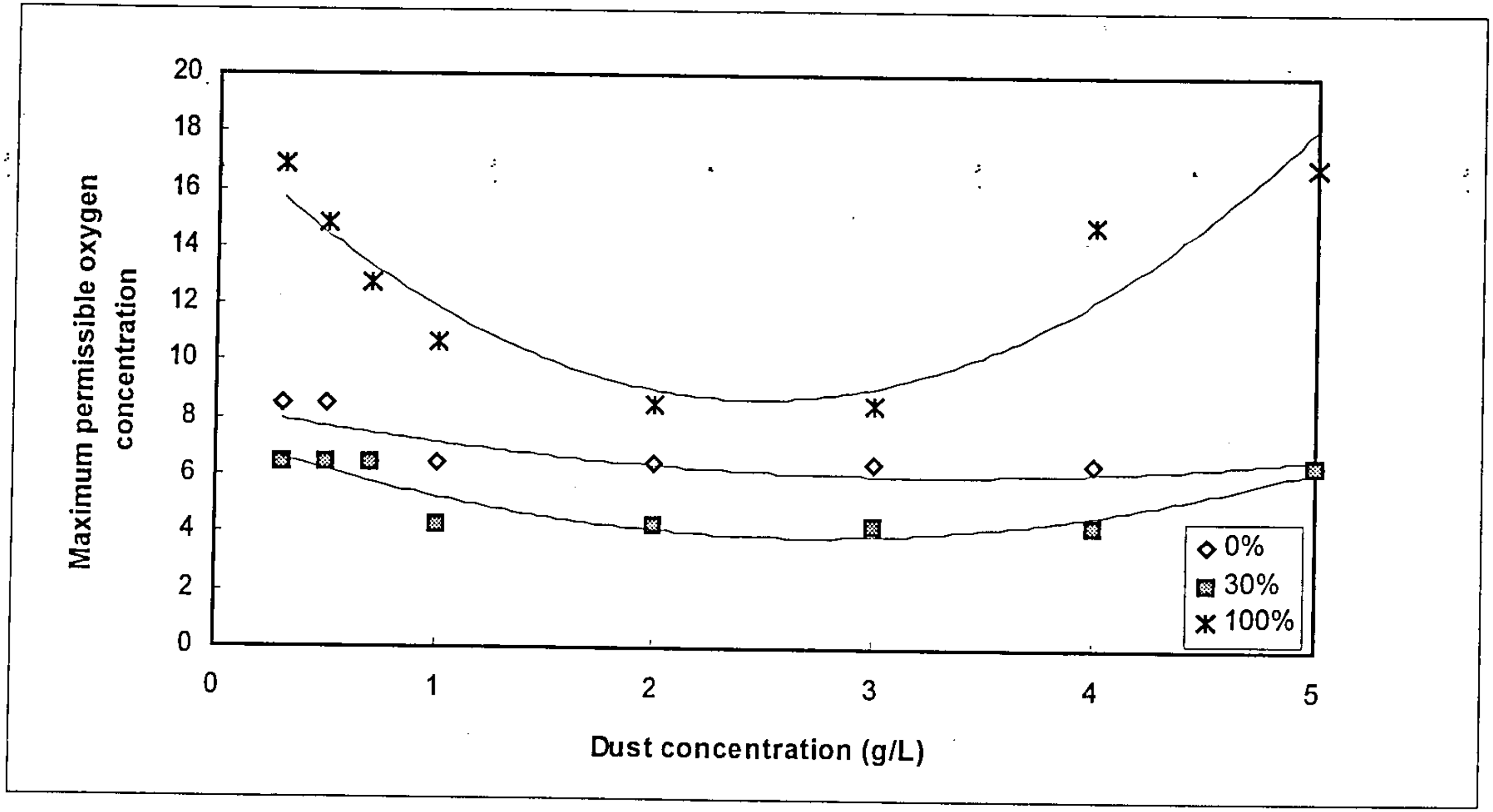

Figure (5.30): variation of maximum permissible oxygen concentration with dust concentration of olive cake for different weight percents of coarse particles in the mixtures

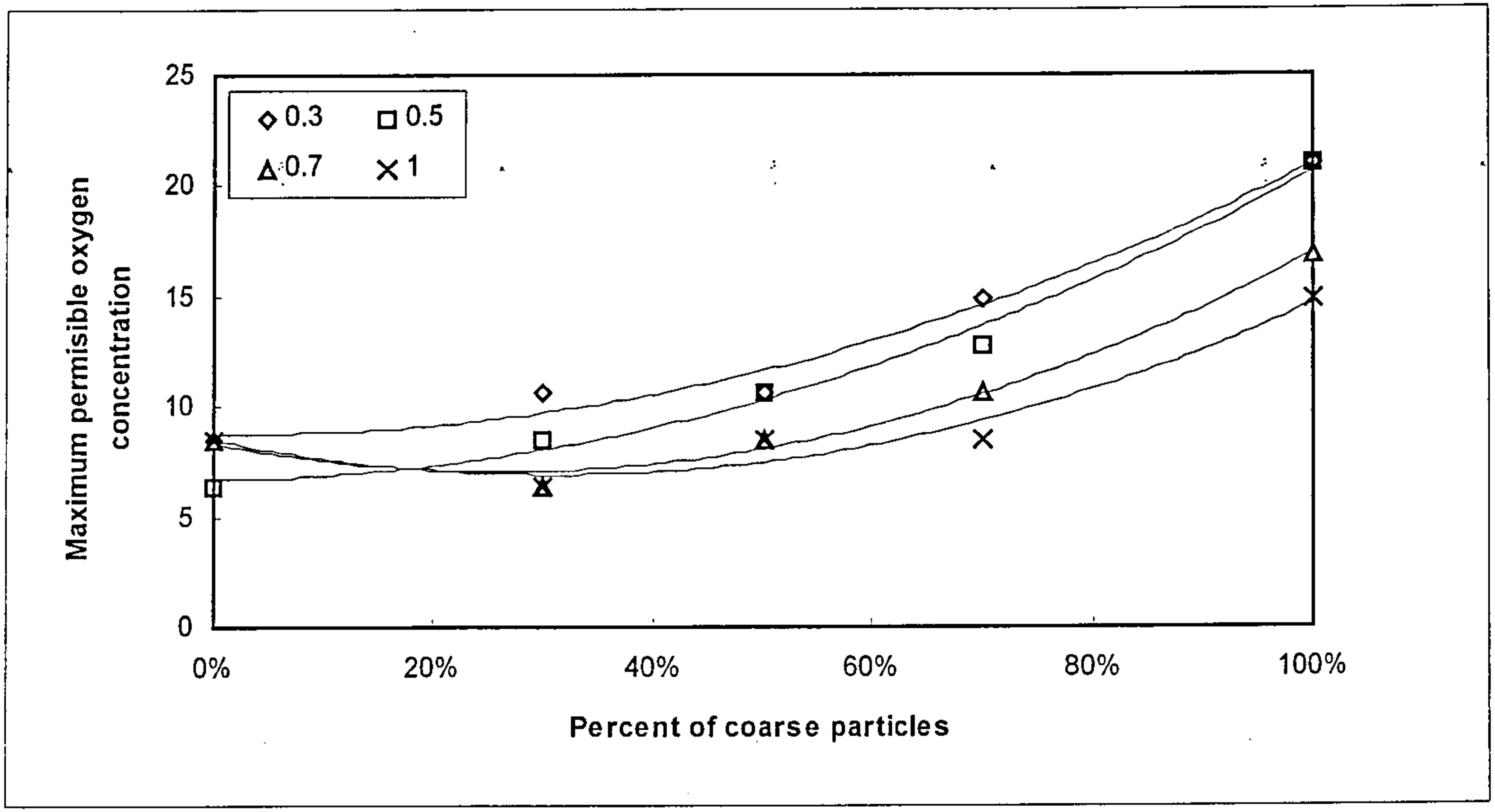

Figure (5.31): variation of maximum permissible oxygen concentration with percent of coarse particles in the mixtures of oil shale for different dust concentration

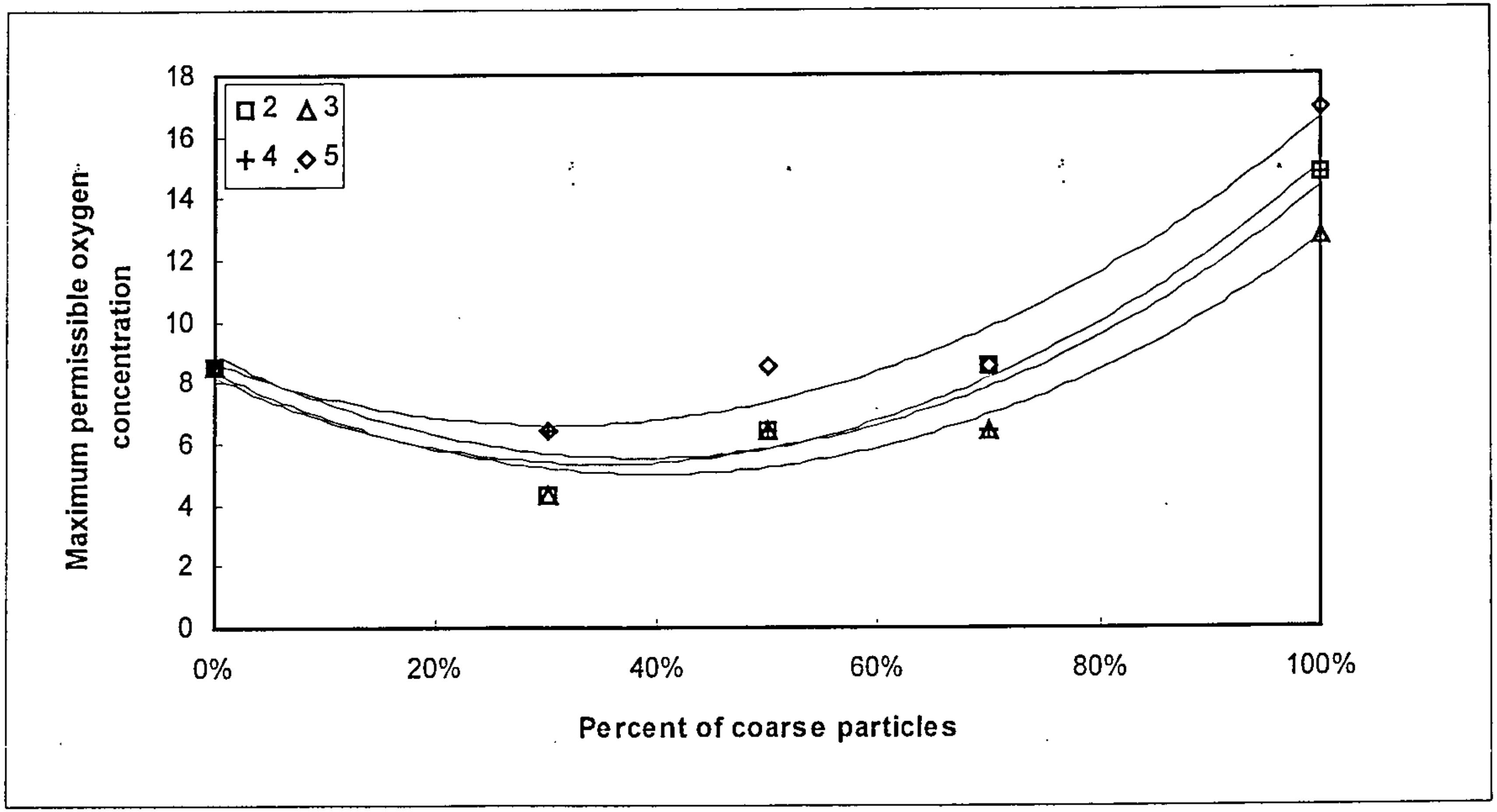

Figure (5.32): variation of maximum permissible oxygen concentration with percent of coarse particles in the mixtures of oil shale for different dust concentration

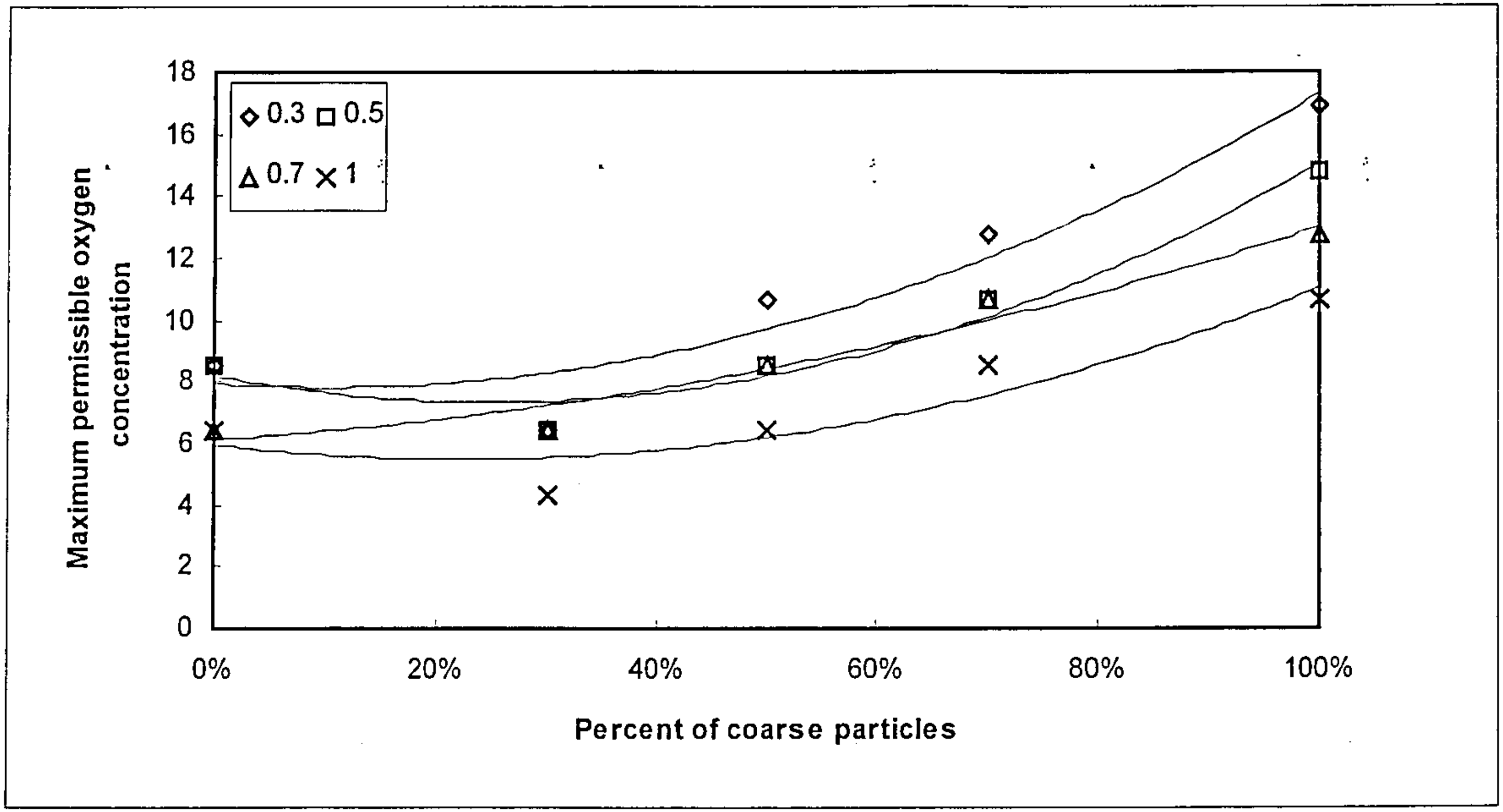

Figure (5.33): variation of maximum permissible oxygen concentration with percent of coarse particles in the mixtures of olive cake for different dust concentration

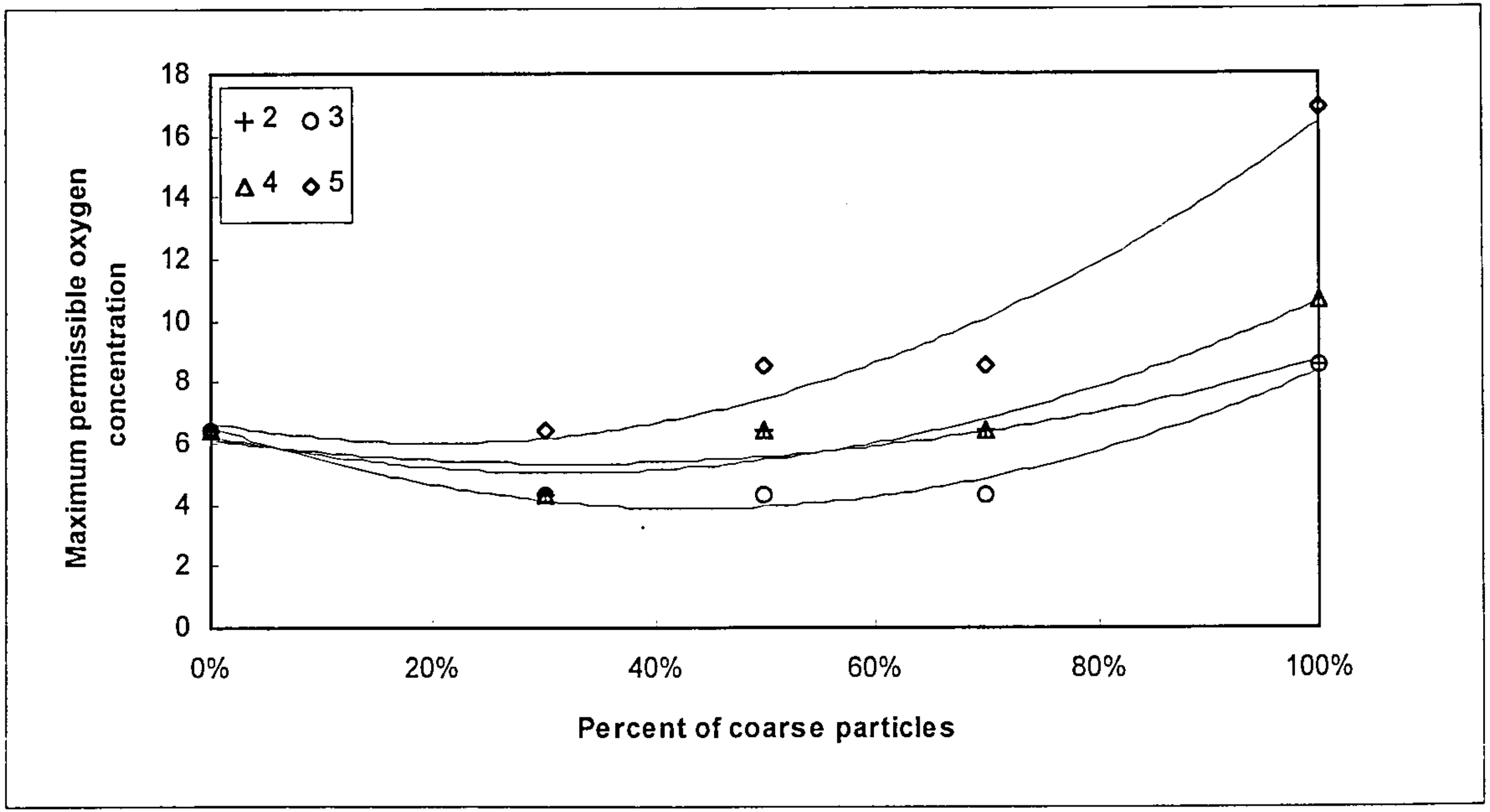

Figure (5.34): variation of maximum permissible oxygen concentration with percent of coarse particles in the mixture of olive cake for different dust concentration

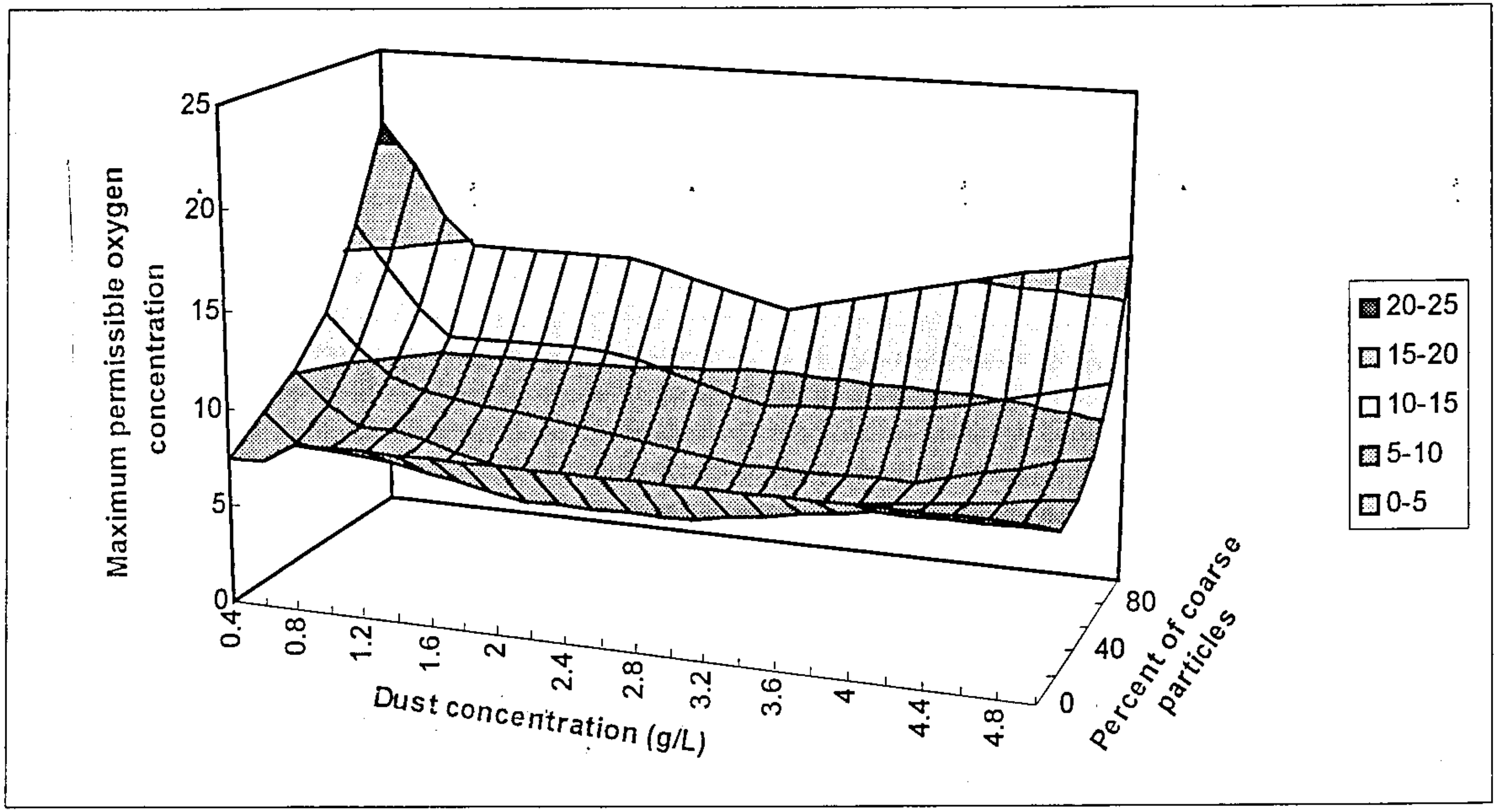

Figure (5.35):variation of maximum permissible oxygen concentration with both percent of coarse particles and dust concentration for oil shale (3-dimensional representation)

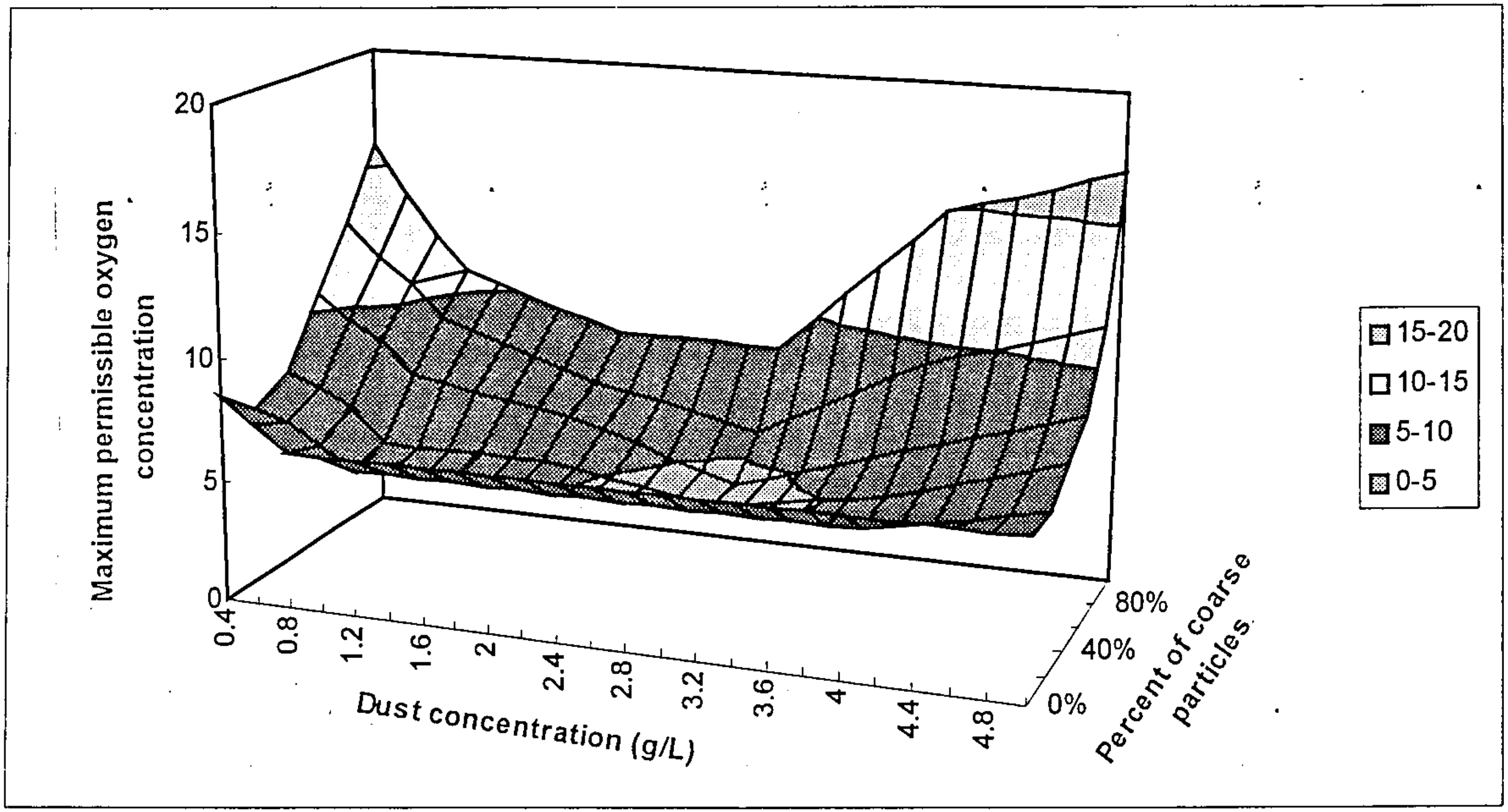

Figure (5.36):variation of maximum permissible oxygen concentration with both percent of coarse particles and dust concentration for olive cake (3-dimensional representation)

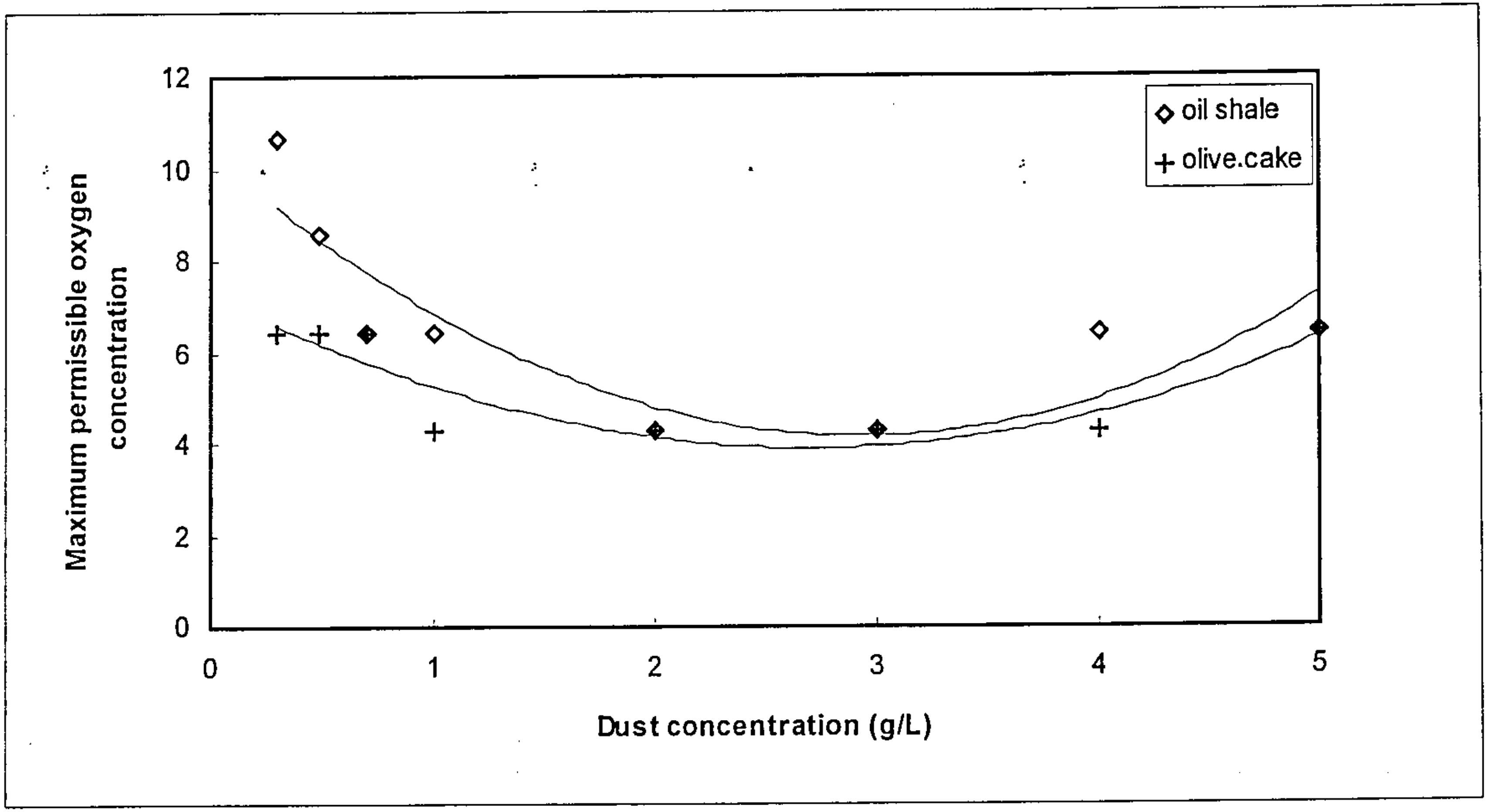

Figure (5.37): variation of maximum permissible oxygen concentration with dust concentration of oil shale and olive cake for (30%) of coarse particles in the mixtures

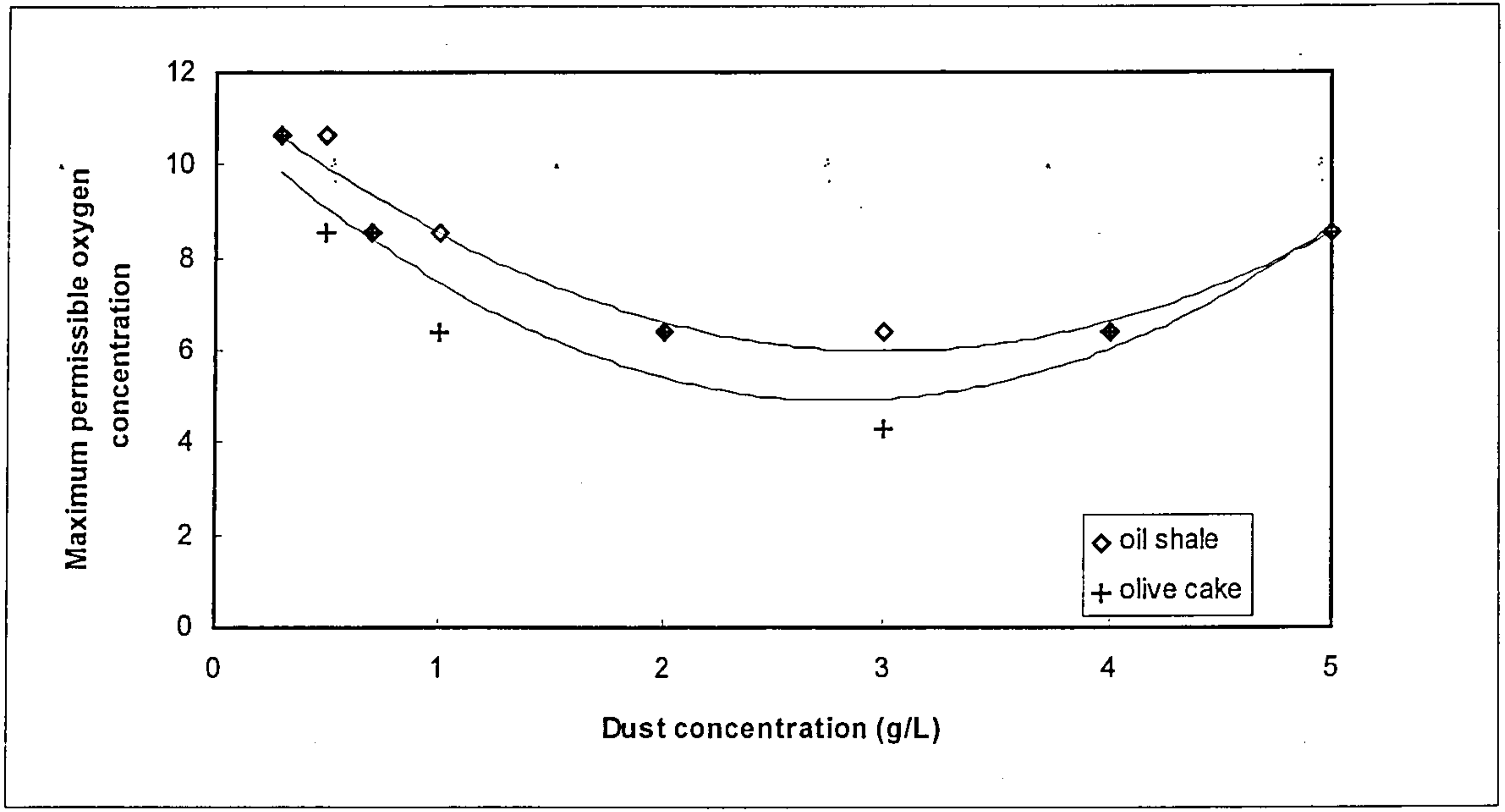

Figure (5.38): variation of maximum permissible oxygen concentration with dust concentration of oil shale and olive cake for (50%) of coarse particles in the mixtures

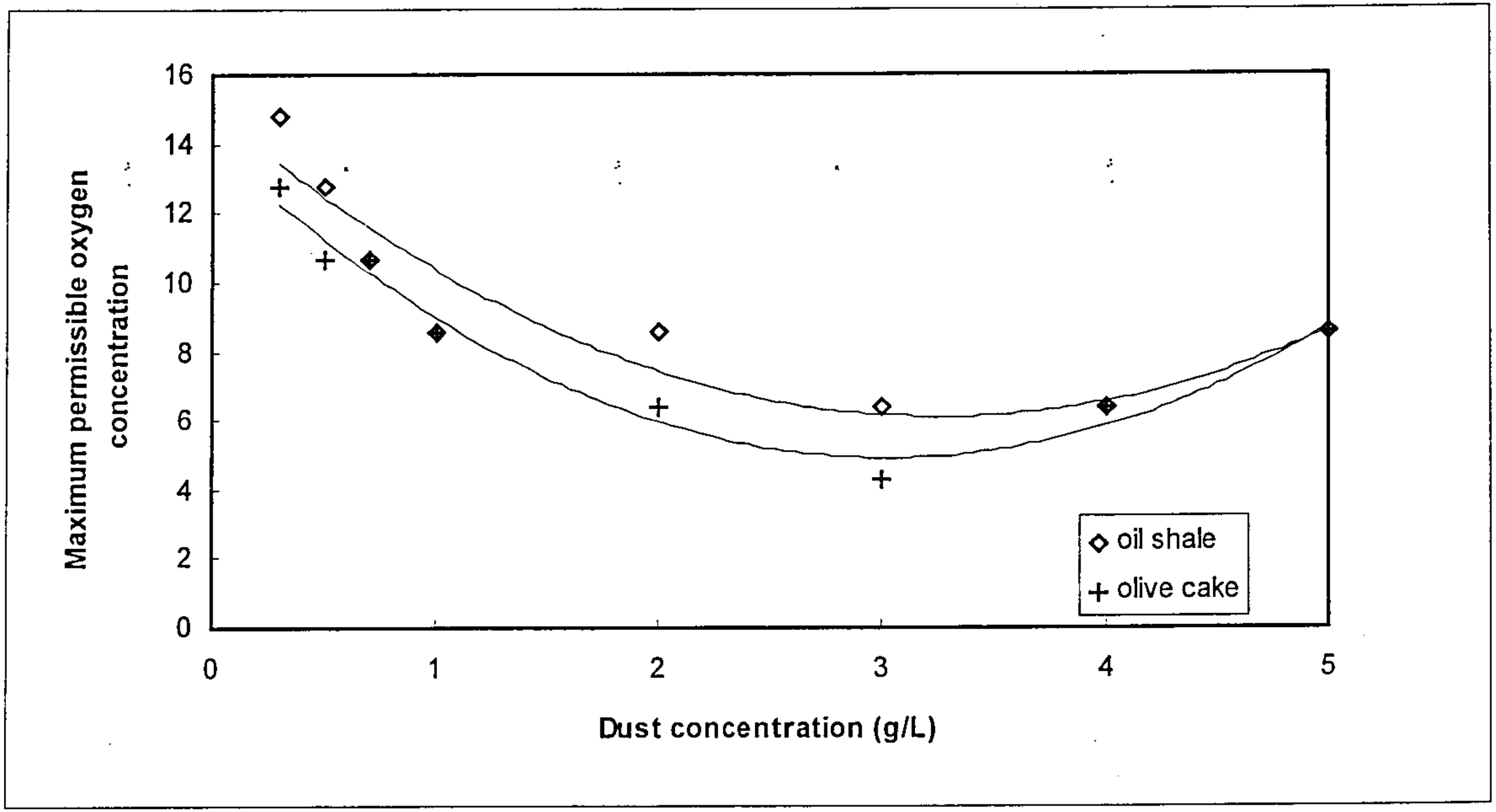

Figure (5.39): variation of maximum permissible oxygen concentration with dust concentration of oil shale and olive cake for (70%) of coarse particles in the mixtures

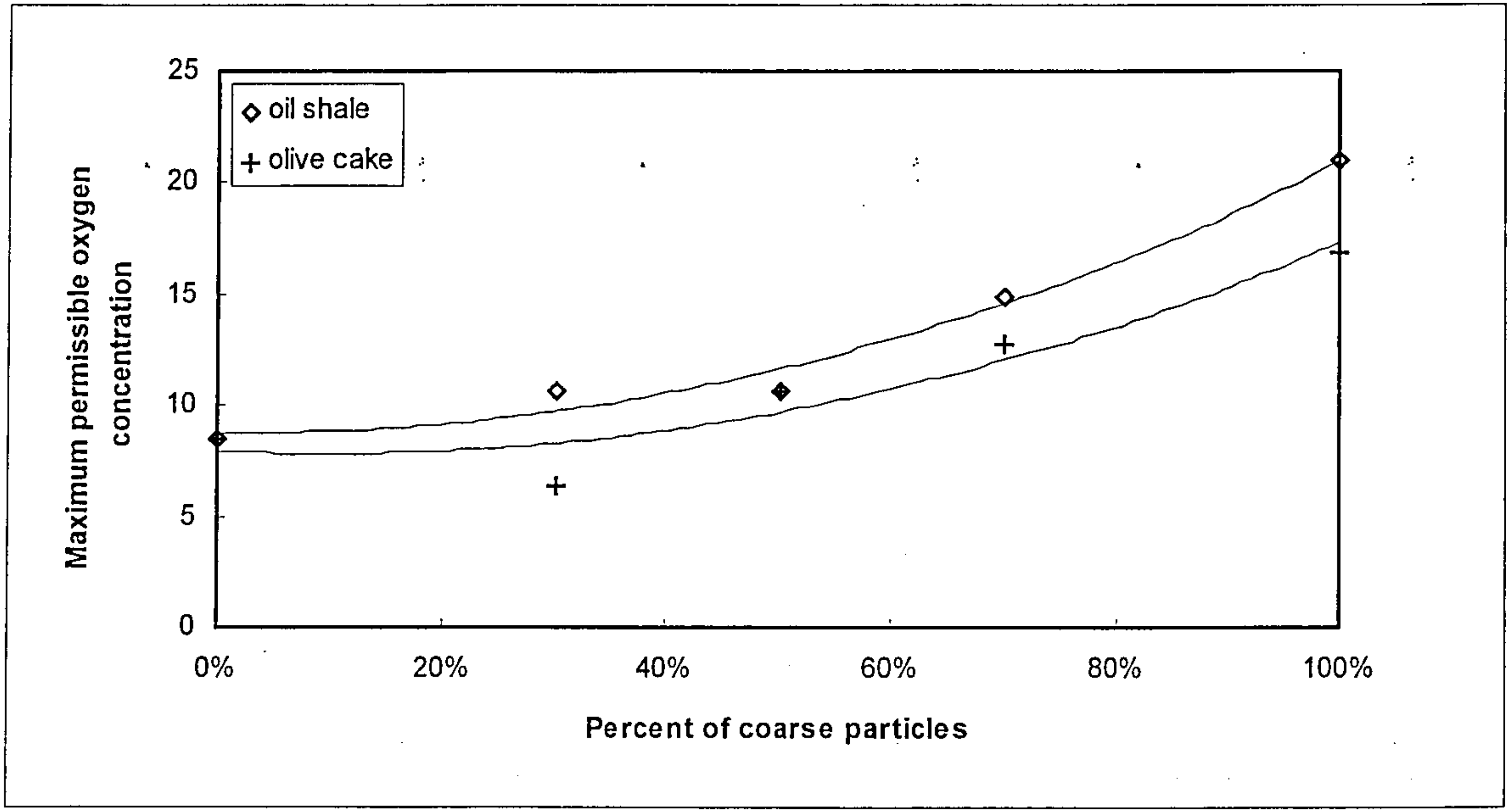

Figure (5.40):variation of maximum permissible oxygen concentration with percent of coarse particles in the mixture for oil shale and olive cake for dust concentration of (0.3g/L)

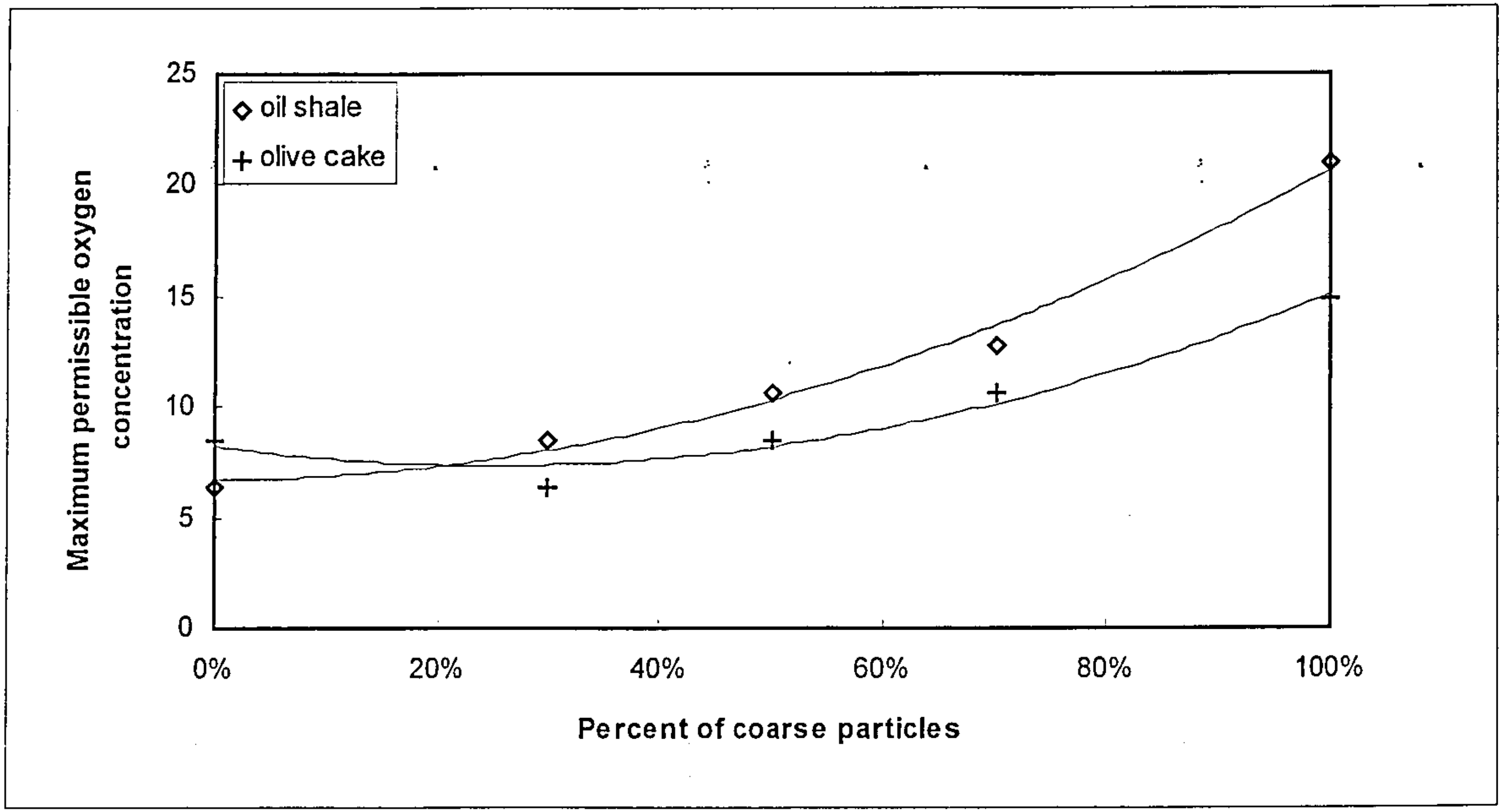

Figure (5.41):variation of maximum permissible oxygen concentration with percent of coarse particles in the mixture for oil shale and olive cake for dust concentration of (0.5g/L)

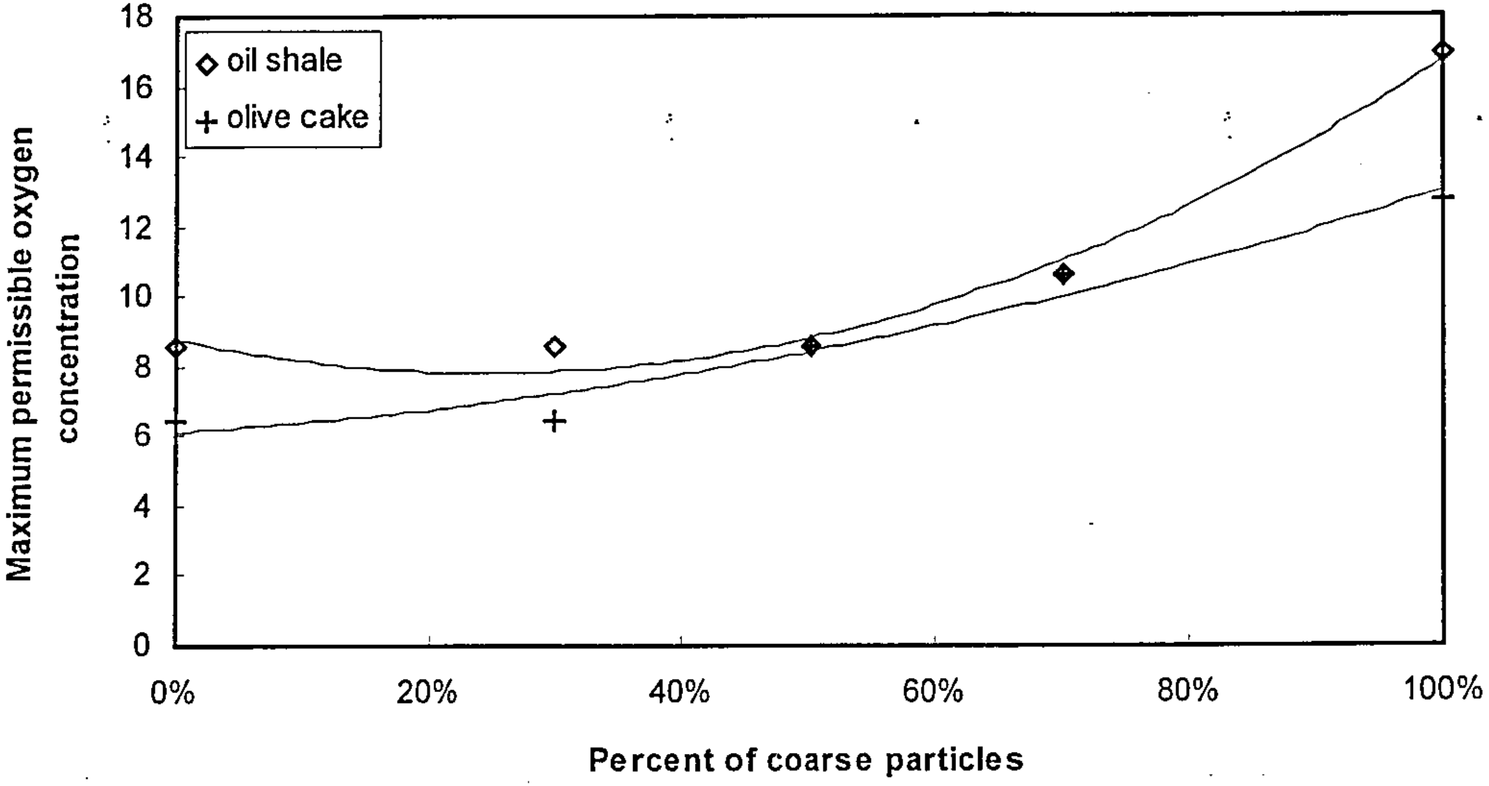

Figure (5.42):variation of maximum permissible oxygen concentration with percent of coarse particles in the mixture for oil shale and olive cake for dust concentration of (0.7g/L)

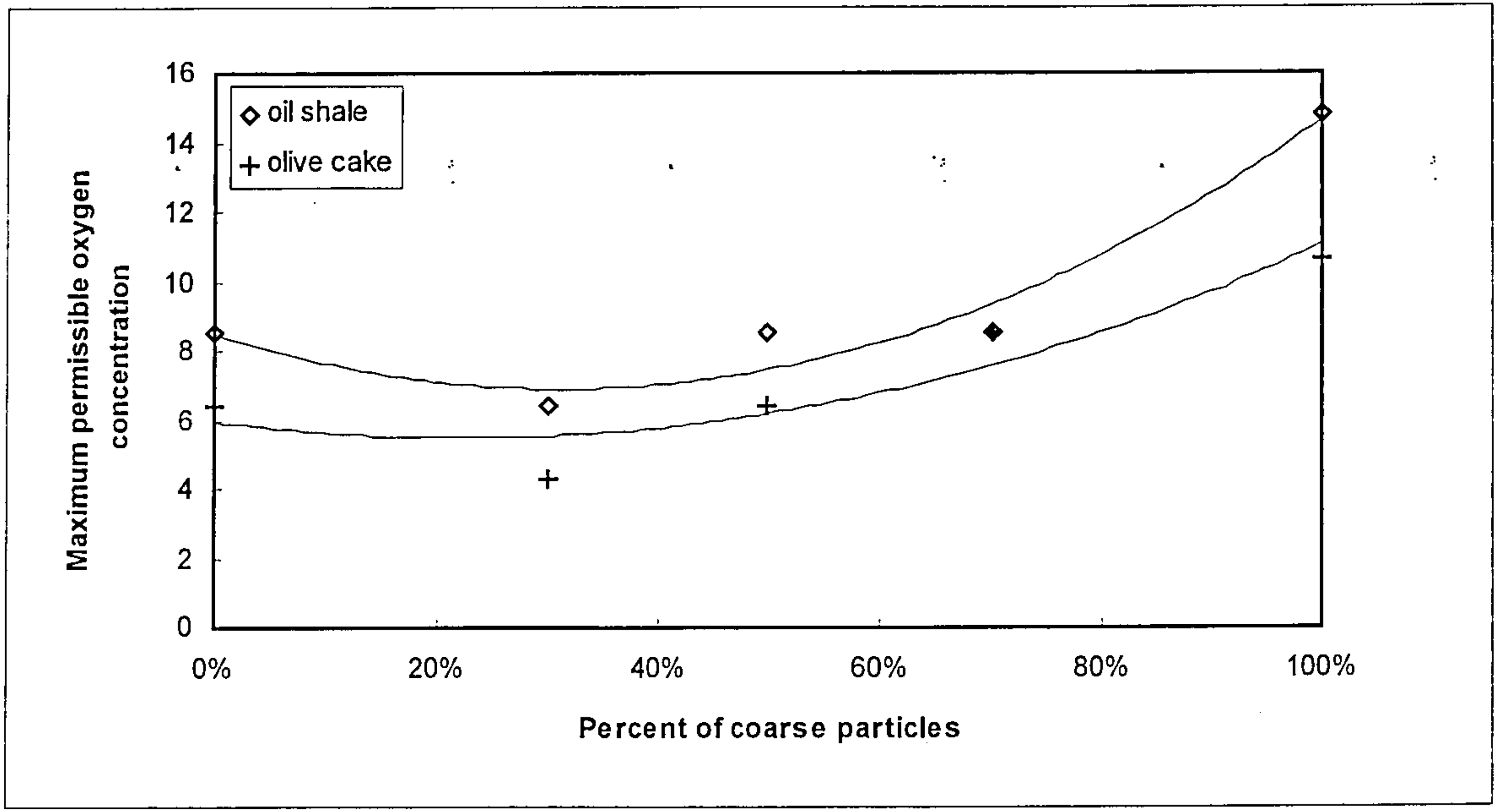

Figure (5.43):variation of maximum permissible oxygen concentration with percent of coarse particles in the mixture for oil shale and olive cake for dust concentration of (1.0g/L)

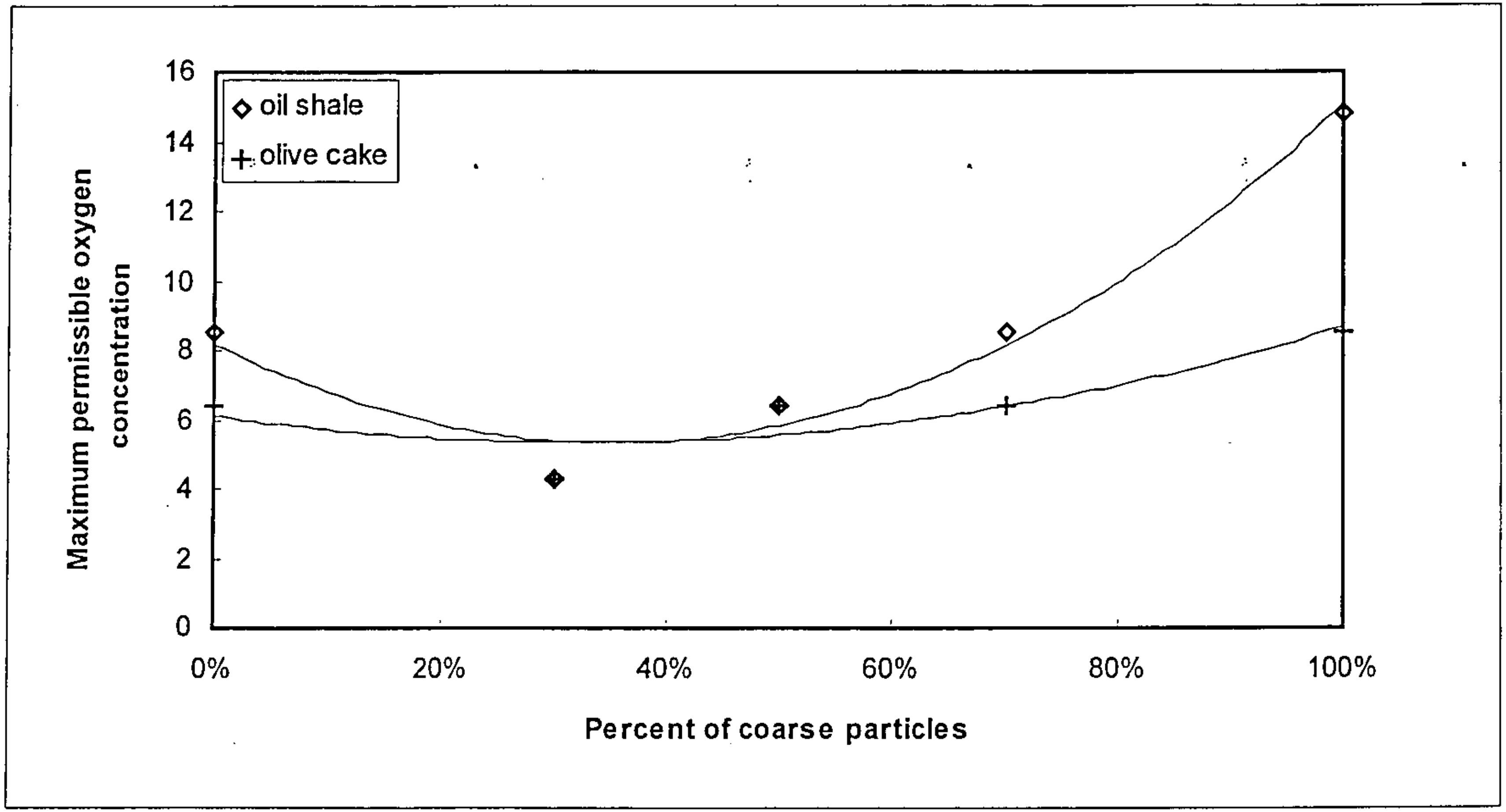

Figure (5.44):variation of maximum permissible oxygen concentration with percent of coarse particles in the mixture for oil shale and olive cake for dust concentration of (2.0g/L)

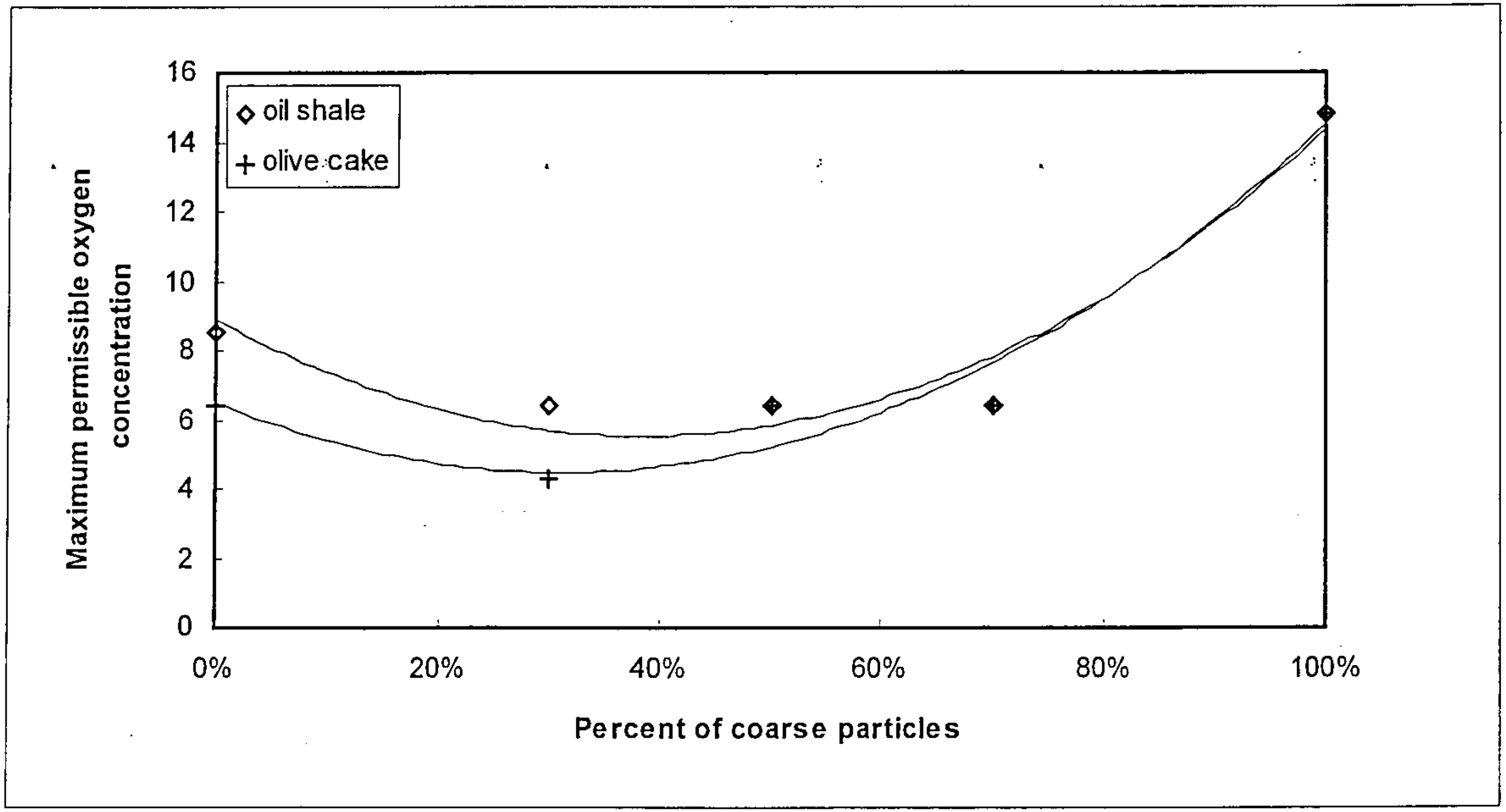

Figure (5.46):variation of maximum permissible oxygen concentration with percent of coarse particles in the mixture for oil shale and olive cake for dust concentration of (4.0g/L)

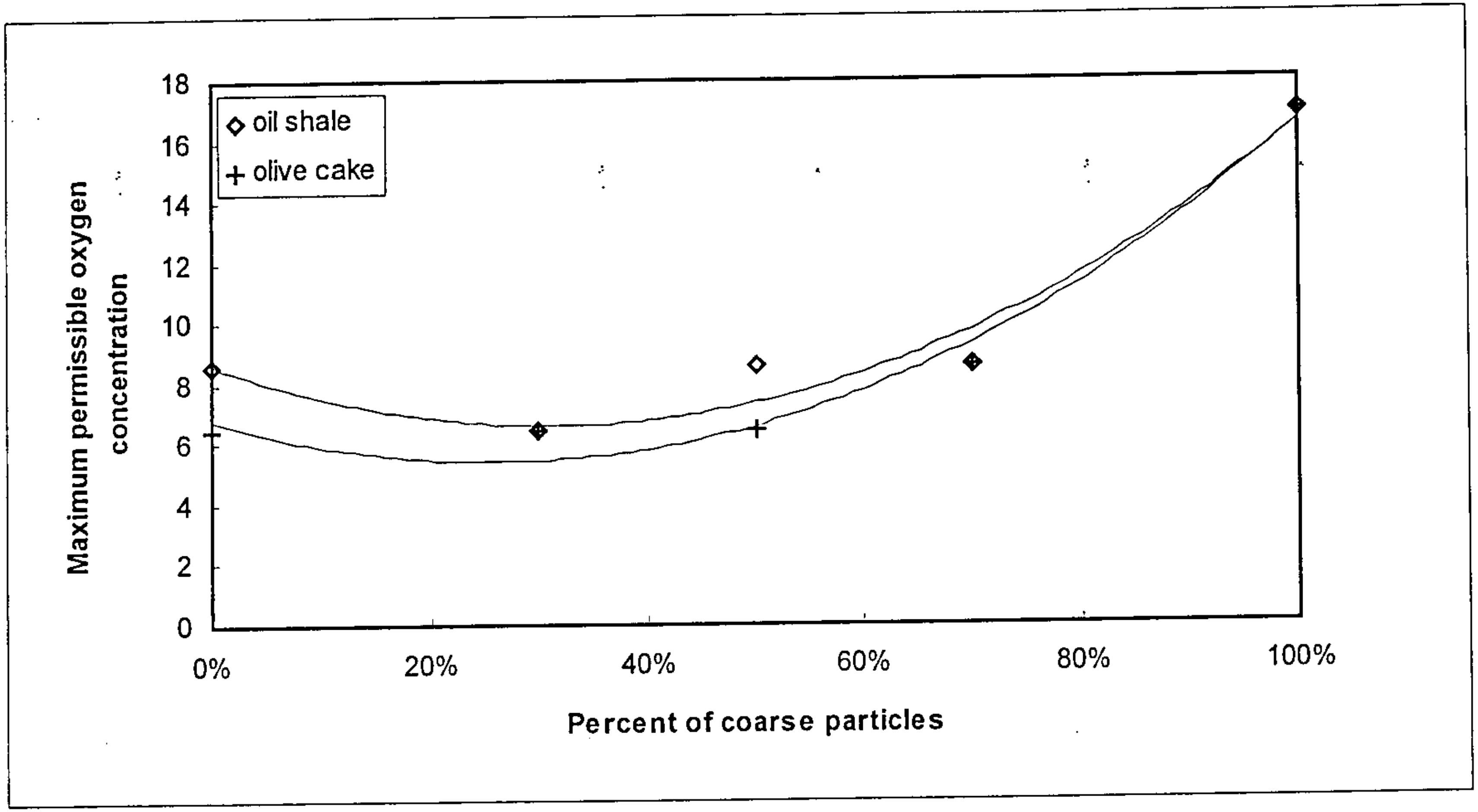

Figure (5.47):variation of maximum permissible oxygen concentration with percent of coarse particles in the mixture for oil shale and olive cake for dust concentration of (5.0g/L)

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Several important points have been emerged from this experimental work, which can be summarized as follows

1- The maximum permissible oxygen concentration for both oil shale and olive cake decreases with dust concentration to a minimum value beyond which it starts to increase for all particle sizes and mixtures of coarse and fine particles.

2- The maximum permissible oxygen concentration increases with increasing the particle size of a given dust concentration.

3- Olive cake is easily ignited than oil shale all over the range of particle sizes, dust concentration and mixtures of coarse and fine particles.

4- The maximum permissible oxygen concentration decreases with an increase of the furnace temperature.

5- To prevent oil shale or olive cake dust explosions at 1000 °C, the maximum permissible oxygen concentration should be 4.3% or less.

6- The mixture with 30% coarse particles is the most easily ignited mixture for both oil shale and olive cake at 1000 °C, and consequently it has the lowest maximum permissible oxygen concentration

7.2 Recommendations

The following are recommended for future work:

1- Using carbon dioxide (CO_2) as an inhibitor of ignition in dust clouds rather than nitrogen.

2- Studying the maximum explosion pressure and maximum rate of pressure rise of the dust explosion.

3- It would be of value to study a mathematical model to predict the parameters of dust explosion as a function of different parameters, such as : dust concentration, particle size.

REFERENCES

Alids, D. F. 1990. Two-Dimensional Analysis of Dust Explosion. *AICHE Journal*, **36 (7)**:1087-1096.

Al-Qubbaj, A. 1996. *Oil Shale Dust Explosion.* Master Thesis, University of Jordan, Jordan.

Amyotte, P. R., Chippett, S. and Pegg, M. J. 1988. Effect of Turbulence on Dust Explosions. *Progress in Energy and Combustion science*, **14 (4)**: 293-310.

Amyotte, P. R., Mintz, K. J., Pegg, M. J. and Sun, Y. H. 1993. The Ignitability of Coal Dust-Air and Methane-Coal Dust in Air Mixtures. *Fuel*, **72 (5)**: 671-679.

Cashdollar, K. L. 1996. Coal Dust Explosibility. *Journal of Loss Prev. Process Ind.*, **9 (1)**: 65-76.

Cassel, H. M. and Liebman, H. 1959. Ignition of Dust Cloud. *Combustion and Flame*, **3**: 467-475.

Health and Safety Executive, Dust Explosion in Factories, UK, 1976.

Hertzberg, M. Cashdollar, K. L. and Zlochower, I. A. 1988. Flammability Limit Measurements for Dust and Gasses. Proc. of the 21st Symp. in Combustion, 303-313, *The combustion Institute*, Pittsburgh.

Kjaldman, L. 1987. Numerical Simulation of Dust Explosion. Proc. of the 2nd International PHOENICS Symp. *Technical Research Center of Finland*, Helsinki, Finland.

Lesikar, B. J., Parnell, C. B. and Garcia, A. 1987. Determination of Grain Dust Explosibility Parameters. *American Society of Agricultural Engineering*, **34 (2)**: 571-576.

Public Fire Brigades, List of Fires and Explosions, 1977-1982, Jordan, 1984.

Long, V. D. and Murray, W. L. 1958., Research Report No. 145, *Safety in Mines Research Establishment*, England.

Mintz, K. J. 1995. Problems in Experimental Measurements of Dust Explosions. *Journal of Hazardous Material*, **42**: 177-186.

Nomura, S. and Tanaka, T. 1992. Theoretical Analysis of Dust Explosions. *Powder Technology*, **71**: 189-196.

Raftery, Monica M. 1968. Explosibility Tests for Industrial Dust. *Fire Research Technical Paper*, **21**.

Rose, H. E. 1970. Ignition of Clouds of Lycopodium. *Industrial Safety*. **15 (3)**: 371-375.

Sweis, F. 1982. *Dust Explosions Studies*. Ph.D. Thesis, University of Manchester, Manchester, UK.

Appendix A: Tables of results

Particle size(µm)	Maximum Permissible Oxygen Concentration								
	0.3	0.5	0.7	1.0	2.0	3.0	4.0	5.0	10.0
<63	8.53	6.42	8.53	8.53	8.53	8.53	8.53	8.53	10.64
75-90	14.82	10.64	10.64	8.53	8.53	8.53	8.53	10.64	12.74
90-125	16.89	14.82	12.74	10.64	8.53	8.53	10.64	12.74	12.74
180-250	18.95	18.95	16.89	12.74	10.64	10.64	12.74	14.82	16.89
250-355	21	21	16.89	14.82	14.82	12.74	14.82	16.89	18.95

Table A.1 Maximum permissible oxygen concentration of oil shale at different Particle sizes for different concentrations.

Particle size(µm)	Maximum Permissible Oxygen Concentration								
	0.3	0.5	0.7	1.0	2.0	3.0	4.0	5.0	10.0
<63	8.53	8.53	6.42	6.42	6.42	6.42	6.42	6.42	6.42
75-90	8.53	6.42	4.29	4.29	4.29	4.29	6.42	8.53	12.74
90-125	10.64	10.64	8.53	8.53	6.42	8.53	8.53	10.64	12.74
180-250	14.82	12.74	12.74	10.64	6.42	8.53	10.64	12.74	14.82
250-355	16.89	14.82	12.74	10.64	8.53	8.53	14.82	16.89	16.89

Table A.2 Maximum permissible oxygen concentration of olive cake at different Particle sizes for different concentrations.

Particle size(µm)	Maximum Permissible Oxygen Concentration								
	0.3	0.5	0.7	1.0	2.0	3.0	4.0	5.0	10.0
0%	8.53	6.42	8.53	8.53	8.53	8.53	8.53	8.53	10.64
30%	10.64	8.53	6.42	6.42	4.29	4.29	6.42	6.42	8.53
50%	10.64	10.64	8.53	8.53	6.42	6.42	6.42	8.53	8.53
70%	14.82	12.74	10.64	8.53	8.53	6.42	6.42	8.53	8.53
100%	21	21	16.89	14.82	14.82	12.74	14.82	16.89	18.95

Table A.3 Maximum permissible oxygen concentration of oil shale at different percents of coarse particles for different concentrations.

Particle size(μm)	Maximum Permissible Oxygen Concentration								
	0.3	0.5	0.7	1.0	2.0	3.0	4.0	5.0	10.0
0%	8.53	8.53	6.42	6.42	6.42	6.42	6.42	6.42	6.42
30%	6.42	6.42	6.42	4.29	4.29	4.29	4.29	6.42	8.53
50%	10.64	8.53	8.53	6.42	6.42	4.29	6.42	8.53	10.64
70%	12.74	10.64	10.64	8.53	6.42	4.29	6.42	8.53	8.53
100%	16.89	14.82	12.74	10.64	8.53	8.53	14.82	16.89	16.89

Table A.4 Maximum permissible oxygen concentration of olive cake at different percents of coarse particles for different concentrations.

Dust concentration (g/L)	Maximum Permissible Oxygen Concentration		
	800	900	1000
0.3	21	21	16.89
0.5	21	21	14.82
0.7	18.95	16.89	12.74
1.0	14.82	12.74	10.64
2.0	12.74	10.64	8.53
3.0	10.64	8.53	8.53
4.0	12.74	12.74	10.64
5.0	16.89	14.82	12.74
10.0	16.89	14.82	12.74

Table A.5 Maximum permissible oxygen concentration of oil shale at different concentrations for different temperatures.

Dust concentration (g/L)	Maximum Permissible Oxygen Concentration		
	800	900	1000
0.3	21	18.95	10.64
0.5	18.95	14.82	10.64
0.7	16.89	12.74	8.53
1.0	14.82	10.64	8.53
2.0	14.82	10.64	6.42
3.0	16.89	10.64	8.53
4.0	18.95	12.74	8.53
5.0	21	14.82	10.64
10.0	21	18.95	12.74

Table A.6 Maximum permissible oxygen concentration of olive cake at different concentrations for different temperatures.

Appendix B: Analysis of the dust

The ultimate analysis of oil shale and olive cake samples as reported by the Natural Resources authority.

Content	Wt. %
Total organic matter	25.88
Moisture content	4.39
Total hydrogen	1.64
Other materials.(by difference)	68.09

Table B1: Ultimate analysis of oil shale

Content	Wt. %
Total organic matter	50.09
Moisture content	6.31
Total hydrogen	6.89
Other materials (by difference)	36.71

Table B2: Ultimate analysis of olive cake

APPENDIX C

BACKGROUND

c.1 Introduction

The explosion of powder or dust can be characterized by the ease with which it ignites and by the violence of the fire or explosion. Although the two are often related it is not necessarily the case that a material easy to ignite, burns violently. Both the ignitability and the effects of ignition may differ according to whether the material is dispersed in a cloud or is more densely packed in a layer or heap.

A dust fire or explosion is essentially a rapid oxidation of the particle surface; therefore, it depends on both the reactivity of the material and the available surface area. There is a strong dependence of ignition properties on particle size, dust with fine particles are more easily ignited and giving more intense explosions.

The water content of the dust may also be a significant factor because evaporation of water can take up some of the heat of reaction and explosions can be considerably affected by small quantities of an additive or impurity in the dust and it is important that these are known.

The behavior of a dust explosion depends not only on the reactivity of the individual particles but also on the way the heat is transmitted between particles. Therefore, ignitability and explosive strength are functions of dust concentration. The ignition of dust in cloud or layer form is a complicated process, An extensive series of tests have been developed over the years to evaluate the ignition properties of materials in a way that can be applied to industrial plants.

c.2 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.

c.3 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 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 (1968).

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 developed at the US Bureau of Mines shown in Fig. (c.1).

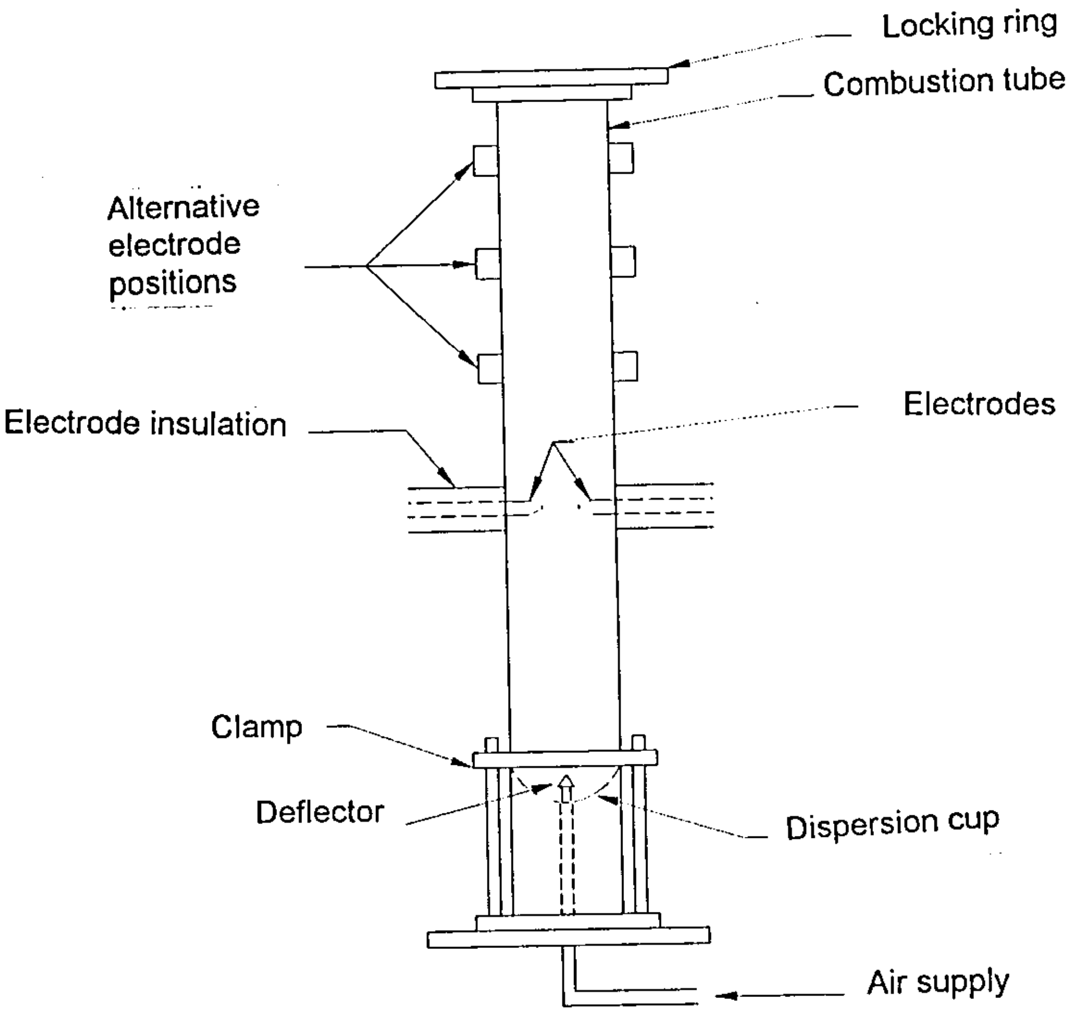

Figure C.1 Vertical tube apparatus

It consists of a perspex combustion tube, 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 liters. 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 kPa (40 $1b/in^2$), 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.

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

2) The Horizontal Tube Apparatus

The horizontal tube apparatus shown in (Fig. c.2) is constructed of glass, which is 1.38 m long and with internal diameter 7.6 cm.

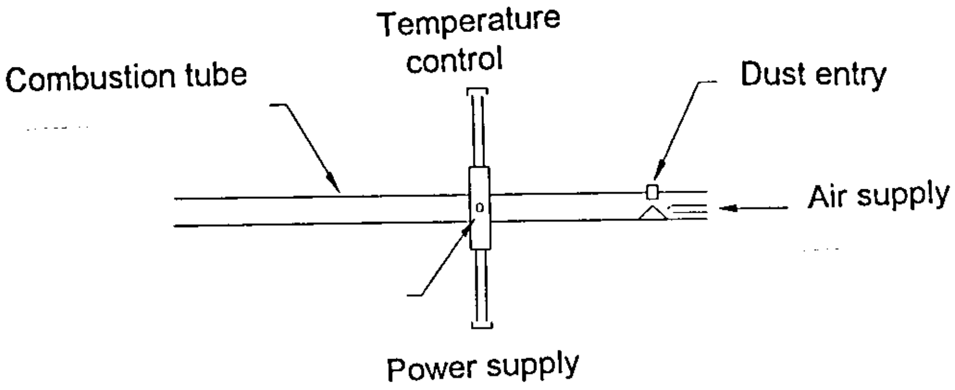

Figure C.2 Horizontal tube apparatus

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, which are easily dispersed. However, it is not recommended for metal dusts which could damage the coil igniter.

3) The Inflammator Apparatus:

With the Inflammator apparatus the dust falls vertically downwards on to the igniting source, Fig. (c.3).

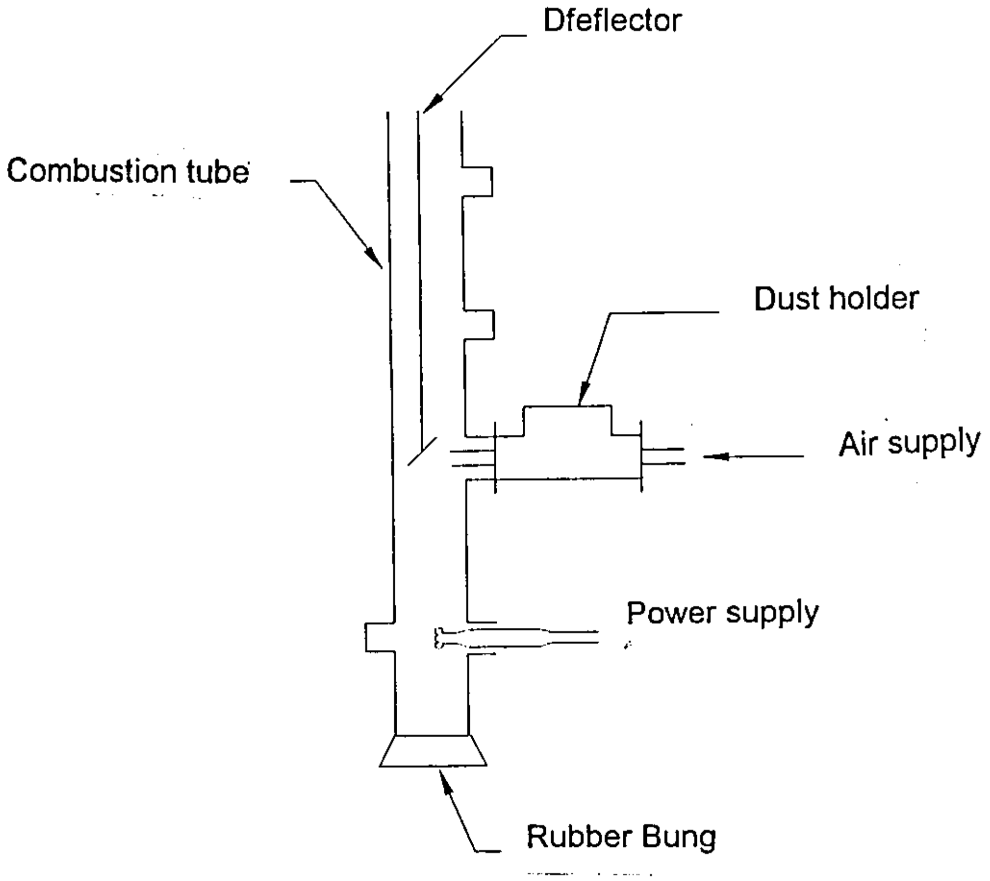

Figure C.3 Inflammator apparatus

It 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 (40 1b/in^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.

c.4 Effects Of A Dust Explosion

The heat produced by the combustion of the dust particles in a dust explosion and, in certain cases, the products of combustion cause a rapid pressure rise at the walls of the vessel containing the dust cloud. In factories it is the effect of this pressure wave on relatively weak items of plant and buildings which has caused the deaths and injuries to persons employed in handling materials giving rise to dust explosions.

Further, since the pressure wave produced by the explosion can cause further dust which may have accumulated in the plant or on internal surfaces of buildings to be thrown into suspension in air, further fuel can thus be fed to the flame and a disastrous secondary explosion can follow.

Additional consequences following a dust explosion pressure wave are the fires that may have been started by the dust flame and the implosion effect on the plant and buildings as the pressure within these rapidly returns to normal.

c.5 Principles Of Explosion Prevention And Protective Measures

In some industrial operations the formation of explosive suspensions in air is inevitable, then most surface precautions against the introduction or generation of sources of ignition must be taken. However, because of unforeseen mechanical or human failures, complete elimination of ignition sources can not be relied upon, particularly where powered machinery is involved. Sooner or later the necessary conditions will occur for a primary dust explosion, namely generation of a suitable cloud of an explosible dust in the presence of a source of ignition. To avoid disaster, reliance must be placed on the adequate functioning of explosion protection provided in advance. Explosion protection will be summarized as follows.

a- Prevention of ignition.

b- Suppression or containment of the explosion flame.

c- Allowing the explosion to take its full course, but to ensure that it does so safely.

The method of protection selected will depend upon a number of factors including the design of the industrial process, the running costs, the economics of alternative protection methods, the extent to which an explosion and its consequences can be foreseen, and the requirements of any authorities concerned.

As a basic technical principle the explosion hazard in a given plant with given materials increases as the amount of energy released by the explosion increases. In trying to minimize the energy developed by an explosion, the most attractive method of protection, technically at least, is to prevent the ignition of the dust cloud, as well as eliminating sources of ignition, an additional method which has been used with success is to reduce or eliminate the presence of the oxidant gas (usually the oxygen of the air). This may be done by

The advantages of using inerting are that explosions are avoided, by positive means, and that in ensuring that the inerting system is working probably, information on the general running of the plant is obtained which assists the rapid detection of malfunctioning of the process. The disadvantages of the inerting technique are that it may only be applicable to closed or semi-closed plant; otherwise the loss of inerting gas is expensive. Monitoring devices of the gas concentrations have to be installed and possible toxicity or suffocation risks to operatives have to be guarded against. The technique may therefore only be practicable and economic in a minority of instances, but it should be considered in the design stage of a new plant as a possible means of obtaining protections.

Once a dust explosion has begun to propagate, its energy may be minimized be either suppressing it rapidly or else by restricting its spread through the plant.

ملخص

كبح الانفجار الغباري

إعداد

أحمد حسن صخريه

المشرف

الأستاذ الدكتور محمد أحمد حمدان

تهدف هذه الدراسة إلى دراسة كبح الانفجار الغباري للصخر الزيتي و جفت الزيتون عند استخدامهما كمصدر بديل للطاقه. اهتمام خاص أعطي لتأثير حجم الحبيبات و أمزجه من الحبيبات الناعمة و الخشنة من نفس المادة على الحد الأعلى المسموح به لتركيز الأكسجين لمنع الانفجار الغباري على عدة تراكيز باستخدام النيتروجين كغاز مخفف لتركيز الأكسجين.

وجد أن جفت الزيتون يشتعل بسهولة أكبر من الصخر الزيتي على كافة أحجام الحبيبات، التركيز، وأمزجة الحبيبات الناعمة والخشنة.

تمت التجارب على أحجام مختلفة، ووجد أن الحد الأعلى المسموح به لتركيز الأكسجين يزداد بازدياد حجم الحبيبات لكل من الصخر الزيتي وجف الزيتون. أمزجة مختلفة من الحبيبات الناعمة والخشنة تم دراستها ووجد أن المزيج المحتوي على ٣٠% حبيبات خشنة هو الأكثر قابلية للانفجار لكل من الصخر الزيتي وجفت الزيتون.